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ORIGINAL RESEARCH

Degradation of the compression strength of spacers made of high-density pressboard used in power transformers under the influence of thermal ageing

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Abstract The structural components inside power transformers are commonly made of high-density pressboard, due to its suitable mechanical and dielectric properties. Among these components are the spacers used in the windings of transformers, which are subjected to compressive loading during operation. The spacers are immersed in dielectric liquid and subjected to high temperatures and chemical reactions during the lifespan of the transformer, which result in the degradation of their dielectric and mechanical properties. The performance and reliability of the power transformer greatly depends on its mechanical integrity, so it is necessary to understand how ageing degrades the mechanical response of the high-density pressboard. In this study, spacers made of high-density pressboard and pieces of copper conductor were immersed in uninhibited paraffinic oil and aged at 150 °C for different periods of time, trying to realistically represent the process suffered by a power transformer during its whole lifespan. The evolution caused by the thermal ageing over some chemical parameters (acidity and moisture content) and dielectric properties (AC breakdown voltage, dielectric dissipation factor, resistivity and degree of polymerisation) of the oil and the pressboard was studied experimentally. Compressive mechanical tests were performed on samples of the aged high-density pressboard, and the compressive stiffness during the ageing process was related with other chemical and dielectric parameters.

Keywords High-density pressboard · Power transformer · Thermal ageing · Compressive mechanical properties · Degree of polymerisation · Acidity

Introduction

Power transformers are key elements of the electrical system and play a vital role in the transmission and distribution of electrical energy. Transformers change the values of the alternating voltage and current, in order to reduce the energy losses and ensure the safety of the users. The reliability of the whole electric system depends on the lifespan of power transformers. Inside them, different kinds of insulation are used to separate the parts which are at a different potential. The most typical insulating liquid is still mineral oil, obtained from crude oil, though various types of ester liquids have been increasingly used in recent years. The insulating oil has two important functions: to strengthen the dielectric properties of

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solid insulation by impregnation, electrically insulating active parts from grounded ones; and to remove the heat generated by the windings of the transformers during service (Fofana et al. 2011). Regarding the solid insulation, paper and pressboard are the most common materials, as their economic cost and physical–chemical properties are appropriate to be used as dielectrics.

In particular, high-density pressboard is used in the major insulation of power transformers. It provides location of other components, and withstands mechanical forces during transportation and service, maintaining the shapes and dimensions of the oil ducts when they are electrically stressed (Bertagnolli 2014). Typically, around 30% of the total winding height is composed of solid insulation materials (Hashemnia et al. 2012). Part of the mechanical resistance of the whole system relies on those elements, which are subjected to both a constant compressive load applied during manufacturing and to a superimposed pulsating compressive force during service (Girlanda et al. 2016). Moreover, power transformers are affected by high temperatures and chemical reactions, which compromise the integrity of the solid insulation, degrading its thermal, electric and mechanical properties over time. It is generally acknowledged that an inadequate response of the cellulosic insulation is one of the critical reasons for transformer failure. Therefore, a better comprehension of its mechanical response and its evolution due to ageing could be helpful to ensure the quality of the cellulosic components during manufacturing, transportation, and operation.

A number of the studies that analyse the mechanical response of board materials was reviewed in Oria et al. (2019). Some of their general features are a highly anisotropic behaviour, non-linear response, different behaviour in tension and compression, visco-elasticity, strain rate sensitivity, damage evolution, and dependency on the moisture content. Here, we will focus on the studies analysing the mechanical behaviour in the through-thickness direction (ZD) of board materials, as the spacers of a power transformer are subjected to compression in ZD, see Sect. "Materials". Some of them propose theoretical models (Stenberg et al. 2001a, b; Stenberg 2003), whose practical application for the case of transformers is limited. Others consider materials used in practice as insulation of transformers and the impact of some relevant variables, such as temperature or moisture content (Girlanda et al. 2012, 2014, 2015). However, it is very infrequent to find studies which actually subject the pressboard to conditions similar to those occurring in power transformers. One example is the work by Swihart and Wright (1976), where the dynamic response of pressboard spacers subjected to transient loading was studied, at different temperatures and preload pressures. More recently, the influence of moisture, temperature and ageing of the pressboard on its compressibility was analysed by Naranpanawa et al. (2018); Ekanayake et al. (2020).

Furthermore, although it is possible to characterise the state of the dielectric oil in a power transformer during service by sample-taking, in general, this method cannot be applied for the solid insulation, because the removal of a relevant amount of paper/board could permanently damage the transformer. Consequently, non-destructive techniques are required to measure parameters that enable an indirect estimation of the loss of mechanical integrity. The degree of polymerisation (DP), which quantifies the average length of the cellulose polymer, is one of the most commonly used parameters. The number of anhydroglucose units in the cellulose chain is the direct indication of the decomposition of the cellulose macromolecules and the formation of ageing products, and gives objective information about the solid insulation health and its electrical breakdown strength (Muhr and Sumereder 2008; Arshad and Islam 2011). However, a sample of insulating paper or board is needed, which makes it unsuitable for operating transformers (Abu-Elanien and Salama 2010). To avoid that limitation, there are studies that correlate other parameters with the DP and make it possible to indirectly derive the mechanical properties of the solid insulation.

Gas chromatography analysis can be used to measure dissolved gases in the oil, such as: CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 (Carrascal et al. 2018). The loss of strength can be correlated with level variations in the ratio CO_2/CO, as the thermal degradation of cellulose produces CO_2 at low temperature and CO at high temperature, increasing the probability of failure significantly at a CO_2/CO ratio of less than 2 (Nelson 1989; Abu-Elanien and Salama 2010). During ageing of the cellulosic insulation, the breaking of the polymer chains generates glucose monomer units which, after several chemical reactions, become one of a family of derivatives of 2-furaldehyde (2-FAL) or furanic compounds (Abu-Elanien and Salama 2010). When the DP of the paper/board drops below about 400, the concentration of furanic compounds in the oil begins to rise exponentially to a maximum value and then decreases, when the insulation is fully degraded (Emsley et al. 2000). The predominant ageing product is always 2-FAL, so the furfural analysis of oil could be particularly useful for the detection of high rates of ageing. The total furfural concentration has a strong empirical correlation with the DP, and a linear relationship in the logarithmic scale between both is commonly accepted (Fofana et al. 2011). However, the absolute correlation of furanic compounds to DP varies from one transformer to another and depends on humidity, operating temperature, type of oil and paper, manufacturer and design ("International Standard: Power Transformers—Part 1: General. IEC 60076-1" 2011). Different physical processes cause the absorption of environmental humidity in the transformer and increase the ageing rate and failure probability as compared to dry conditions, accelerating the depolymerisation of the cellulosic insulation and reducing the breakdown voltage and dielectric strength of dielectric oil (Muhr and Sumereder 2008; Arshad and Islam 2011). Moreover, water forms as a reaction product of the chemical reactions that happen during the degradation of the cellulose and the ageing of oil.

The compressive mechanical response in ZD of high-density pressboard under realistic operating conditions has not been well documented in the literature, leading to difficulties in understanding the loss of mechanical integrity of the spacers, made of high-density pressboard, of a core-type power transformer. Reliable techniques are required to detect loose clamping conditions in the winding of transformers when they are affected by compressive loading, caused in-service by axial electromagnetic forces or other mechanical loads, at different ageing levels during their whole operating life. A study is needed on the influence of both the dielectric oil in which the solid insulation is immersed and the ageing conditions on its compressive response. Thus, the high-density pressboard was subjected to a pronounced thermal ageing process, trying to represent the whole operating life of the power transformer. The remainder of this paper is organised as follows: first, the studied materials (high-density pressboard insulation immersed into paraffinic dielectric oil) and applied experimental methods are described, see Sect. "Materials and methods". Then, Sect. "Experimental results" reports the experimental results derived from laboratory tests (the accelerated ageing process, and chemical, dielectric and mechanical tests). Those results are discussed in Sect. "Discussion", and the conclusions of this study can be found in Sect. "Conclusions".

