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Modeling and experimental validation of the mechanical behavior of pressboard

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Abstract - **High density (HD) pressboard is an essential element in power transformers combining good electrical insulation properties with effective mechanical characteristics that well suit design requirements of power transformers. In order to ensure a correctly functioning transformer, it is therefore very important to characterize and to understand the mechanical properties of pressboard under different operating conditions.**

Pressboard is composed of natural polymeric chains, whose mechanical properties are affected by moisture and temperature. Moreover, temperature and moisture conditions in power transformers vary throughout manufacturing process and service/operation life-time. An accurate definition of the mechanical properties is, therefore, necessary.

The present article focuses on the effect of different combinations of temperature/moisture and mechanical load on the deformation behavior of HD pressboard samples. A mechanical constitutive model is developed for finite element (FEM) simulation based on a viscoelastic–viscoplastic material description. Special attention is given on the complex through-thickness deformation behavior of HD pressboard. Thorough analyses are performed based on the comparisons between the results of experimental characterization and FEM modeling and simulations. The good agreement between experimental and modeling results shows a great potential for application in mechanical design of transformer insulation.

Keywords - Pressboard, Mechanical properties, Temperature–moisture sensitivity, Compressbility test

I. INTRODUCTION

Solid insulation materials in oil immersed transformers mainly consist of cellulose based materials. In order to reduce uncertainties during manufacturing and to ensure the correct functioning of the system, the physical properties of the insulating components should be well defined and controlled. The present work focuses on the mechanical properties of cellulose-based insulation elements, in particular pressboard components. It is known that the out-of-plane properties of pressboard affect the size and the tolerances of a transformer during production. Cellulose is a polymer which is sensitive to moisture and temperature. A change in one of the two parameters causes changes both in the dimension of the components, swelling or shrinkage, and alters the mechanical properties as well. Studies on the effects of moisture and temperature on in-plane mechanical properties of cellulose materials show that the elastic modulus decreases with increasing temperature and moisture content as reported by, e.g. Salmén and Hagen [1].

The out-of-plane behavior of cellulose based materials is a much less investigated topic in the literature. Experimental results on cyclic out-of-plane compressive deformation of High Density (HD) and Low Density (LD) pressboard can be found in [2], where also the influence of temperature was studied. The results show that dry and warm material is stiffer than moist and cold one. Also plastic deformation due to cycling load was larger in moist material compared to dry even if tested at high temperature. A further step towards a better utilization of the material in transformers is represented by the description of the behavior of pressboard using a 3-D continuum material model. The basics of such modeling have been described in [3]. The model was calibrated with data from compression experiments and validated by comparing the results from compressibility tests and creep tests. The material model is implemented into a standard finite element (FE) program for simulations.

In the present work, the material model is further adapted to capture the behavior at different moisture contents and temperatures. Calibrations at given moisture contents and temperature are performed. The validation is then performed by comparing the predicted compressive curves with experimental results at other temperatures and moisture contents.

II. MATERIALS AND METHODS

The tests presented here were performed on High Density pressboard produced by ABB Figeholm. In particular the test material was a 3 mm thick calibrated pressboard. The test pieces were 25 mm by 25 mm in size as specified by IEC 60641-2 – Compressibility and reversible compressibility tests [4]. The test pieces consisted of stacks made of pressboard bits. The stack was placed in between two metallic plates with polished surfaces and compressed. The deformation of the system was measured by three inductive displacement transducers LVDT (HBM type K-WA 10 mm) fastened to the top plate and measuring the distance to the bottom plate. The load was measured by a load cell with maximum load of 100 kN. The experimental set-up is depicted in Fig. 1. The value of the loading speed was 5 min/mm, and it was chosen according to [4].

