Data Article

Experimental dataset on the tensile and compressive mechanical properties of plain Kraft and crepe papers used as insulation in power transformers after ageing in mineral oil

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ABSTRACT

The solid insulation in the windings of power transformers, which generally consists of oil-impregnated thin paper, is one of the key elements for the performance and durability of these electrical machines. Insulation paper is subjected to static and dynamic forces of electromagnetic origin, in combination with high temperatures and chemical reactions, during the operating life of a power transformer. The mechanical properties of the cellulosic insulation are relevant parameters because its breakage could result in the electric failure of the transformer. Indeed, paper manufacturers usually provide values of the tensile strength and elongation at breakage of the insulating paper in its two principal material directions, the MD (machine direction) and CD (cross-direction). However, paper is a highly anisotropic material and its material properties evolve as the paper insulation ages. The paper insulation in an operating transformer is subjected to a multiaxial stress state field including compressive and shear stresses. This article reports experimental data on the ten-

sile and compressive mechanical properties of two types of paper, plain Kraft and crepe paper, typically used as insulation in power transformers, under different ageing states (which were induced through accelerated thermal ageing and quantified by means of the degree of polymerisation). These data could be reused for several purposes. They can improve the current understanding of the mechanical response and degradation processes of the cellulosic insulation in power transformers, and give some reference values that can be compared with others obtained in the factory by manufacturers. In the field of engineering failure analysis, those values could be reused for the assessment of mechanical failure of paper materials used in power transformers, see [1].

Specifications Table

Subject	Mechanics of Materials
Specific subject area	Mechanical properties of paper insulation for power transformers
Type of data	Table
	Graph
	Figure
How data were acquired	Experimental dataset has been acquired using the average viscometric degree of polymerisation, according to IEC 60450 [2], and in-plane tensile/ edgewise compressive testing, adapting standards ISO 1924–2 [3] and ISO 12192 [4].
Data format	Analysed
Parameters for data collection	Samples of paper insulation for power transformers (plain Kraft and crepe) with appropriate dimensions for mechanical testing, were impregnated in naphthenic oil, introduced into sealed vessels with copper pieces (same ratio paper/copper that a commercial insulated conductor), and aged in convective ovens at 150 °C for different periods. After ageing, the paper was washed using hexane.
Description of data collection	The degree of polymerisation was measured in pieces of new and aged insulation, following IEC 60450. Dog-bone shaped samples were used for in-plane tensile testing at 35° to the MD, with a constant rate of elongation equivalent to the one proposed in ISO 1924–2. A modification of ISO 12192 was used to measure the edgewise compressive properties of paper samples which consisted of two concentric cylinders.
Data source location	The insulation paper was provided by Ahlstrom-Munksjö. The experimental testing was carried out at the Electrical and Energy Department, and at the Laboratory of Science and Engineering of Materials (University of Cantabria), in Santander, Cantabria, SPAIN.
Data accessibility	Within the article and in http://dx.doi.org/10.17632/y8c9426hdy.1
Related research article	C. Oria, D. Ferreño, I. Carrascal, A. Ortiz, I. Fernández
	Study on the mechanical failure of the cellulosic insulation of continuously transposed conductors in power transformers under the influence of short circuits and thermal ageing Engineering Failure Analysis https://doi.org/10.1016/j.engfailanal.2021.105356

Value of the Data

• It is generally acknowledged that the electrical, chemical and mechanical degradations of the insulation paper are the main reasons for the end of life of transformers, causing failure by diverse mechanisms [5]. The collected data quantify the loss of mechanical strength of the

Kraft and crepe insulation papers, which is valuable to establish an end-of-life criterion of the transformer [6].

- Manufacturers only provide the tensile strength in the MD and CD of the insulation in the as-fabricated condition, but the properties of the aged insulation are relevant to assess the actual performance of the transformer. The paper insulation which wraps the winding conductors is subjected to a complex stress-state, in which compression and shear stresses are present. The collected data include compression and shear properties under different ageing conditions.
- Paper manufacturers, power transformer manufacturers and researchers working in the field of paper mechanics can benefit from the presented data.
- The data presented can be reused for assessment during manufacturing processes to achieve insulation materials with better mechanical properties. Besides, they can be reused for failure analysis of the studied types of paper insulation (plain Kraft and crepe) with similar grammage, thickness and in a comparable ageing state in an operating power transformer.