Materials and methods

Materials

The coils of oil-filled core-type power transformers consist of a number of stacked layers of insulated conductors. These winding layers are separated by radial spacers made of pressboard, arranged perpendicularly to the conductors, see Fig. 1, which provide support and distance between the winding disks, as well as free passage to the dielectric oil through horizontal cooling ducts (Bertagnolli 2014). Here, the mechanical response of radial spacers made of high-density pressboard, provided by the company Imefy, was analysed. The raw material was unbleached kraft pulp and the surface had wire marks; other manufacturing properties are listed in Table 1. Furthermore, the diverse types of insulating liquids vary on their dielectric and chemical properties and are going to affect the ageing that the solid insulation suffers differently. As mineral oil is still the most frequent dielectric liquid used in power transformers, in this case, the pressboard has been immersed into uninhibited paraffinic oil, whose properties are listed in Table 2, for its thermal ageing process, described in Sect. "Accelerated thermal ageing of the spacers made of high-density pressboard".

Experimental methods

Accelerated thermal ageing of the spacers made of high-density pressboard

Typical values of the temperature inside a power transformer are between 60 and 90 °C and, at those temperatures, the lifespan of the components inside the electrical machine could be up to 40 years. However, as a result of overloading and of prolonged power–frequency voltage rise, the temperature

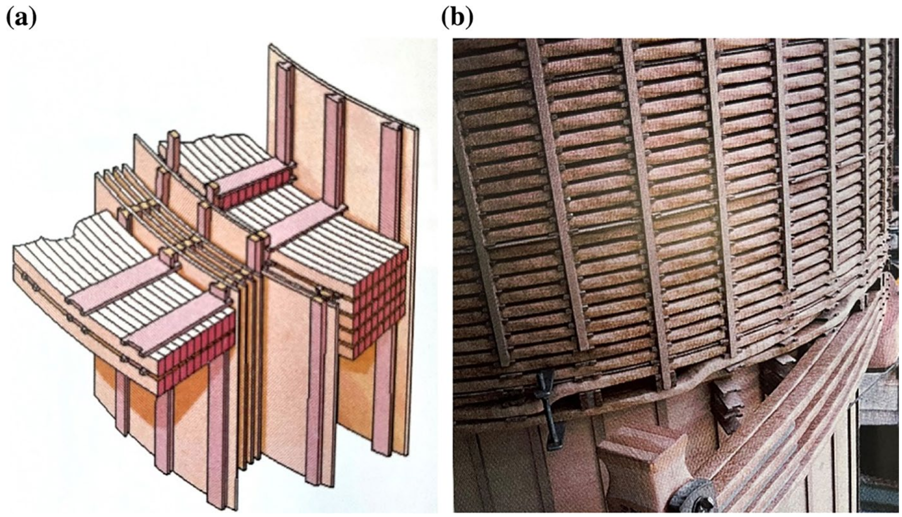

Fig. 1 **a** Diagram of a partial section of two windings in a core-type transformer with radial spacers between the conductors. **b** Real coil of a core-type transformer with pressboard radial spacers, from (Bertagnolli 2014)

Table 1 Manufacturing properties of the tested radial spacers made of high-density pressboard

Property	Unit	Value
Thermal class	°C	105
Apparent density	g/cm^3	1.2
Nominal Thickness	mm	2
Tensile Strength in MD	MPa	124
Tensile Strength in CD	MPa	92
Elongation at breakage in MD	%	3.9
Elongation at breakage in CD	%	4.6
Compressibility	%	4.8
Shrinkage, in ZD	%	4.4
Shrinkage, in MD	%	0.4
Shrinkage, in CD	%	0.5
Oil absorption	%	13

Table 2 Main properties of the paraffinic dielectric oil used in the experiments

Property	Unit	Value
Density at 20 °C	g/cm^3	0.839
Viscosity at 40 °C	mm^2/s	9.98
Viscosity at − 30 °C	mm^2/s	925.85
Flash point	°C	176
Pour point	°C	− 48
Interfacial tension	mN/m	43
Dielectric dissipation factor, 90°C	–	0.00198
Acidity	mg KOH/g	< 0.01
Water content	mg/kg	15
Furfural content	mg/kg	< 0.05

rises. An electrical overload produces a temperature increase in the power transformer, which reduces both the dielectric strength and the ohmic resistance of paper, resulting in the flow of more current in the insulation (Kulkarni and Khaparde 2004). Due to the increase in dielectric loss, insulation temperature goes up higher, and it may finally lead to the current run-away condition and eventual breakdown. Besides, as paper is heated, a number of physical and chemical changes affect its properties.

Then, in order to study how the mechanical and dielectric properties of the solid insulation in a power transformer vary throughout its whole lifespan, accelerated thermal tests are widely used. In the present study, first of all, square samples of side 30 mm were made from the high-density pressboard spacers. Then, those samples were introduced into an oven, together with pieces of common thin Kraft paper insulation, and dried at 105 °C for 4 h, see Fig. 2a. The final moisture content of the Kraft paper after the drying process was 1%, measured according to "IEC 60814:1997. Insulating Liquids–Oil-Impregnated Paper and Pressboard—Determination of Water by Automatic Coulometric Karl Fischer Titration" (1997). The moisture content of the high-density pressboard could not be precisely measured, due to its greater thickness and porous microstructure, but a constant mass of pressboard was reached at the end

(a) (b)

Fig. 2 **a** Initial drying process for the solid dielectric materials. **b** Vessel being prepared for the ageing process

of the drying process, meaning that a higher reduction in moisture content was not possible with the laboratory equipment available. The paraffinic oil was also vacuum-dried at 105 °C for 3 h, to reduce its initial moisture content up to 32.1 ppm. After drying, the pressboard was immersed in oil for its impregnation, at 60 °C during 24 h.

After the initial drying and oil-impregnation, the pressboard samples were divided into groups of 45 samples (with a total mass of approximately 95 g), which were introduced into a stainless-steel vessel filled with 700 ml of mineral oil, and with some pieces of copper conductor (with a total mass of 1340 g), in approximately the same pressboard/copper proportion that we find in the windings of power transformers, to include any possible catalytic effect of this material in the ageing of the pressboard. For comparison purposes, the mass ratio of copper/oil used in this work coincides with that used in Oria et al. (2021). Once closed, the vessels were vacuum-sealed, and an inert atmosphere was created by filling them with nitrogen, see Fig. 2b. After that, they were introduced into temperature-controlled ovens and aged at 150 °C for different durations: 3 days, 1 week, 2 weeks, 6 weeks, 12 weeks and 20 weeks. Some of them were not aged and will be considered as the initial condition of the insulation material. Pieces of thin Kraft paper insulation were also introduced into each vessel, in order to compare their state with that of the high-density pressboard when they are subjected to the same ageing process.

Chemical and dielectric characterisation of the aged high-density pressboard

Different dielectric properties of the paraffinic oil were measured to characterise its degradation. One of them was its AC breakdown voltage (BDV), which is defined as the minimum voltage that causes a portion of the dielectric liquid to experience electrical breakdown and become electrically conductive. The BDV was measured at room temperature following "IEC 60156. Insulating Liquids—Determination of the Breakdown Voltage at Power Frequency—Test Method" (2018). Semi spherical electrodes separated by 2.5 mm oil gap were used. The voltage was increased from 0 kV up to the voltage at which the breakdown occurred, with a 2 kV/s rate.

The dielectric dissipation factor (tan δ), relative permittivity and resistivity of the oil quantify the dielectric losses in the insulating fluid when used in an alternating electric field. The relative permittivity is a nondimensional physical value which indicates the ability of the oil to polarise and acquire electrical capacity. The dielectric dissipation factor is defined as the ratio of the imaginary (ϵ'') to the real part (ϵ') of the permittivity: $\tan\delta = \frac{\epsilon''}{\epsilon'}$, and represents the dielectric loss in the insulating fluid. Tan δ is usually used as an ageing indicator, since it depends on the polarity of the sample, which increased with the ageing due to the appearance of pollutants in the dielectric liquid. The resistivity of the oil is another essential parameter to assess the transformer insulation condition, based on the fact that its value is sensitive to the oil degradation (Mu et al. 2016). The previous parameters were measured in the same laboratory test, which was carried out at 90 °C. The tan δ and permittivity were determined at 50 Hz, whereas the resistivity was measured in direct current at 500 V, following "IEC 60247. Measurement of Relative Permittivity, Dielectric Dissipation Factor and d.c. Resistivity of Insulating Liquids" (2004).