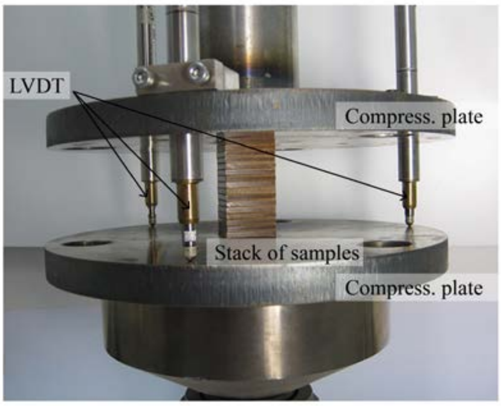

Figure 1: Typical experimental set-up for pressboard compressive test.

The experimental results hereby presented include two different sets of experiments. The first set analyses the effect of three different temperature levels, as shown in Table I. For these experiments the test pieces were first dried in hot air and then at vacuum at 110°C. The test pieces were then conditioned for 24 hours in vacuum at the temperature planned for the test. The experiments at 70°C and 110°C were performed by mounting the compression plates, the connection to the piston of the tensile testing machine and the displacement transducers in an oven that fits within the frame of the tensile testing machine.

In the second set of experiments the influence of moisture contents on mechanical properties of pressboard is analyzed (see Table II).

TABLE I. TEMPERATURE AND MOISTURE COMBINATIONS FOR EXPERIMENTS SET 1

Temperature	23°C	70°C	110°C
Moisture content	Dry	Dry	Dry

TABLE II TEMPERATURE AND MOISTURE COMBINATIONS FOR EXPERIMENTS SET 2

Temperature	23°C	23°C	23°C
Moisture content	Dry	3 wt.%	7 wt.%

III. MECHANICAL MODELING

In order to perform a more comprehensive analysis of the mechanical behavior of HD pressboard, a three-dimensional, continuum-based, mechanical model is developed. For the sake of simplicity, only the most relevant aspects of the model are highlighted in this report. More details on the formulation of model governing equations and its numerical implementation aspects can be found elsewhere (e.g. [5]).

The model formulation is based on a standard viscoelastic–viscoplastic constitutive material law that accounts for strong anisotropy, where the total strain $\boldsymbol{\varepsilon}$ is decomposed into the elastic part ($\boldsymbol{\varepsilon}_e$), the plastic part ($\boldsymbol{\varepsilon}_p$), and the thermal/hygro expansion part ($\boldsymbol{\varepsilon}_v$), such that

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_e + \boldsymbol{\varepsilon}_p + \boldsymbol{\varepsilon}_v$$

A standard linear viscoelastic law is applied to describe the time-dependent viscoelastic behavior, such that the overall stress response is related to the magnitude of the elastic strain, as well as the history of the elastic deformation [6], $\boldsymbol{\sigma} = \boldsymbol{\sigma}(\boldsymbol{\varepsilon}_e, \dot{\boldsymbol{\varepsilon}}_e)$. In this case, the overall stiffness of the material is non-linear, which incorporated the effects of temperature (θ) and moisture content (ρ),

$$\overline{\boldsymbol{C}} = \boldsymbol{C}_0 \Phi^e(\theta) \Psi^e(\rho)$$

where $\boldsymbol{C}_0$ represented the elastic stiffness at the reference climate condition $\boldsymbol{C}_0 = \boldsymbol{C}_0(\xi, \theta_0, \rho_0)$, with ξ a parameter describing the through-thickness densification process. In the above equation Φ^e and Ψ^e are empirical functions representing the effects of, respectively, temperature and moisture content on the elastic stiffness.

