Moisture sorption and thickness swelling of wood-based materials intended for structural use in humid conditions and bonded with melamine resin

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Abstract. When used in construction, the properties of wood-based materials they are mainly affected by moisture. Moisture sorption and the associated swelling has an impact on the resistance of materials to biocidal attacks, on their mechanical properties or air permeability, and on comfort of use and durability of the structure. Equilibrium moisture content (EMC) and thickness swelling (TS) depending on the relative humidity for plywood (PW), particleboard (PB) and oriented strand board (OSB), for load-bearing purposes in humid environments and bonded with melamine-urea-formaldehyde resin (MUF), are studied in detail in this paper. Equilibrium moisture content and thickness swelling are influenced by the type of material, density, quantity of adhesive composition, and paraffin. The highest values of equilibrium moisture content were found in plywood, whilst the highest thickness swelling was achieved by OSB. A high dependency of nonrecoverable thickness swelling on the equilibrium moisture of the material was also ascertained. The proportion of nonrecoverable thickness swelling increases exponentially, in particular if the material’s equilibrium moisture content exceeds 12%.

1. Introduction

In the construction industry, wood-based materials are widely used for ceiling and floor constructions, for reinforcing vertical column structures, for facade systems, roof construction, etc. Wood-based materials may be exposed to increased humidity in all of these application methods.

During moisture sorption, swelling occurs for both wood-based materials and solid wood. While the cross-bonding of the wood elements makes the linear expansion in the board surface low, thickness swelling is significantly higher [1,2]. In addition, during swelling up to thickness, wood-based materials behave differently than solid wood. While solid wood returns to the same dimensions after swelling and re-drying, for wood-based materials, part of the thickness swelling is nonrecoverable [2,3]. As a result of nonrecoverable thickness swelling, the strength of the bonded joints is reduced and consequently the strength of all board materials [4,5] is lost. For OSBs, which are often used in structures as a vapor retarder, their permeability also increases [6]. The factors that most affect the sorption and swelling of wood-based materials primarily include: the density profile of the material,
the type and quantity of adhesive used, hydrophobic agents, and the temperature affecting the materials during pressing [7,11].

The uniform density profile and lower compression of the wood elements during pressing reduces both the overall thickness and the proportion of nonrecoverable thickness swelling. However, it also negatively influences mechanical properties, in particular the modulus of elasticity and flexural strength [7]. In terms of the used adhesive, there are big differences not only in their properties but also in price. For the relevant class of material use, MUF adhesives are the most suitable, as they offer relatively good moisture resistance with simultaneous economic advantage. The MUF adhesive is usually added at 6-10%, whereas a higher adhesive deposition reduces thickness swelling while also improving the mechanical properties of the materials [8,9]. Various agents can be used as hydrophobic agents, such as silicones or oils. However, the most effective of these agents is paraffin, which is added to wood chips in the form of an emulsion, usually at 0.5-1.0% [9,11]. The pressing temperature differs in particular with regard to the different types of adhesives, and depends on whether the curing process is based on a temperature increase or pH change. The use of higher temperature and prolonged pressing time generally leads to a reduction in moisture sorption in wood-based materials compared to solid wood [2,7,12]. Achieving lower equilibrium moisture in wood-based materials is generally advantageous, not only because of smaller dimensional changes, but also because increased moisture causes easier vulnerability of wood parts to biotic agents.

The determination of equilibrium moisture, thickness change and proportion of nonrecoverable thickness swelling depending on moisture is therefore one of the most important tasks in evaluating the properties of wood-based materials. It is also important to ensure the use of materials under conditions that do not result in nonrecoverable swelling, and thereby deterioration of their properties.

2. Materials and methods

2.1. Materials

For the purposes of this research, samples of commercially-available materials produced in the Czech Republic were used, which are bonded with the same base adhesive, and the adhesive is cured at a similar pressing temperature. A urea formaldehyde adhesive with the addition of melamine (up to 30%) was used for the production of plywood and particleboard. Since OSBs are only produced in the Czech Republic by one production plant, which mainly uses isocyanates (MDI) for their bonding, it was not possible to evaluate OSBs bonded completely with MUF adhesive. An OSB type was chosen where the centre layer is bonded with MDI adhesive and the surface layers are bonded with MUF adhesive. Previous research has demonstrated [10] that high density surface layers have the largest share in OSB thickness swelling. In addition, the lower-density core layer is bonded with a cross-linked MDI adhesive and only marginally contributes to the nonrecoverable thickness swelling. Therefore, the OSBs were also included for comparison with materials exclusively bonded with MUF adhesive. Basic information on the tested materials is specified in Table 1.