1. Data Description

Table 1 gives the manufacturing properties of the tested paper insulation (plain Kraft paper and crepe paper) provided by Ahlstrom-Munksjö. Table 2 provides the properties of the naphthenic oil in which the insulation paper was impregnated for its ageing. Graph 1 gives the variation in the degree of polymerisation (DP) of the paper insulations as a function of the ageing duration.

Fig. 1(a) shows the configuration of the cylindrical samples for compressive testing over the paper insulation, and Fig. 1(b) shows a cylindrical paper sample undergoing compressive testing. Graphs 2 and 3 show the compressive stress-strain curves over the cylindrical samples of plain Kraft paper, with their edges oriented in the MD and CD, respectively. Graphs 4 and 5 show the same information but, in this case, for cylindrical samples made of crepe paper.

Fig. 2(a) and (b) show the geometry of the paper samples prepared for tensile testing at 35° to the MD, and Fig. 2(c) shows one of those paper samples undergoing tensile testing.

Table 1
Manufacturing properties of the tested paper insulation materials.

PROPERTY	UNIT	TEST METHOD	Plain Kraft paper	Crepe paper
Nominal Grammage	g/m^2	ISO 536	62.0	80.0
Nominal Thickness	μm	ISO 543	82	80
Nominal Density	kg/m^3	ISO 543	760	1000
Minimum Tensile Strength in MD	MPa	ISO 1924	93.5	87.5
Minimum Tensile Strength in CD	MPa	ISO 1924	33.9	25.0
Minimum Elongation at break in MD	%	ISO 1924	2	15
Minimum Elongation at break in CD	%	ISO 1924	4	5

Table 2
Main properties of the mineral dielectric oil used in the experiments.