The post-yield material behavior is described by an anisotropic viscoplastic model, where the evolution of the plastic deformation follows a power-law kinetic equation (see *e.g.* [7]),

$$\dot{\boldsymbol{\varepsilon}}_p = \dot{\boldsymbol{\varepsilon}}_p(\boldsymbol{\sigma}, \boldsymbol{s_Y})$$

where $\boldsymbol{\sigma}$ is the stress tensor and $\boldsymbol{s_Y}$ described the resistance against plastic deformation or the yield strength Analogous to the elastic stiffness, the plastic resistance is also a function of temperature and moisture as,

$$\boldsymbol{s}_Y = \boldsymbol{s}_0 \Phi^p(\theta) \Psi^p(\rho)$$

where $\boldsymbol{s}_0$ represents the yield strength at the reference climate condition $\boldsymbol{s}_0 = \boldsymbol{s}_0(\xi, \theta_0, \rho_0)$, whereas Φ^p and Ψ^p are empirical functions characterizing the effects of temperature and moisture content on the overall plastic yield strength. The specific expressions for the temperature functions $\Phi^{e,p}$ and moisture functions $\Psi^{e,p}$ will be presented in Section IV.

Furthermore, the present model included a specific hardening model adopting an exponential law, which is typically applied in the modeling of porous media, e.g. paperboard [6, 8]. Upon compression, the material undergoes a compaction process, which is reflected by the evolution of densification parameter ξ being a function of the out-of-plane strain $\varepsilon_{\mathrm{ZD}}$ as follows:

$$\xi = (1 + \xi_0) \exp \varepsilon_{\mathrm{ZD}} - 1$$

where ξ_0 represents the initial pores-to-fiber ratio and $\varepsilon_{\mathrm{ZD}}$ is the normal component of the total strain ε in the out-of-plane direction.

IV. RESULTS AND DISCUSSION

The present article includes experimental stress-strain curves obtained by compressing HD pressboard at different temperatures and moisture contents. These results are then used to calibrate functions included in the material model. In order to define the accuracy of the calibration, the simulated curves and experimental curves are then compared.

A. Experimental results

The experimental results are presented in form of stress–strain curves, which include two consecutive loading-unloading cycles. As already reported [3], the first loading cycle generates large irreversible deformations of the material. The herein presented experimental curves are obtained by averaging the data from three experiments for each temperature and moisture combination. Note that in the present analysis the initial deformations occurring below 0.5 MPa have been filtered out.

Fig. 2 shows the results for the experiments on dry pressboard performed at different temperatures. Over the considered range of temperatures, the overall features of the stress–strain response, particularly the hysteresis during loading–unloading, are very similar. As expected higher temperature leads to reduction in stiffness, i.e. larger compliance, and a lower effective strength.

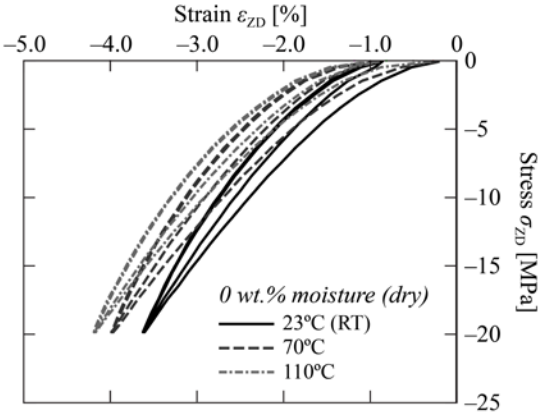

Figure 2: Temperature effects on the compressive stress–strain response of dry pressboard.

The results of the experiments performed at room temperature for different moisture contents are presented in Fig. 3. In general, moisture influences pressboard in a similar way as temperature, i.e. higher moisture content leads to reduction in stiffness and lower effective strength.

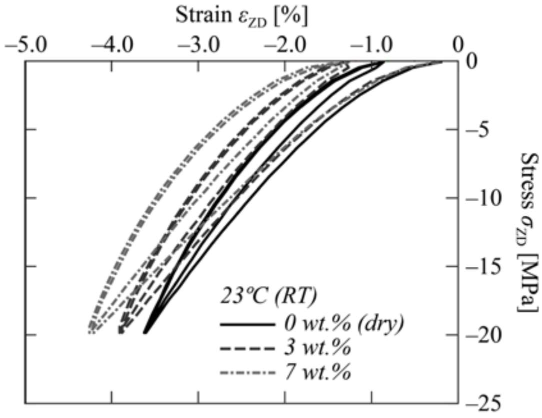

Figure 3: Moisture effects on the compressive stress–strain response of pressboard at room temperature.