In power transformers filled with mineral oil, thermal hydrolysis is one of the main degradation processes affecting the solid insulation. The rate of chain scissions in the cellulose depends on the carboxylic acids dissociated in water. As both water and carboxylic acids are produced during ageing of cellulose, this process auto accelerates during ageing (Mohan Rao et al. 2021). Due to the crucial impact of moisture content on the dielectric properties of the oil and, also, on the mechanical performance of dielectric paper and board, as explained in Sect. "Introduction", the moisture content was measured through Karl Fischer titration following "IEC 60814:1997. Insulating Liquids–Oil-Impregnated Paper and Pressboard—Determination of Water by Automatic Coulometric Karl Fischer Titration" (1997). The generated acids increase the ageing rate of the solid insulation, so this parameter is commonly used as an ageing indicator (see, for instance, Yoshida et al. (1987); Emsley et al. (2000); Coulibaly et al. (2013); Matharage et al. (2016)). In the present investigation, acidity of the oil was measured through potentiometric titration according to "IEC 62021-1. Insulating Liquids—Determination of Acidity—Part 1: Automatic Potentiometric Titration" (2003).

Finally, the polymerisation degree (DP) is the most frequent parameter for the characterisation of the solid cellulosic insulation, as mentioned in Sect. "Introduction", and was obtained here according to "ASTM D4243. Standard Test Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards" (2016). In the literature devoted to dielectric materials in power transformers, it is more frequent to find typical DP values of aged thin insulation wrapping the windings of transformers than those of aged high-density pressboard. Thus, for comparison purposes, it was of interest to determine the DP value for samples of thin Kraft paper subjected to the same thermal ageing process of the pressboard inside the vessels. To measure the DP of the aged high-density pressboard, firstly, it was de-oiled using distilled hexane. Then, a sample of said material was crumbled and solved in 22.5 g of deionised water and 24.75 g of cupriethylenediamine hydroxide solution. The solution was submitted to magnetic stirring for 16 h, with glass balls filling the air gap of the vial to avoid moisture absorption. Then, its kinematic viscosity at 20 °C was measured, which is related to the molecular weight of the material.

The variation of the said chemical and dielectric properties as a result of thermal ageing was measured and is presented in Sect. "Chemical and dielectric properties of the aged high-density pressboard".

Compressive mechanical characterisation of the aged high-density pressboard

The main purpose of this study is to analyse the mechanical response to compressive loading of spacers made of commercial high-density pressboard. There are two main differences between the assessment of tensile and compressive mechanical properties of the cellulosic insulation. The first is that the amount of material needed to perform a tensile test is much higher than that required for a compressive test. This is due to the fact that the length of the paper sample affects its response to tension and the particular failure mechanism, as reported by Tryding (1996). In the case of a compressive test over pressboard components, the mechanical response is independent from the size of the tested sample, and this is an advantage, because it would allow the extraction of small samples for the monitoring of an operating transformer, which could be useful in some situations. The other difference is that there is a standard of widespread use for obtaining tensile properties "ISO 1924-2:2008. Paper and Board. Determination of Tensile Properties. Part 2: Constant Rate of Elongation Method (20 Mm/Min)" (2008), but there are no accepted standards to measure compressive properties of pressboard used for electrical purposes.

Some publications, such as Naranpanawa et al. (2018); Ekanayake et al. (2020), consider the variation of the compressibility of high-density pressboard, which is the compressive strain (%) for one particular compressive stress (MPa), depending on different testing conditions (ageing, temperature or moisture content). There are standards for other materials, such as concrete and polymers, see "EN 12390-13. Testing Hardened Concrete—Part 13: Determination of

Secant Modulus of Elasticity in Compression" 2021; "EN 13146-9. Railway Applications—Track—Test Methods for Fastening Systems—Part 9: Determination of Stiffness" (2020), which consider the compressive stiffness as the key parameter for describing the compressive mechanical response. This parameter, in this case, would measure the ability of the pressboard to withstand deformations in the thickness direction when subjected to compressive loads. If the stiffness is high, that implies lower deformations in the components made of high-density pressboard, and a better mechanical integrity for the whole power transformer. It is, then, of interest to determine how the compressive stiffness varies depending on the ageing duration, and if the presence of the dielectric oil at a certain temperature affects its value.

The small thickness of the pressboard, of only 2 mm, makes it unsuitable to measure deformations while performing the compressive tests over a single square sample. As it is easier to measure larger deformations, leading to more precise and representative values, 5 square pressboard samples, with a 30 mm side, were stacked to make a prism that was subjected to three cycles of loading and unloading by means of a servo-hydraulic universal testing machine, equipped with a ± 5 kN load cell and an actuator with a ± 50 mm stroke. The load was transferred through a 24 mm diameter steel loading plate equipped with a ball joint ensuring that the loading is perpendicular to the pressboard faces, see Fig. 3a. According to Naranpanawa et al. (2018), pre-compression of the pressboard has a relevant influence on its stress–strain behaviour, so, in this study, the first two cycles stabilise the sample, and the stiffness of the material is obtained from the third cycle, neglecting its initial section, as shown in Fig. 4.

During loading cycles, the servo hydraulic testing machine increases the load up to 4 kN, at a speed of 0.1 kN/s, and records the compressive load (N), by means of the load cell, and the deformation of the paper sample (mm) by the displacement of the hydraulic actuator. The compressive stress would be obtained as in Eq. (1), where F is the compressive load (in N). The maximum compressive stress in the tests is 8.84 MPa, which could be a typical value of the clamping pressure in a power transformer,

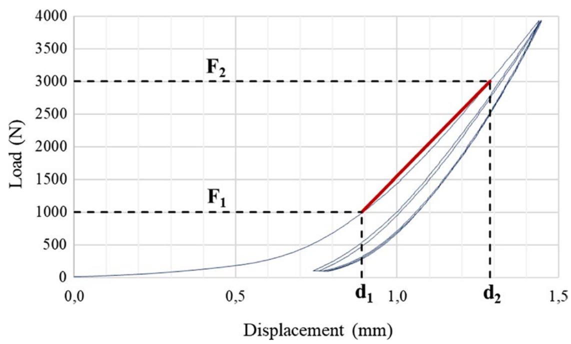

Fig. 4 Process for obtaining the compressive stiffness of the high-density pressboard, in this case for the first compressive cycle, from the force–displacement curves

Fig. 3 Prism made of high-density pressboard samples being subjected to compressive tests **a** type A, in open-air, and **b** type B, immersed in dielectric oil

according to Naranpanawa et al. (2018). The deformation suffered by the compressed prism is the sum of the deformations suffered by each of the 5 square pressboard samples, and it can be assumed that the deformation of each pressboard sample is approximately equal. That allows us to define the stiffness of the material, $K_{\text{pressboard}}$, as five times the stiffness of the tested pressboard prism, K_{prism}, see Eq. (2):

$$\sigma = \frac{F}{\pi 12^2}(MPa) \tag{1}$$

$$K_{pressboard} = 5 \cdot K_{prism}(N/mm) \tag{2}$$

In this study, two types of compressive tests were performed on the prisms made of aged of high-density pressboard. In the first type, hereinafter designated as "Tests A", the aged pressboard samples were cleaned using distilled hexane, to remove the remaining dielectric oil after the thermal ageing. Then, the compression was performed in open-air at room temperature, see Fig. 3a. In the second type, "Tests B", the aged pressboard samples were subjected to compression while being immersed in the same paraffinic dielectric oil used for the ageing process (see Sect. "Accelerated thermal ageing of the spacers made of high-density pressboard") and at a 80 °C, which could be a typical temperature in an operating power transformer, see Fig. 3b.