PROPERTIES	Method	Value
Density at 20 °C (g/cm^3)	ISO 12,185	0.84
Viscosity at 40 °C (mm^2/s)	ASTM D445	10.3
Viscosity at 100 °C (mm^2/s)	ASTM D445	2.7
Viscosity at −30 °C (mm^2/s)	ASTM D445	807
Freezing point (°C)	ASTM D97	−48
Interfacial tension (dynes/cm)	ASTM D971	42
Acidity (mg KOH/g)	ASTM D974	<0.01
Water content (mg/kg)	IEC 60,814	15
Furfural content (mg/kg)	IEC 61,198	<0.05
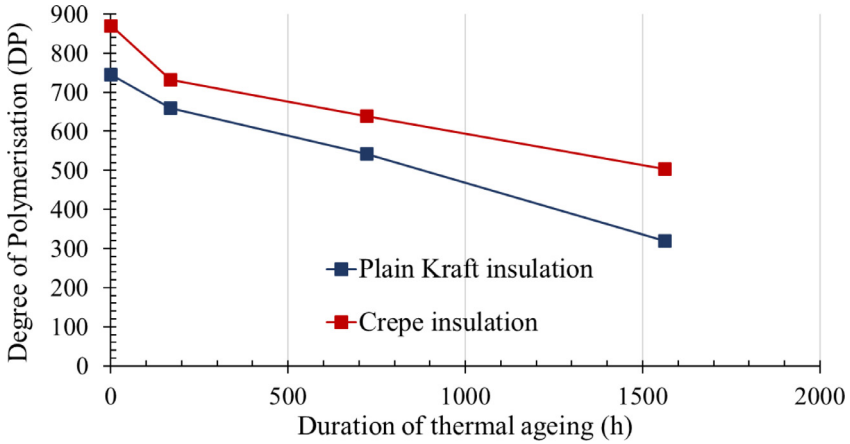
Graph 1. Reduction of the DP for the insulation papers as a function of the duration of thermal ageing.
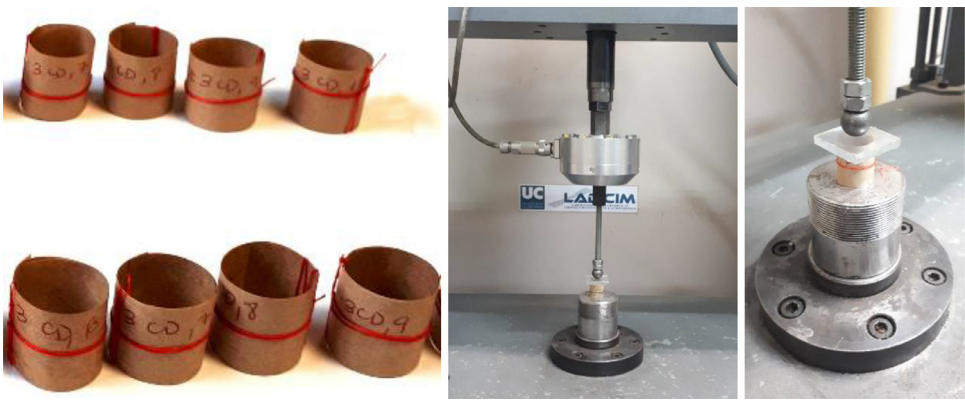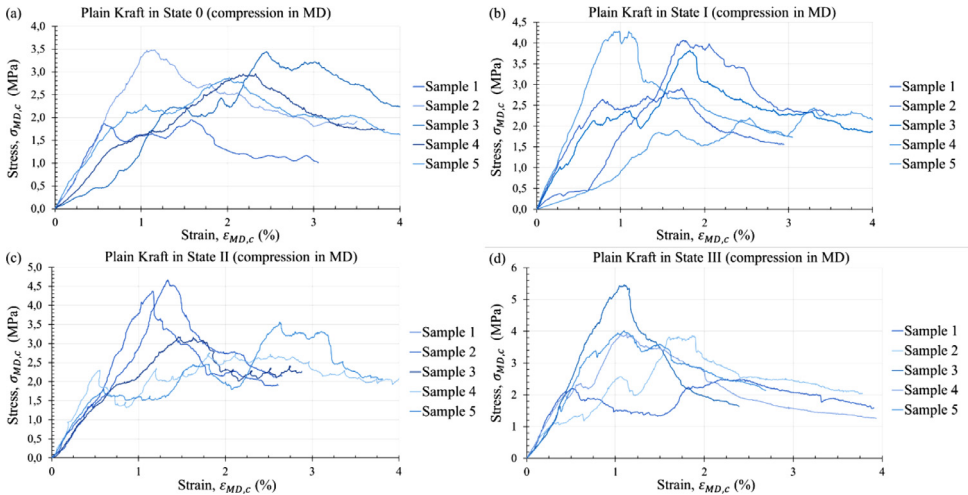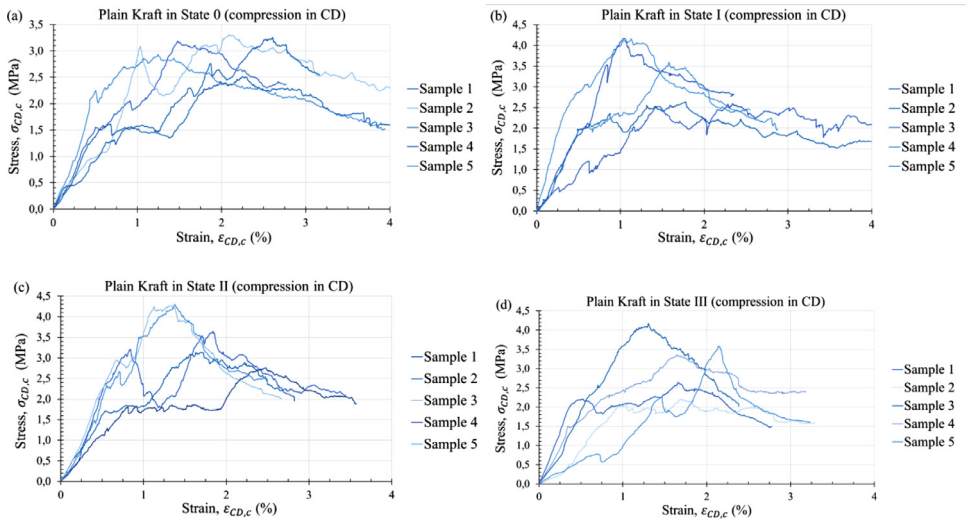

Fig. 1. (a) Paper cylinders for compressive testing; (b) Cylindrical paper sample being subjected to a compressive test.

Graph 2. Edgewise compression in MD for the plain Kraft paper in ageing states (a) 0, (b) I, (c) II and (d) III.

Graph 3. Edgewise compression in CD for the plain Kraft paper in ageing states (a) 0, (b) I, (c) II and (d) III.