Moreover, in comparison to the temperature effects, the effects of moisture content on the stress–strain hysteresis are more visible. During unloading, a larger amount of permanent plastic strain is observed with increasing moisture, which indicates that moisture content affects the plastic yield strength more than the elastic stiffness (see also Figs. 4 and 5).

B. Calibration of the model

The experimental data are used to calibrate two functions that independently describe the influence of temperature and moisture content on the through-thickness behavior of HD pressboard.

TABLE III. TEMPERATURE EFFECT ON THE ELASTIC–PLASTIC PROPERTIES OF DRY PRESSBOARD

Temperature	23°C	70°C	110°C
Elastic stiffness $\bar{\boldsymbol{C}}/\boldsymbol{C}_0$	1.00	0.86	0.80
Yield strength $\boldsymbol{s}_{\boldsymbol{Y}}/\boldsymbol{s}_0$	1.00	0.93	0.90

TABLE IV. MOISTURE EFFECT ON THE ELASTIC–PLASTIC PROPERTIES OF PRESSBOARD AT ROOM TEMPERATURE

Moisture content	Dry	3 wt.%	7 wt.%
Elastic stiffness $\bar{C}/C_0$	1.00	0.94	0.88
Yield strength s_Y/s_0	1.00	0.85	0.70

Tables III and IV illustrate the effects of temperature and moisture content on the overall elastic–plastic behavior of the pressboard. In these tables, the overall elastic stiffness $\bar{C}$ and the plastic yield strength s_Y have been normalized by the reference values C_0 and s_0 (for dry pressboard at 23°C). As indicated in Table III, temperature effects tend to saturate at higher temperature range, i.e. the material elastic stiffness and the plastic yield strength become less sensitive to temperature in the high temperature regime. Within the considered range of moisture levels, 0 wt.% to 7 wt.%, the effects of moisture on the elastic stiffness and the plastic yield strength are quite linear, as shown in Table IV.

In order to adequately capture these effects, the present model adopted a combined linear–exponential function for both temperature and moisture effects, such that

$$\Phi^{e,p} = A_1^{e,p}(\theta - \theta_0) + A_2^{e,p}\{\exp A_3^{e,p}(\theta - \theta_0) - 1\} + 1$$
$$\Psi^{e,p} = B_1^{e,p}(\rho - \rho_0) + B_2^{e,p}\{\exp B_3^{e,p}(\rho - \rho_0) - 1\} + 1$$

with reference condition $\theta_0 = 23°\mathrm{C}$ (296 K) and $\rho_0 = 0\%$ (i.e. dry pressboard at RT). Note that in the above expressions, temperature (θ) is expressed in Kelvin (K) and moisture content (ρ) in weight percent (wt.%).

Model parameters $A_i^{e,p}$ and $B_i^{e,p}$ for the temperature and moisture functions are directly calibrated to experimental data for the normalized elastic stiffness and yield strength, as shown in Figs. 4 and 5. The list of actual values of the parameters $A_i^{e,p}$ and $B_i^{e,p}$ used in the functions $\Phi^{e,p}$ and $\Psi^{e,p}$ are presented in Table V.

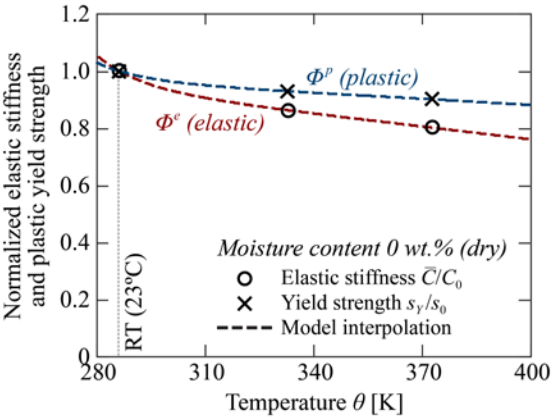

Figure 4: Temperature effects on the overall elastic stiffness and plastic yield strength of dry pressboard.