The compressive stiffness of the pressboard prism, or secant modulus of elasticity in compression, was obtained as the slope of the load curve in the first and third cycle, following Eq. (3). F_1 and F_2 are two load levels (in N), and d_1 and d_2 are the compressive displacements (in mm) produced by those forces. Figure 4 shows those values for the first loading cycle. As there are no accepted standards for compressive tests over this cellulosic material used in power transformer, some different load levels, F_1 and F_2, were considered in this analysis for obtaining the stiffness, as presented in Sect. "Mechanical response of the aged high-density pressboard to compressive tests".

$$K_{prism} = \frac{F_2 - F_1}{d_2(F_2) - d_1(F_1)}(N/mm) \tag{3}$$

Experimental results

Chemical and dielectric properties of the aged high-density pressboard

In Fig. 5a, the BDV is plotted together with the moisture content in the oil. During the studied ageing period, the BDV decreased up to 58.59%, due to the formation of ageing subproducts. Nevertheless, the BDV also depends on the moisture content and, at certain ageing states in which the moisture content decreased (1008 and 2016 h) the BDV was slightly higher than with less ageing duration (336 h). Indeed, the highest BDV was obtained for

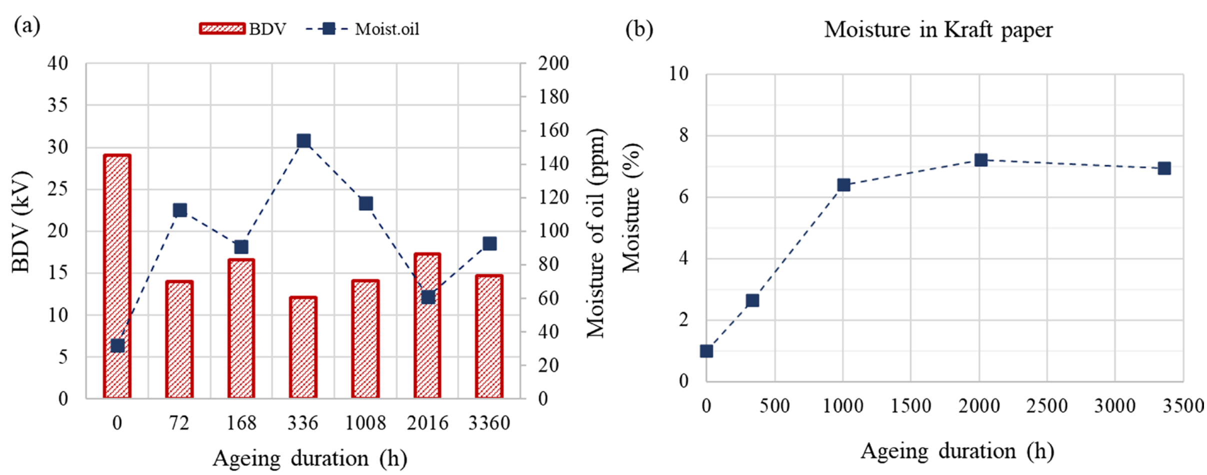

Fig. 5 **a** AC breakdown voltage (BDV) and moisture content of the dielectric oil, **b** Moisture content in the Kraft paper insulation, as a function of the duration of thermal ageing

an ageing time of 2016 h, which gave the lowest moisture content; and the lowest BDV was measured for an ageing duration of 336 h, corresponding to the highest moisture content. In Fig. 5b, the moisture content in the thin Kraft insulation is represented as a function of the ageing duration. During the first stages of the ageing process, up to 6 weeks at 150 °C, there was a high increase in the moisture content, up to a value around 6.4%, as a result of the aggressive ageing conditions. After that, the moisture content remained more or less constant. That moisture content shows that the thin insulation is in a very degraded condition and will be related with low values of the DP and the mechanical integrity.

The dielectric dissipation factor, tan δ, increased 450% with the ageing, as can be seen in Fig. 6. The tan δ depends on the conductivity and polarity of the dielectric fluid and on the moisture content. As with the BDV, the effect of ageing was especially noticeable at the beginning of the ageing duration. After that, the effect of moisture was relevant and a decrease in the tan δ was noticed after 2016 h of ageing. At this ageing state, the samples had the lowest moisture content, which explains the reduction in the conductivity. The behaviour of the resistivity is the opposite to the one of tan δ. The resistivity decreased especially at the beginning of the ageing process and, at certain stages of the considered ageing states, a slight increase was detected, coinciding with the reduction of the tan δ, as represented in Fig. 6. In both cases, the changes are

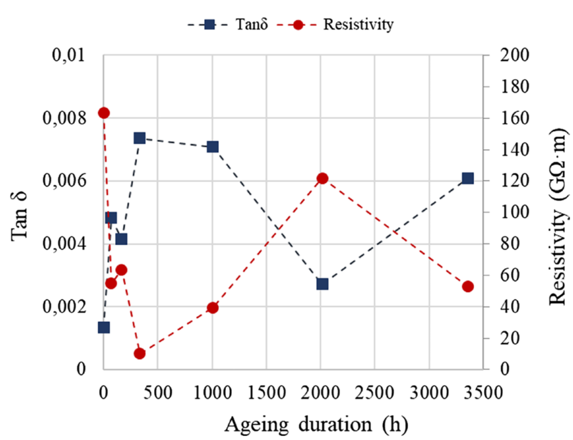

Fig. 6 Dielectric dissipation factor (tan δ) and resistivity as a function of the duration of thermal ageing

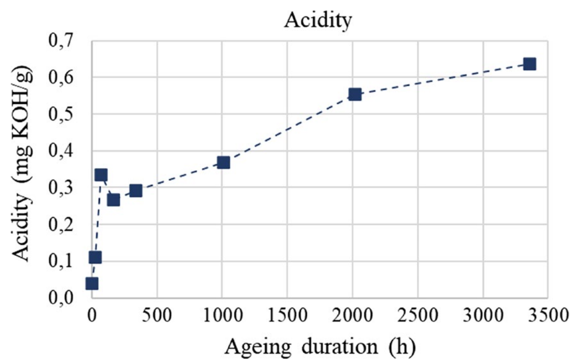

Fig. 7 Acidity in the oil as a function of the duration of thermal ageing

caused by the reduction of conductivity due to a low moisture content.

With respect to the chemical properties, the acidity of the oil is shown in Fig. 7. Both the oil and the cellulose generate acids during the thermal ageing process through different mechanisms. In the case of mineral oil, these acids are of low molecular weight, which means that they can react with the cellulose through acid hydrolysis. The oxidation of the cellulose, which occurs in different alcohol groups, produces different compounds, depending on the affected –OH group, including aldehydes, ketones and carboxylic acids (Lelekakis et al. 2012b). The acidity increased during the ageing due to the degradation of both compounds, and it reached a value of 0.63 mg KOH/g, which is higher than the maximum value for using the oil in the transformer (0.3 mg KOH/g). This high increase can be partially justified by the fact that the dielectric liquid used is uninhibited oil ("IEC 60422:2013. Mineral Insulating Oils in Electrical Equipment—Supervision and Maintenance Guidance." 2013). The high acidity, together with the drastic reduction of the BDV and the high increase of the tan δ, indicate a significant degradation of the mineral oil during the studied ageing period.

The oxidation of the cellulose causes the decrease of the DP, and the generated acids are catalysers for the hydrolysis of the cellulose (Trnka et al. 2020), which subsequently leads to DP reduction (Lelekakis et al. 2012a). Oxidation also generates water that can react later on through hydrolysis. Besides, the ageing of mineral oil can generate low molecular weight acids, and hydrogen ions can also contribute to the breakage of the cellulose chain. Water and acids not only degrade the cellulosic insulation, but also produce changes in the dielectric properties of the oil ("IEC 60422:2013. Mineral Insulating Oils in Electrical Equipment—Supervision and Maintenance Guidance." 2013). Consequently, oxidation and hydrolysis are catalysts for each other, and the thermal ageing is a crossed phenomenon.

Table 3 shows the results of the DP measurements over the studied dielectric materials, and Fig. 8 shows the variation in the DP during the whole ageing duration. As it is much more common to find the DP of thin Kraft paper insulation in the literature and, in a real power transformer, both insulating materials are subjected to similar ageing conditions, the DP of the thin paper was also obtained as reference. The thin insulation had a higher initial DP, of 1100, in comparison with the pressboard, and the same occurs during the whole ageing process, up to 20 weeks of ageing. For both materials, the most dramatic reduction in the DP happens during the first day of thermal ageing at 150 °C with the conditions described in Sect. "Accelerated thermal ageing of the spacers made of high-density pressboard", being that reduction of 46.00% for the Kraft paper insulation and 63.37% for the pressboard. Both cellulosic materials were subjected to the same ageing conditions, so the higher rate of degradation of the pressboard has to be due to a higher initial moisture content at the start of the ageing duration, which could not be determined with precision. After the first day of ageing, the reduction in DP slows down, see Fig. 8, where the slope of the graph is not as steep as the time duration increases. The solid insulation continues its degradation up to the end of the ageing process. However, although the thin Kraft insulation was totally fragile after two weeks of ageing, and incapable of withstanding even very small deformations without breaking, the apparent consistency of the pressboard was more or less similar during the whole ageing process, and the most significant variation was in its colour, which was darker as the ageing duration increased. That suggests that other parameters, other than the DP, should be used to infer the mechanical compressive integrity of high-density pressboard.