Graph 6 shows the tensile stress-strain curves over the paper samples whose edges are oriented at 35° to the MD for the plain Kraft paper in the different ageing states, as well as an average stress-strain curve ± the standard deviations. Graph 7 shows the same information, but in this case, for the crepe paper.

2. Experimental Design, Materials and Methods

### 2.1. Accelerated thermal ageing of the dielectric papers

Two paper materials commonly used as insulation in power transformers, plain Kraft and crepe papers, were provided by the company Ahlstrom-Munksjö. Their manufacturing properties are specified in Table 1. The factory-new material was vacuum-dried in an oven at 100 °C for 3 h, in order to reduce their initial moisture content due to its inherent hygroscopy. The dried material was impregnated in naphthenic dielectric oil, whose properties are listed in Table 2, and introduced in vessels with a ratio of 10 g paper/400 g oil, with some pieces of copper, with approximately the same mass ratio of copper and paper that exists in an insulated conductor with four layers of paper insulation. The sealed vessels were aged isothermally in temperature-controlled ovens, to reproduce the degradation process of the insulation after years of operation of the power transformer. Four different ageing states were considered: the non-aged material (State 0) and aged at 150 °C for 1 week (State I), 4 weeks (State II) and 9 weeks (State III). Once the ageing process had finished, the paper samples were washed, using hexane, to remove the remaining dielectric oil. The ageing level of each material was characterised through the DP, following [2], and the measured values are shown in Graph 1.