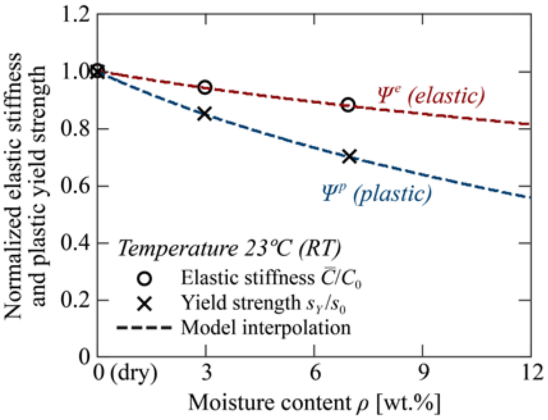

Figure 5: Moisture effects on the overall elastic stiffness and plastic yield strength of pressboard at room temperature.

TABLE V. LIST OF TEMPERATURE AND MOISTURE FUNCTIONS PARAMETERS CALIBRATED TO HD PRESSBOARD

$A_1^e = -0.0015$	$A_2^e = 0.07$	$A_3^e = -0.08$
$A_1^p = -0.0007$	$A_2^p = 0.04$	$A_3^p = -0.08$
$B_1^e = -0.01$	$B_2^e = 0.08$	$B_3^e = -0.16$
$B_1^p = -0.02$	$B_2^p = 0.24$	$B_3^p = -0.16$

C. Simulated results

The through-thickness stress-strain curves for HD pressboard are simulated using the material model that includes the parameters obtained from the above calibration. Figs. 6–8 compare the experimental and the simulated curve for dry material at three different temperatures. The agreement between the simulated curves and the measured ones is relatively good, which suggests that the weight functions $\Phi^{e,p}$ introduced in the model are able to capture the effects of temperature on the elastic-plastic behavior of the material.

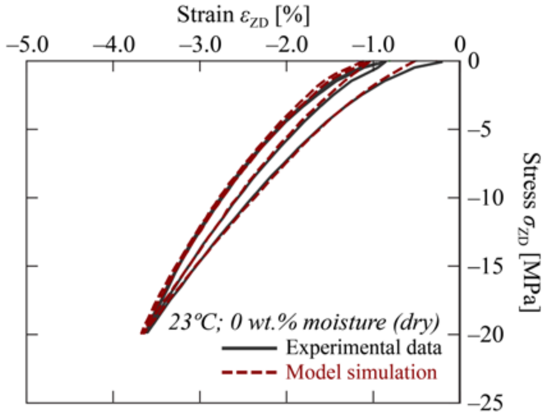

Figure 6: Through-thickness stress strain curves for dry pressboard compressed at 23°C.

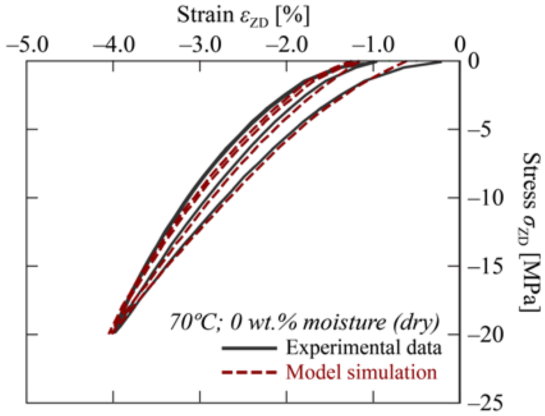

Figure 7: Through-thickness stress strain curves for dry pressboard compressed at 70°C.