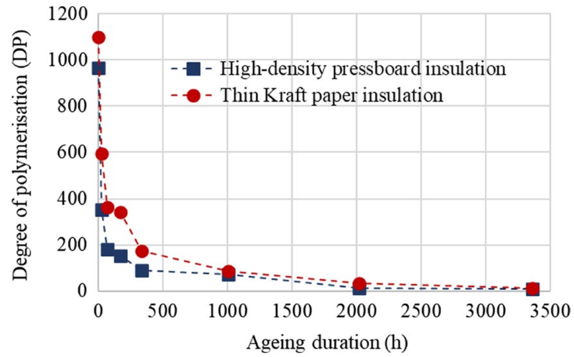

Fig. 8 Reduction of the DP as a function of the duration of thermal ageing

Table 3 Results of average viscometric Degree of Polymerisation (DP) measurements

Ageing duration	Thin Kraft paper insulation		High-density pressboard	
	DP	% reduction	DP	% reduction
0	1100	–	966.3343	–
3 days	363.0	67.00	180.0	81.37
1 week	343.0	68.82	153.0	84.17
2 weeks	174.4	84.15	91.1	90.58
6 weeks	88.2	91.98	74.3	92.32
12 weeks	33.3	96.97	14.3	98.53
20 weeks	15.2	98.62	10.2	98.95

Mechanical response of the aged high-density pressboard to compressive tests

For each of the considered ageing periods, three compressive tests were performed over the pressboard prism, in order to obtain average values for the compressive stiffness of the material. Pressboard is

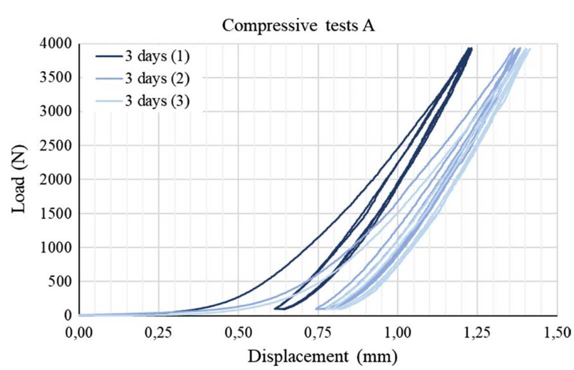

Fig. 9 Load–displacement curve for compressive Test A over the pressboard prism, with three cycles of loading–unloading, for an ageing duration of 3 days

a cellulosic polymer with a porous structure, so its behaviour in ZD is strongly non-linear, as can be seen in Fig. 9, which shows the results for an ageing duration of three days. In those curves, there are two noticeable regions: one, at the beginning of the first loading cycle in which the compressive deformation increases remarkably with a small increase in the compressive force. This response is due to the porous structure of the material, which collapses as it is compressed in ZD, introducing a plastic deformation. After that, there is a region in which the slope of the curve increases, and a higher force is needed to increase the compressive deformation, due to the increase in both elastic stiffness and plastic hardening (Naranpanawa et al. 2018).

As mentioned in Sect. 2.2.3, the first two cycles stabilise the sample, so Figs. 10 and 11 show only the third cycle of tests A (compressed in open-air) and B (immersed in dielectric oil) over the prism made of pressboard. Figure 10 shows that, as the duration of thermal ageing increases, the same load level produces larger compressive deformations in the pressboard prism. Figure 11 shows the results of compressive tests B, in which the prism made of pressboard was cyclically compressed while being immersed in dielectric oil at 80 °C. Comparing the results of tests B, the increase in the duration of thermal ageing causes larger compressive deformations, as happened with tests A. Besides,

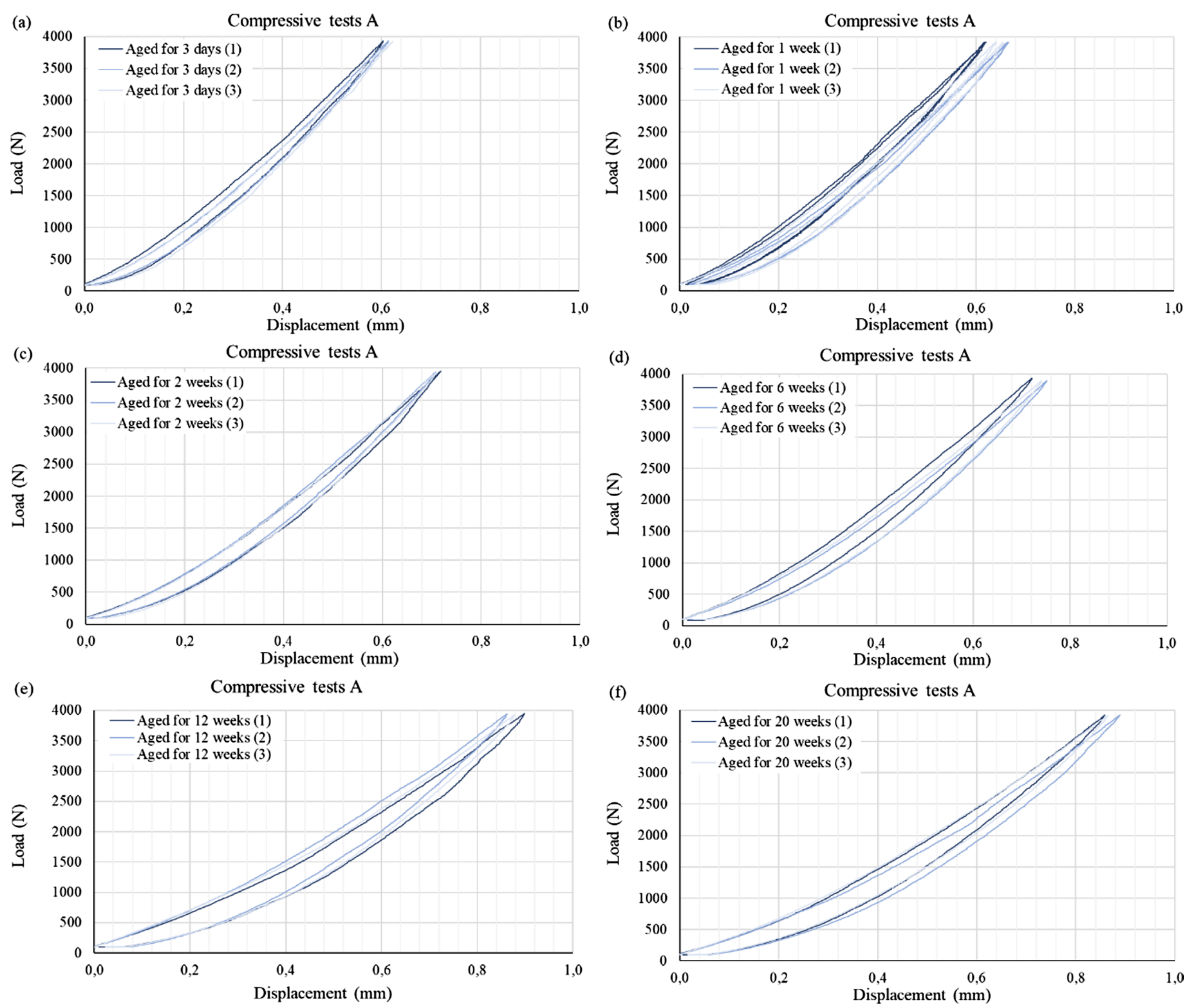

Fig. 10 Load–displacement curves for the third cycle in compressive tests A, for ageing durations of **a** 3 days, **b**)1 week, **c** 2 weeks, **d** 6 weeks, **e** 12 weeks and **f** 20 weeks