2.2. Edgewise mechanical compressive properties of the dielectric papers

A method to determine the edgewise compressive strength of paper and paperboard using cylindrical samples is specified in [4], applicable to all paper and paperboard with a thickness between 100 and 580 μm. However, the dielectric insulation studied here has a thickness of
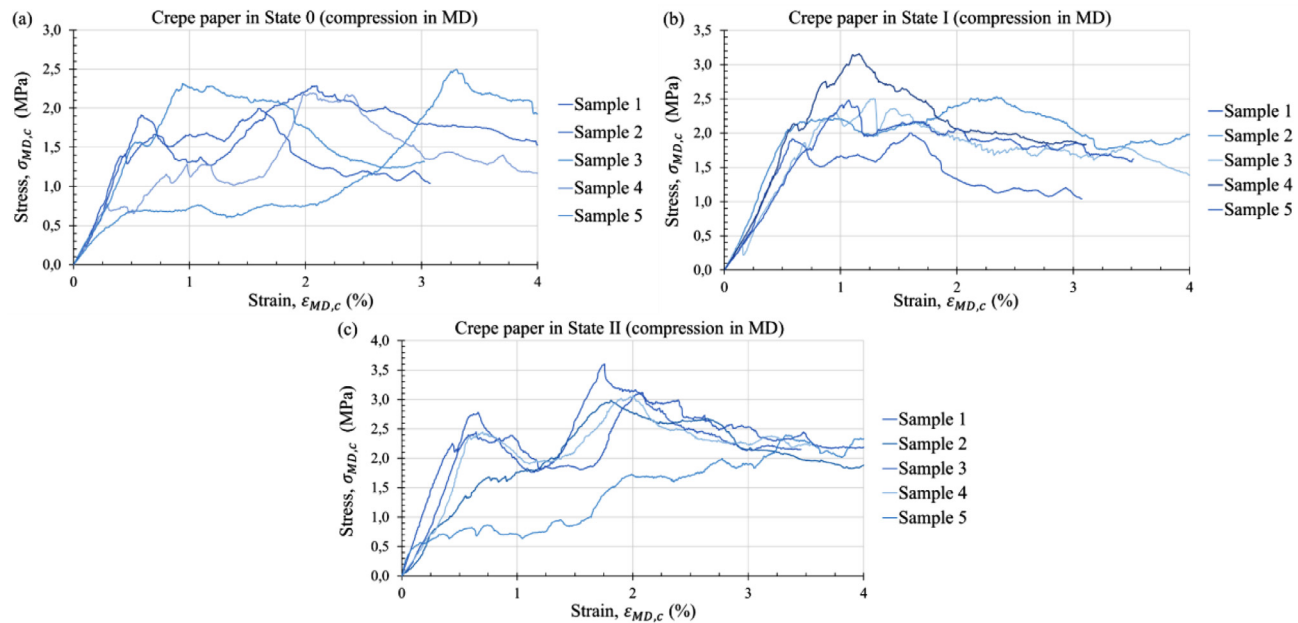
Graph 4. Edgewise compression in MD for the crepe paper in ageing states (a) 0, (b) I, and (c) II.
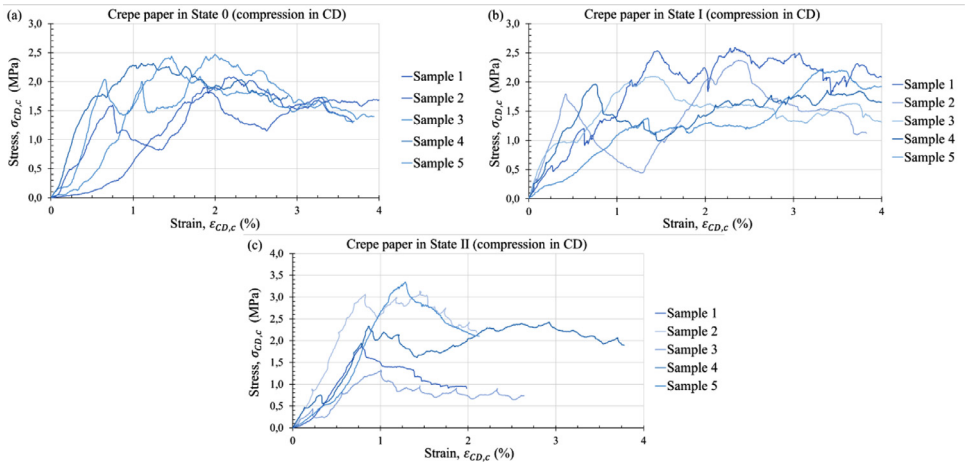
Graph 5. Edgewise compression in CD for the crepe paper in ageing states (a) 0, (b) I, and (c) II.
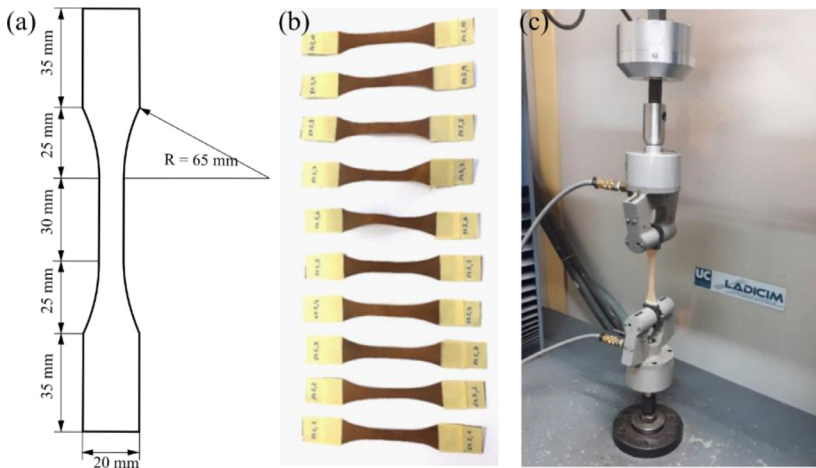
Fig. 2. (a) Geometry of the paper samples; (b) Ten plain Kraft paper samples of ageing state I; (c) Paper sample being subjected to a tensile test.

80–82 μm, so the proposed experimental method was adapted in order to study its response to edgewise compression. The experiments described in this section were carried out for the study [1], in which the mechanical failure of a continuously transposed conductor of a power transformer is analysed. Then, the geometry of the samples for compressive testing resembles the shape of the insulation of that conductor and consists of two concentric cylinders made of paper insulation, with 20 mm height and 10 mm radius. A sewing thread was used, with the intention of constraining the cylinder to open circumferentially, but trying to avoid an artificial rigidisation as far as possible, see Fig. 1(a).