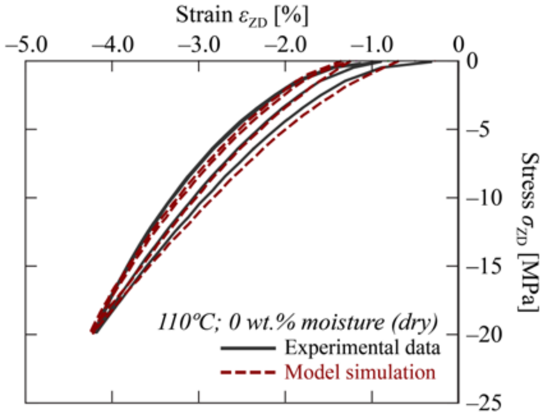

Figure 8: Through-thickness stress strain curves for dry pressboard compressed at 110°C.

Figs. 9 and 10 depict the compressive stress-strain curves for two different moisture contents, respectively 3 wt.% and 7 wt.%. Note that the curve for dry material tested at 23°C is already presented in Fig. 6. These figures show that the simulated curves are in good agreement with the experimental curves for all tested moisture contents.

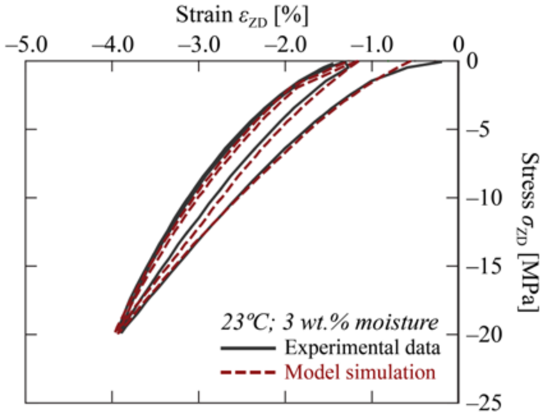

Figure 9: Stress strain curves for pressboard at room temperature at 3 wt.% moisture content.

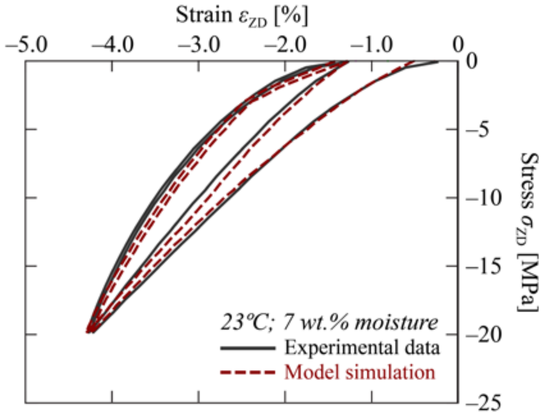

Figure 10: Stress strain curves for pressboard at room temperature at 7 wt.% moisture content.

In addition, it can be seen from the comparisons between the experimental and the simulated curves, Figs. 6–10, that the model with its densification feature is able to properly capture the difference in the stress-strain responses between the first and the second cycles.

V. CONCLUSIONS

The present paper shows the experimental steps taken for a material model for depicting the mechanical behavior of pressboard. The activities mainly focused on describing the through-thickness mechanical behavior of the material under different temperature and moisture conditions. The experimental curves describing compressive cycles suggest that pressboard is more sensitive to moisture than to temperature. Both temperature and moisture effects are, in general, non-linear and mainly affect the elastic modulus and the plastic deformation. This behavior was then translated into weight functions that were applied in the material modeling.

The experimental through-thickness compressive curves were then compared with the simulated ones. The experimental and the simulated results show good agreement which shows that the adopted model is able to capture the mechanical non-linear behavior of the pressboard in the specified temperature range and moisture contents. Thus far, the effects of temperature and moisture were analyzed independently. The combined effect of the coupling between moisture and temperature effects, including the effects on transient behavior of the material, is subject for further investigation. The model presented herein shows the potential of the method for a number of practical applications within the field of pressboard-based insulation materials.

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