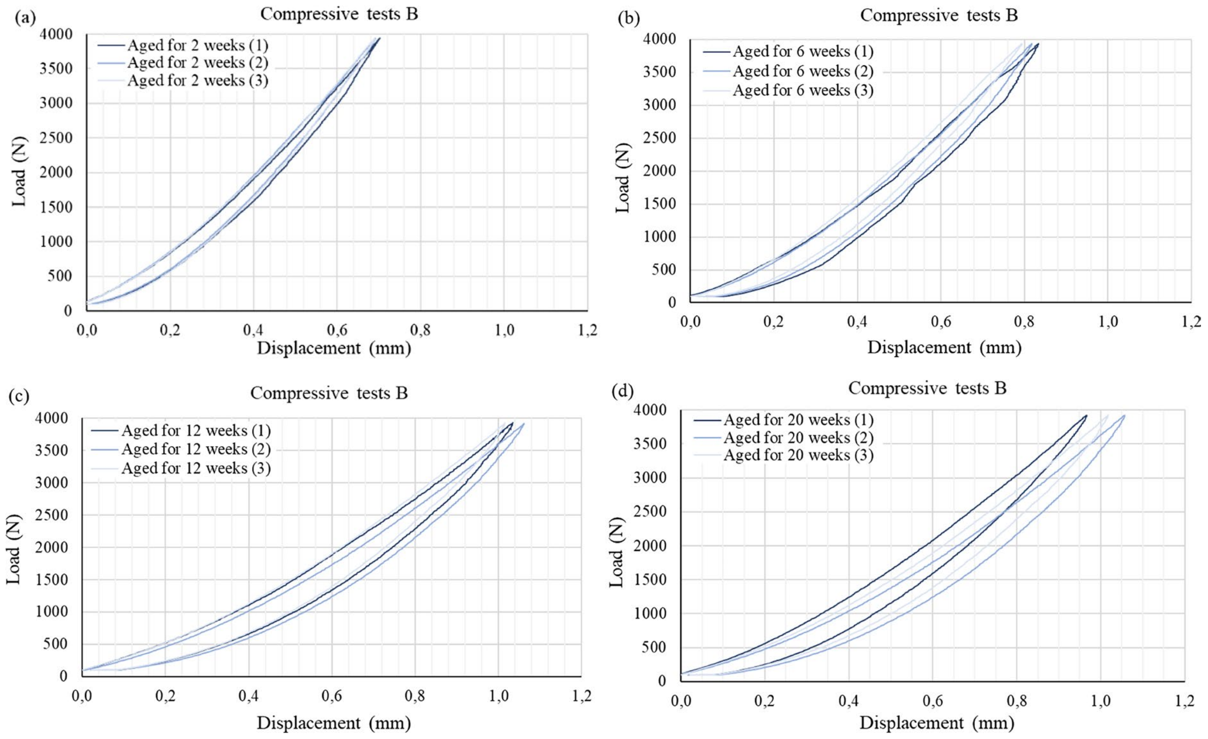

Fig. 11 Load–displacement curves for the third cycle in compressive tests B, for ageing durations of **a** 2 weeks, **b** 6 weeks, **c** 12 weeks and **d** 20 weeks

Table 4 Average compressive stiffness of the high-density pressboard, $K_{pressboard}$, in tests A when the material was aged for two weeks, obtained from different load levels

F_1 (N)	F_2 (N)	First loading cycle K (kN/mm)	Third loading cycle K (kN/mm)
1000	2500	24.81	31.92
1000	3000	25.96	33.01
1000	3500	26.89	33.85
1500	3000	27.82	34.61
1500	3500	28.62	35.34

in comparing tests A and tests B, for the same ageing duration, the high-density pressboard is more deformable when compressed immersed in dielectric oil at 80 °C. As explained in Sect.2.2.3, there are no accepted standards for obtaining the compressive stiffness of high-density pressboard, thus, different load levels were considered and introduced into Eq. (1). In Table 4, the average values of the compressive stiffness obtained from tests A, when the material was aged for two weeks, are presented for both the first and third loading cycles and different load levels. It can be seen that the response is more rigid after two cycles of loading–unloading, and that happens for all the considered ageing periods, due to the densification previously mentioned.

Figures 12 and 13 show the different values of the pressboard stiffness, $K_{pressboard}$, obtained after Tests A and B. Although the different load levels introduced in Eq. (1) lead to different stiffness values, the tendency in the variation of the compressive stiffness as a function of ageing is very similar in all cases. Thus, the intermediate value, which corresponds to $F_1 = 1000N$ and $F_2 = 3500N$, will be used from now on to represent the behaviour of the high-density pressboard in compression mode, leading to Eqs. (4 and 5). Those force levels used to define the compressive stiffness, when introduced in Eq. (1), lead to compressive stresses of 2.21 and 7.37 MPa, respectively.

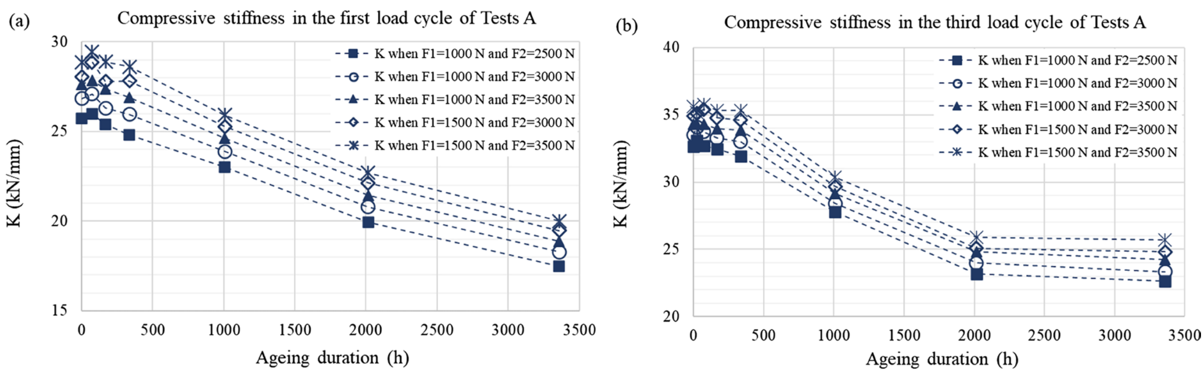

Fig. 12 Different values of the compressive stiffness of high-density pressboard, $K_{pressboard}$, as a function of the ageing duration in **a** the first load and **b** the third loading cycle of Tests A

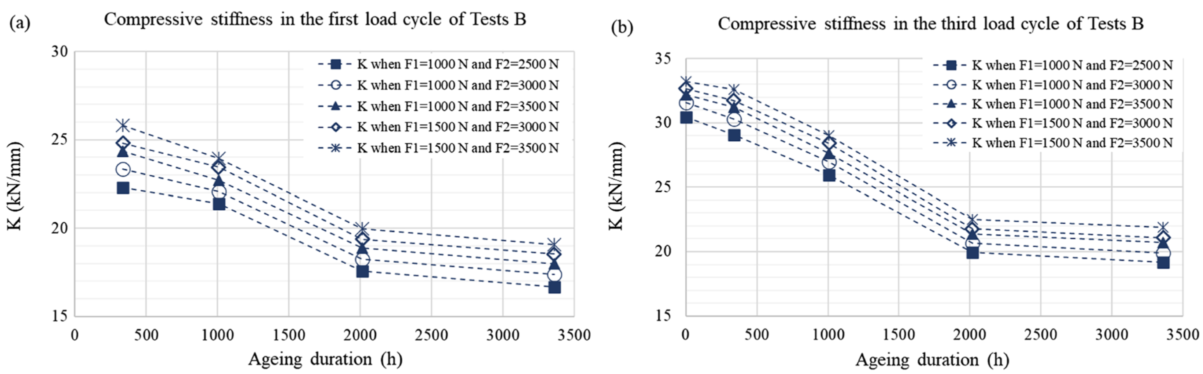

Fig. 13 Different values of the compressive stiffness of high-density pressboard, $K_{pressboard}$, as a function of the ageing duration in **a** the first load and **b** the third loading cycle of Tests B

$$K_{prism} = \frac{3500 - 1000}{d_2(3500) - d_1(1000)}(N/mm) \quad (4)$$

$$K_{pressboard} = 5 \cdot \frac{3500 - 1000}{d_2(3500) - d_1(1000)}(N/mm) \quad (5)$$

Figure 14a represents the evolution of the compressive stiffness of the high-density pressboard in the third compression cycle as a function of the ageing duration. Equations (6 and 7) show second-degree polynomial functions giving the relationship between ageing duration and compressive stiffness, respectively for tests A and B. The R-squared values are higher than 0.97, indicating a strong correlation. It is of interest to know if there is a relationship between the stiffness in the third compressive cycle measured in both tests, as it is considerably more complicated to test the pressboard under compression while immersing it in oil at a high temperature. This relation is plotted in Fig. 14b, where it can be seen that the data fit quite well in a linear regression given by Eq. (10).