The compressive tests were performed with the strain rate proposed in [3], of 0.00185 s^{-1}, which is equivalent to 0.25 mm/min, and transmitting the loading force through a plastic plane surface, to reduce damage of edges or stress concentrations, see Fig. 1(b). The testing machine records the compressive load (N) by means of the load cell, and the elongation of the paper sample (mm) by the moving crosshead. The uniaxial load-elongation curves are recorded by a PC. To transform the measured data to stress-strain curves, relationships (1) and (2) were
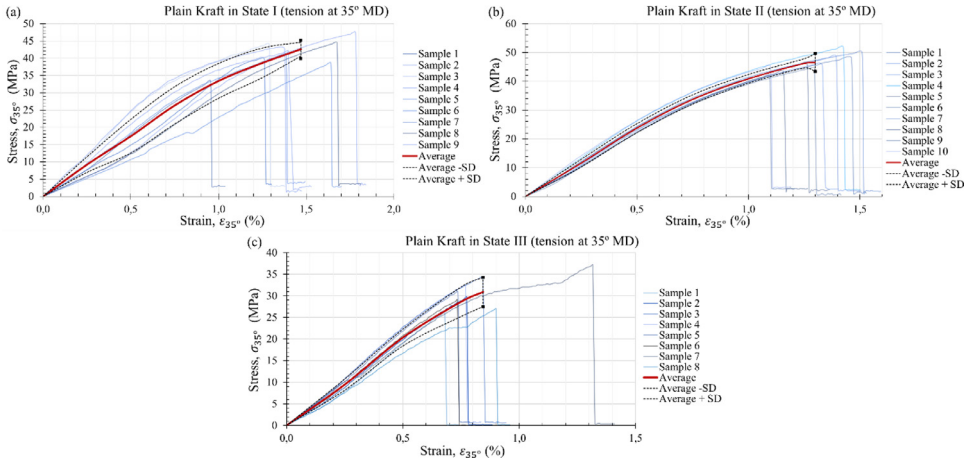
Graph 6. Tensile test at 35° MD for the plain Kraft paper in ageing states (a) I, (b) II and (c) III.

considered.

$$\varepsilon\ (\%) = \frac{H_0 - H}{H_0} \cdot 100 \tag{1}$$

$$\sigma\ (MPa) = \frac{F}{A} = \frac{F}{4\pi \cdot 10 \cdot t} \tag{2}$$

Where:

$H\ (mm)$: Height of the cylindrical sample measured by the actuator of the testing machine.

$H_0\ (mm)$: Initial height of the cylindrical sample.

$F\ (N)$: Force recorded by the tensile machine.

$A\ (mm^2)$: Cross-sectional area of the cylinder that is in contact with the plastic loading surface, $A = 2\ (2\pi R \cdot t) = 4\pi R \cdot t = 4\pi \cdot 10 \cdot t\ mm^2 t\ (mm)$: Thickness of the material.

Five cylindrical samples made of each insulation paper (plain Kraft and crepe) with their edge direction oriented in the MD and in each of the considered ageing states (State 0-III) were prepared, and the same number of samples with their edge oriented in CD. All those samples were subjected to compressive testing up to a strain of 4%, and the obtained stress-strain curves are shown in Graphs 2–5. Note that the strains are compressive, although they have been represented in absolute value in the horizontal axis.

2.3. Tensile testing of the dielectric papers at 35° to MD

The experiments described in this section were carried out for the study [1], where it was of interest to make an estimation of the shear strength (or shear strain at breakage) of the paper material. Several authors propose to infer the shear properties of paper from in-plane uniaxial tests at 45° to the MD, as that generates a biaxial stress state equivalent to a state of pure shear. On the other hand, paper materials with similar grammage and thickness to the ones analysed here were tested in [7], where it was found that an angle of 35° to the MD pronounces the shear stress component, while reducing the effect of normal stress components. The results of [7] were confirmed in [8] and [9]. Due to that, tensile tests over paper strips oriented at 35° to the MD were carried out over samples of the plain Kraft and crepe papers in the different ageing states.