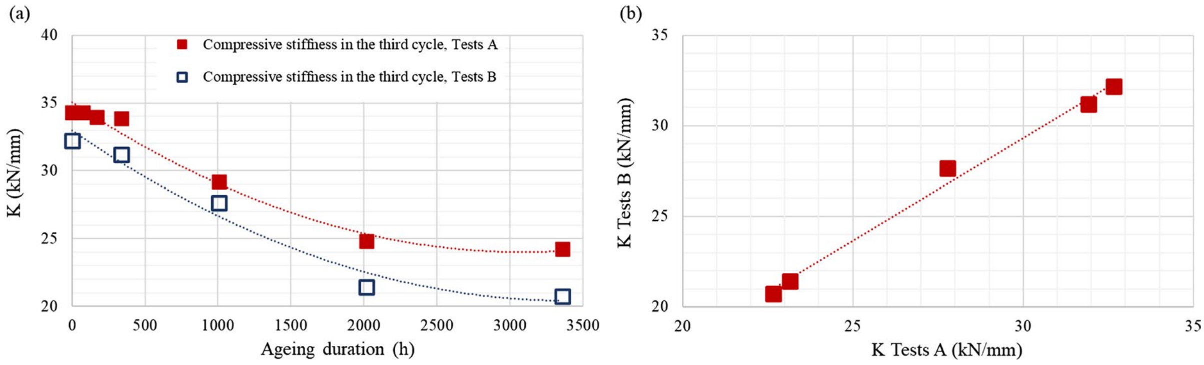

Fig. 14 **a** Evolution of the compressive stiffness of the high-density pressboard as a function of ageing duration, for both tests A and B; **b** Relationship between the compressive stiffnesses in the third loading cycle for tests A and B

$$K_{pressboard\,Tests\,A} = 10^{-6}\,t^2 - 0.0071\,t + 35.042\left(\frac{kN}{mm}\right),\ R^2 = 0.9831 \quad (6)$$

$$K_{pressboard\,Tests\,B} = 10^{-6}\,t^2 - 0.0074\,t + 32.975\left(\frac{kN}{mm}\right),\ R^2 = 0.9717 \quad (7)$$

$$K_{pressboard\,Tests\,B} = 1.135 \cdot K_{pressboard\,Tests\,A} - 4.7336\left(\frac{kN}{mm}\right),\ R^2 = 0.9918 \quad (8)$$

Figure 15a shows the evolution in the compressive stiffness as a function of the DP of the high-density pressboard for the considered ageing period. Although the DP of the pressboard decreased dramatically and, after three days of ageing at 150 °C, it had been reduced to 81.37% of the initial value, see Sect. "Chemical and dielectric properties of the aged high-density pressboard", the same does not happen with the compressive stiffness. The logarithmic functions presented in Eqs. (9 and 10) are the ones which best fit the experimental data, with R-squared values higher than 0.79. Figure 15b shows how the compressive stiffness of the material, $K_{pressboard}$, varies as a function of the acidity of the oil in mg KOH/g, named as "A" in Eqs. (11 and 12), see Sect. "Chemical and dielectric properties of the aged high-density pressboard". A quadratic fitting shows a good correlation between both magnitudes.

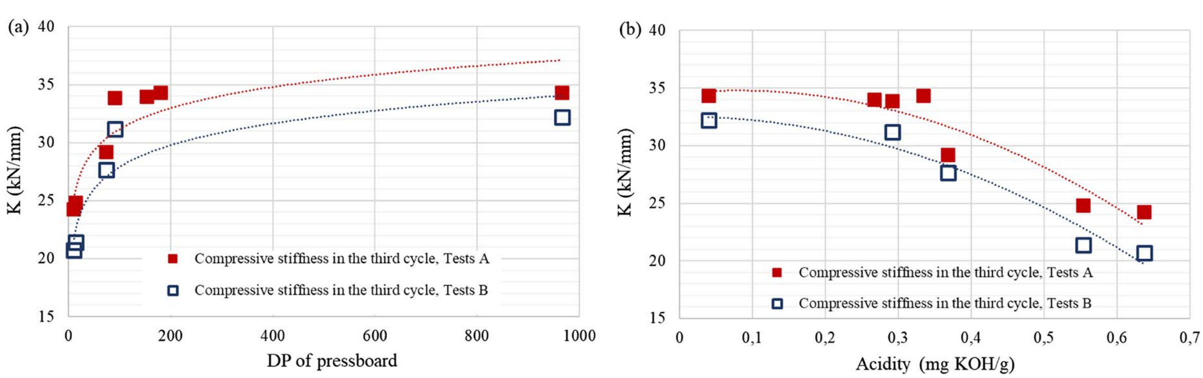

Fig. 15 **a** Relationship between the compressive stiffness of the high-density pressboard and the degree of polymerisation, DP; **b** Relationship between the compressive stiffness of the high-density pressboard and the acidity

$$K_{pressboard\,Tests\,A} = 2.6171 \cdot \ln(DP) + 19.117\left(\frac{kN}{mm}\right),\ R^2 = 0.7943 \quad (9)$$

$$K_{pressboard\,Tests\,B} = 2.7062 \cdot \ln(DP) + 15.441\left(\frac{kN}{mm}\right),\ R^2 = 0.8367 \quad (10)$$

$$K_{pressboard\,Tests\,A} = -37.665A^2 + 6.0073A + 34.55\left(\frac{kN}{mm}\right),\ R^2 = 0.8824 \quad (11)$$

$$K_{pressboard\,Tests\,B} = -31.724A^2 + 0.0922A + 32.531\left(\frac{kN}{mm}\right),\ R^2 = 0.9533 \quad (12)$$

Assuming that the compressive stiffness of high-density pressboard is the parameter which better represents the mechanical response under compressive loading, a deterioration model based on a damage parameter D, analogously as in Carrascal et al. (2018), can be defined based on Eq. (13), where $\left(K_{pressboard}\right)_0$ is the initial value of the stiffness, when the material has not being aged, and $\left(K_{pressboard}\right)_t$ is the value of the stiffness after an ageing duration of "t" hours. The damage parameter has been represented for both tests A and B in Fig. 16.

$$D = 1 - \frac{\left(K_{pressboard}\right)_t}{\left(K_{pressboard}\right)_0} \quad (13)$$

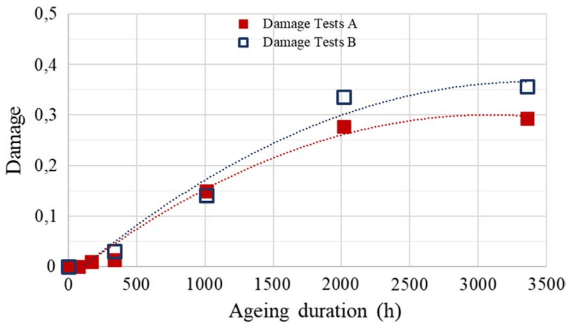

Fig. 16 Evolution of the damage, D, as a function of ageing duration

Discussion

The goal of our work was to resemble as closely as possible the most extreme conditions that could exist in power transformers during their whole lifespan. In order to degrade the mechanical and chemical properties of the solid insulation in a suitable period of time (less than 20 weeks) and to analyse what those properties would be near the end-of-life of an operating power transformer, a very high ageing temperature of 150 °C was applied, and other parameters with a severe influence on pressboard deterioration were included, such as a high mass of copper pieces in the vessels. That last parameter, which has an impact as a catalyst of ageing, is not considered in many ageing studies, while it is present in the real environment to which the paper and pressboard are subjected in an actual power transformer.

During transformer operation, different degradation mechanisms affect both paper and oil, such as hydrolysis, oxidation, pyrolysis, and electrical stress, see Mohan Rao et al. (2021). In our work, the ageing was purely thermal, so there was no electrical stress, and a temperature of 150 °C is not enough to cause pyrolysis. Despite the ageing being carried out in a nitrogen atmosphere, it is possible that some oxygen remains in the vessel, so oxidation has likely affected both the oil and the paper. Moreover, the increase of the moisture content could indicate that oxidation has occurred, since this process always generates water. Furthermore, the high moisture content indicates that hydrolysis has occurred in the cellulose, producing the breakage of the cellulose chains in D-glucose molecules. Both degradation processes have played a role, and both. occur simultaneously, and one serves as a catalyst for the other.

Both the performed compressive tests gave a strong quadratic relationship between ageing duration and compressive stiffness of the high-density pressboard, for an ageing temperature of 150 °C, see Sect. "Mechanical response of the aged high-density pressboard to compressive tests". The mechanical response differs in both tests: the paraffinic dielectric oil at high temperature produces larger compressive deformations for the same load level (lower stiffness). However, there is a linear strong relationship between the compressive stiffnesses measured in tests A and B, see Sect. "Mechanical response of the aged high-density pressboard to compressive tests". This is a really useful finding, because testing the material immersed in oil at high temperature is much more complex and time consuming when compared to testing in open-air.

A remarkable reduction in the DP was observed as a consequence of the applied ageing conditions, leading to consider the findings of Borrega et al. (2018); Nourinaeini et al. (2020), where the influence of alkaline treatments to control the artificial reduction in the DP produced by the ageing in an acidic environment was studied. They suggest the use of pre-treatments of the cellulosic material with $Ca(OH)_2$ and NaOH. Although a lower DP reduction would have been obtained if we had applied those pre-treatments to the high-density pressboard, those pre-treatments are very infrequent in the field of thermal ageing applied to dielectric materials used in power transformers. Our purpose is, precisely, to obtain results comparable to those, and thus we are applying the international standard widely used in this field of research and in the industry for DP measurement ("ASTM D4243. Standard Test Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards" 2016).

It is relevant to highlight that the same ageing process produced a more marked reduction in the DP of the high-density pressboard than that of the thin Kraft paper. As mentioned in Sect. "Chemical and dielectric properties of the aged high-density pressboard", this must be caused by a higher initial moisture content for the high-density pressboard, which could not be exactly determined, in comparison with the initial content of 1% for the thin paper. The DP reduction of the pressboard was 81.37%, up to a value of 180, after 72 h of ageing, which seems to be very radical, but the results presented are a consequence of the ageing conditions. For instance, a DP lower than 300 was obtained by Lelekakis et al. (2012a, b) after ageing for 100 h at 140 °C and with 2.7% moisture content. Another study (Lelekakis et al. 2014) presents a DP reduction up to 200 after only 500 h of ageing at 120 °C, due to a moisture content in the paper of 2.7%. Carcedo et al. (2016) measured a reduction in the DP up to 200 after ageing at 150 °C for 50 h, but the moisture content of the paper was 0.5% in that case. Regarding studies taking into consideration the impact of copper as a catalyst of the ageing, a DP reduction up to 200 was obtained by Liao et al. (2010) after ageing at 130 °C for 20 days, with mass ratio copper/oil of 0.5/1. In García et al. (2017), an ageing process at 130 °C, with moisture content of 1% and considering the influence of copper, resulted in a DP lower than 500 after 125 h. The ageing rates obtained by those studies are slower than that presented here, but it must be considered that our ageing temperature is higher (and the effect of a temperature increase between 10 and 30 °C is not negligible at all), our moisture content is higher, and, also, the copper content was higher, with a copper/oil mass ratio in our study is of 2.3/1. Those reasons can justify the faster deterioration rate observed in our experiments. Other different ageing conditions can be applied in order to compare the results and the impact of the different variables having an influence on the DP reduction.

Furthermore, one important finding is that similar reductions in the DP due to ageing have totally different mechanical implications when considering the thin Kraft insulation and the pressboard. The reduction in the DP of thin paper insulation used to wrap the conductors of the windings makes it less deformable, due to the reduction in the number of anhydroglucose units in the cellulose chain, and lower length of the cellulose polymer, getting more fragile and suffering breakage due to any deformation in the windings, see Oria et al. (2021). However, with the same DP value, the pressboard subjected to compression will still have a good mechanical integrity and will be able to withstand compressive loads. That means that, in most cases, the end-of-life of the power transformer due to failure of the insulation will be originated in the thin cellulosic insulation before than in the structural components made of pressboard. Furthermore, while for the thin insulation, deformability is an advantage, as it can better absorb the tensile stresses produced by electrodynamic effects, the opposite happens with the high-density pressboard. During the drying process in its manufacture, single fibres approach each other closely, and the hydroxyl groups form hydrogen bonds which constitute a rigid and compact structure with high density (Mark et al. 2002). The reduction of the DP is linked with the weakening of the bonding between the individual fibres, and the geometrical structure of the bonded fibrous network ("IEC 60076-7. Power Transformers—Part 7: Loading Guide for Mineral-Oil-Immersed Power Transformers." 2018). A reduction in DP means a weaker microscopic structure, which is less rigid and more deformable when subjected to compressive stresses.

Equations (6 and 7) presented in Sect. "Mechanical response of the aged high-density pressboard to compressive tests", which relate the compressive stiffness with the ageing duration, can only be used for the particular ageing conditions applied in this study. Different ageing conditions will derive into other expressions, but the relevant finding is that a quadratic equation can be used to model the reduction of the mechanical compressive stiffness with time, as the high-density pressboard ages. The relationship between the DP of the high-density pressboard and the compressive stiffness during the whole ageing duration was studied, and a moderately strong logarithmic function was obtained, see Eqs. (9 and 10) in Sect. "Mechanical response of the aged high-density pressboard to compressive tests", allowing us to infer the stiffness from the DP value. Although the DP is one of the parameters most commonly used for the estimation of the degradation of the cellulosic insulation inside power transformers, its use is not very useful when analysing the mechanical integrity of the components made of high-density pressboard and subjected to compressive loads, as is the case of radial spacers. The reason is that the aggressive accelerated ageing process to which the material is subjected in this study radically reduces the DP, see Fig. 8, but the same does not happen with the compressive stiffness, see Figs. 12 and 13. Indeed, there is a 90.58% reduction in the DP value of the high-density pressboard after two weeks of ageing, see Table 3, while the compressive stiffness in the third loading compressive cycle only reduces between 1.33 and 3.10%, respectively for Tests A and B, in the same period of time. Then, it will not be appropriate to use one particular value of the DP as end-of-life criterion for high-density pressboard components, as it is usually done with the thin paper insulation.

The relationship between the acidity of the oil (in mg KOH/g), which increased during the ageing duration at 150 °C, and the compressive stiffness was analysed, see Eqs. (11 and 12) in Sect. "Mechanical response of the aged high-density pressboard to compressive tests". In this case, a second-degree polynomial function was the best fit for the experimental data. The use of the acidity as chemical parameter related with the mechanical properties is very convenient when trying to monitor the state of power transformers during operation, because its measurement does not need sample extraction of the high-density pressboard, which would be unfeasible in most cases because that material is not easily accessible, and its extraction could damage the electric machine.

Conclusions

This work studies the influence of the dielectric oil used in operating power transformers on the compressive mechanical response of radial spacers made of high-density pressboard. Our findings prove that the compressive stiffness of high-density pressboard immersed in dielectric oil at 80 °C can be inferred from the stiffness of the material with the same degree of ageing but tested in open air. This is a valuable tool, as the testing will be simpler and more time-efficient if performed in open air. Furthermore, it would be interesting to test the high-density pressboard immersed in oil at other temperatures typical in operating power transformers, and using other dielectric liquids, in order to investigate their effect on the compressive properties.

After studying the evolution of several chemical parameters, see Sect. "Chemical and dielectric properties of the aged high-density pressboard", and the compressive mechanical properties, it can be concluded that the value of DP is not an appropriate measure of the mechanical integrity when talking about high-density cellulosic materials used in electric applications, because a high reduction in DP does not imply a relevant worsening of compressive properties. This is something quite novel, as all the references devoted to cellulosic insulation generally use the DP value as an indicator of the mechanical performance, and that could only be suitable when studying thin paper insulation.

On the other hand, the increase in the acidity of the oil in mg KOH/g, measured as indicated in "IEC 62021-1. Insulating Liquids—Determination of Acidity—Part 1: Automatic Potentiometric Titration" (2003), has a strong correlation with the degradation of compressive properties of high-density pressboard. This would be a very useful chemical parameter, as it does not require pieces of pressboard as was the case with measurement of the DP. Then, it can be easily measured in an operating power transformer, as it only requires a small amount of dielectric oil for its quantification. Besides, it can be inferred that a reduction in the formation of acids, which could be achieved by changing some operating conditions or using other dielectric liquids, would better preserve the compressive properties of high-density cellulosic components in power transformers in operation. In the future, it would be interesting to study the compressive mechanical response of high-density pressboard when using other dielectric liquids, as it has been reported that the use of vegetable oil better preserves the tensile mechanical properties of thin paper during ageing, see Oria et al. (2022), but there is no information about the effects of using this oil on compressive properties of pressboard.

Finally, it has to be highlighted that, despite the aggressive thermal ageing, a relevant softening of the high-density pressboard has not been reached. The material maintained a relatively good mechanical integrity even at the end of the ageing duration (150 °C for 20 weeks). This confirms the suitability of high-density cellulosic materials as dielectric and structural materials in power transformers. In future research, it would be interesting to include the presence of moisture during the thermal ageing, as this parameter is known to have an impact on the degradation of cellulosic components.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interest to disclose.

Ethics approval Not applicable.

Consent for publication Not applicable.

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