Ten dog-bone shaped paper samples were prepared for each insulation material (plain Kraft and crepe papers) and ageing state (States 0-III), see Fig. 2(a) and (b). The purpose of that
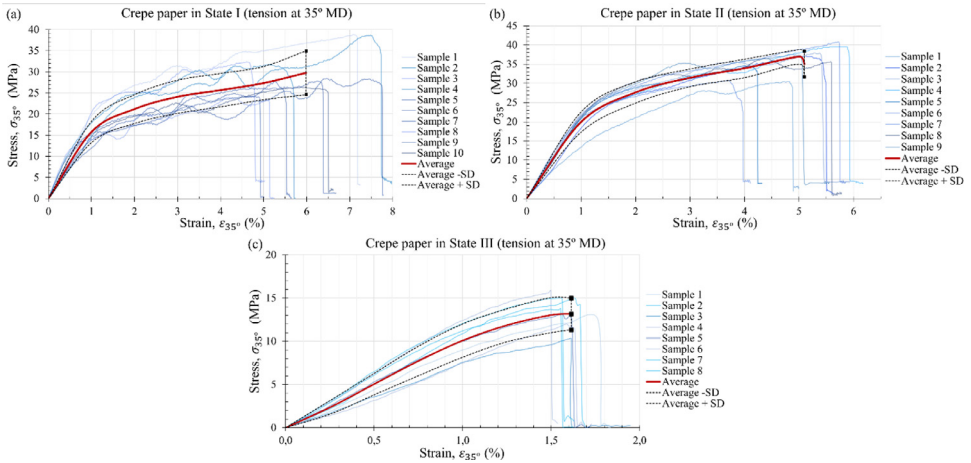
Graph 7. Tensile test at 35° MD for the crepe paper in ageing states (a) I, (b) II and (c) III.

geometry is to limit the major part of the deformation to the central area of the sample, whose length is 30 mm and whose width is 10 mm. Paper tape was used to avoid the indentation of the machine grips in the paper samples and, then, the samples were subjected to tensile forces up to fracture, Fig. 2(c), with a constant rate of elongation of 3.33 mm/min, to comply with the strain rate proposed in [3]. The testing machine records the load (N), and the elongation of the paper sample (mm). The uniaxial load-elongation curves are recorded by a PC. To transform the measured data to stress-strain curves, relationships (3) and (4) have to be considered.

$$\varepsilon \ (\%) = \frac{L - L_0}{L_0} \cdot 100 \tag{3}$$

$$\sigma \ (MPa) = \frac{F}{A} = \frac{F}{w \cdot t} \tag{4}$$

Where:

$L \ (mm)$: Distance between jaws measured by the actuator of the testing machine.

$L_0 \ (mm)$: Initial distance between jawns in the tensile test.

$F \ (N)$: Force recorded by the tensile machine.

$A \ (mm^2)$: Cross-sectional area of the paper strip, which is the product of the width by the thickness, $A = w \cdot t$.

All the prepared samples were subjected to tensile testing up to fracture, and the obtained stress-strain curves are shown in Graphs 6 and 7. An average stress-strain curve was calculated from all the tests of one particular ageing state over the plain Kraft or the crepe papers. The standard deviations of the obtained values were also calculated.

CRediT Author Statement

Carmela Oria: Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization; **Isidro Carrascal:** Methodology, Investigation; **Diego Ferreño:** Conceptualization, Methodology, Writing - Review & Editing, Supervision; **Inmaculada Fernández:** Investigation, Resources; **Alfredo Ortiz:** Conceptualization, Methodology, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

References

[1] C. Oria, D. Ferreño, I. Carrascal, A. Ortiz, I. Fernández, Study on the mechanical failure of the cellulosic insulation of continuously transposed conductors in power transformers under the influence of short circuits and thermal ageing, Eng. Fail. Anal. 124 (2021).
[2] Measurement of the Average Viscometric Degree of Polymerization of New and Aged Cellulosic Electrically Insulating Materials (2007).
[3] "ISO 1924-2:2008 Paper and board. Determination of Tensile properties. Part 2: Constant rate of Elongation Method (20Mm/Min)." ISO, 2008.
[4] "ISO 12192:2011. Paper and Board-Determination of Compressive Strength-Ring crush Method." ISO, 2011.
[5] S.V. Kulkarni, S.A. Khaparde, Transformer Engineering, Marcel Dek, New York, 2004.
[6] H. Yoshida, Y. Ishioka, T. Suzuki, Degradation of insulating materials of transformers, IEEE Trans. Electr. Insul. EI-22 (6) (1987) 795.
[7] H. Yoshihara, M. Yoshinobu, Off-axis tensile strength and evaluation of the in-plane shear strength of paper, Holzforsch 68 (5) (2014) 583–590 Gruyter.
[8] H. Yoshihara, M. Yoshinobu, In-plane shear strength of paper measured by asymmetric four-point bending test, Holzforsch 69 (1) (2015) 41–46 Gruyter.
[9] H. Yoshihara, M. Yoshinobu, Evaluation of the in-plane shear strength of paper measured by tensile-loaded shear test, Nord. Pulp Pap. Res. J. 32 (1) (2017) 126–131.