| Panel type (Standard) | Thickness (mm) | Wood species | Adhesive | Wax (kg/m²) | Press. temp. (°C) | Specification |
|----------------------|----------------|--------------|----------|-------------|------------------|---------------|
| OSB /3 (EN 300)      | 12.0           | Spruce (80%) | Face: MUF 8.5% | 1.2         | 210              | Face to Core weight ratio: approx. 50/50 |
|                      |                | Pine (20%)   | Core: MDI 3.5%  |             |                  |               |
| PB P5 (EN 312)       | 12.1           | Spruce (80%) | MUF 11.5%      | 2.4         | 165              | Pigments added to the adhesive. |
|                      |                | Hardwoods (20%) |          |             |                  |               |
| PW 2/S (EN 636-2)    | 11.9           | Spruce (core layers) | MUF 160 g/m2 (approx. 16%) | 0     | 150              | Layers: 11 Flour added to the adhesive. |
|                      |                | Beech (face) |          |             |                  |               |
2.2. Experimental methods
Test specimens were taken from commercially-available materials in accordance with EN 326-1. The deviation from the standard procedure consisted only of the number of selected specimens. The numbers of removed specimens were adjusted to determine the nonrecoverable proportion of thickness swelling. For each material, samples were taken from 10 boards so that 6 samples were randomly selected from each board. The samples were subsequently divided into 6 groups of 10 samples each. In each group, each board was represented by one sample. There were 180 samples in total for three types of materials.

The test samples were oven-dried and then air-conditioned in an air-conditioning chamber at 6 humidity levels at 15, 35, 50, 65, 85 and 100% relative air humidity at 20 °C. Density, moisture content, thickness swelling and nonrecoverable thickness swelling were then determined at all humidity levels.

In order to determine the density, the standard procedure according to standard EN 323 was used (see equation 1). The moisture content was determined according to standard EN 322 (see equation 2).

\[
\rho = \frac{m_1}{l \cdot b \cdot t} \cdot 10^6 \quad \text{[kg/m}^3]\]

\[
w = \frac{m_1 - m_0}{m_0} \cdot 100 \quad \text{[%]} \tag{1, 2}
\]

where \(m_1\) is the mass of the test specimen after air-conditioning in individual humidity stages (g); \(l, b, t\) are the length, width and thickness of the specimen (mm) and \(m_0\) is the mass of the test specimen after drying (g).

Thickness swelling (Eq. 3) was ascertained according to standard EN 318 and nonrecoverable thickness swelling (Eq. 4) was ascertained in such a way that after air-conditioning of the samples and ascertaining thickness swelling for the relevant moisture level, a group of samples re-dried at a temperature of \((103 \pm 2)\) °C was selected.

\[
\Delta T = \frac{t_e - t_0}{t_0} \cdot 100 \quad \text{[%]} \\
\Delta T_N = \frac{t_{e0} - t_0}{t_0} \cdot 100 \quad \text{[%]} \tag{3, 4}
\]

where \(t_0\) is the thickness of the test specimen after drying (mm); \(t_e\) is the thickness of test specimens after air-conditioning at individual humidity levels (mm); \(t_{e0}\) is the thickness of re-dried test specimens after air-conditioning at individual humidity levels.

X-ray density profile analyzer DPX300-LTE (Imal, Modena, Italy) was used to ascertain the vertical density profile (VDP) of the tested materials. Measured data evaluation and statistical analyses were performed using the Statistica 13 (TIBCO Software, USA) program.

3. Results and discussion

3.1. Density
The density of the tested materials was first analysed, as the moisture sorption and thickness swelling are affected by density. For solid wood, the higher the density of wood, the more it swells [3] during air moisture sorption. However, this rule may not always apply to wood-based materials. In addition to average density, the moisture sorption of wood-based materials and their thickness swelling is also affected by the shape of their vertical density profile, wood particle size, the used adhesive composition and additives and other manufacturing parameters, as well as their interaction [2,12]. The density of the tested materials, calculated at 20 °C and 65% relative humidity, is shown in Figure 1.
Particleboard has the highest average density of the tested materials, 717 kg/m$^3$, and particleboard has the smallest margin of density values. In contrast, the largest margin of density values was found in OSBs. Unlike particleboard, in the production of OSBs, small fractions of strands are removed. Thus, the OSB mat forming is not as uniform as particleboard due to large-area strands. Large strands are not easy to form - larger voids are created and the density profile is not uniform.

The plywood density profile is particularly influenced by the selection of individual veneers for layering.

The vertical density profiles of individual materials are shown in Figures 2-4.

![Fig. 2. Vertical density profile of particleboard.](image1)

![Fig. 3. Vertical density profile of OSB.](image2)

![Fig. 4. Vertical density profile of plywood.](image3)
In the figures with the vertical density profiles of the tested materials, the thickness of the board in millimetres (in this case 12 mm) is shown on the X axis, and the density in kg/m$^3$ is shown on the Y axis. It can be seen from the figures that the various materials have a different cross-sectional density profile, and that the usually-specified average density data may not be sufficient to assess the causes of thickness swelling.

Both particleboard and OSBs have a typical U-shaped density profile, and they only differ in that the density of the particleboard is slightly higher. However, since the particleboard has been surface treated via sanding, the highest density layers are on the surface of the board. For OSBs that have not been sanded, the layers with the highest density are below the surface of the board and the surface layers have a lower density.

On the vertical density profile of plywood, some variability in the density of individual veneers was observed, as well as increased density in bonded joints. It is obvious from the density profile of bonded joints that the adhesive penetrated the pores in the wood and the bonded joints have a very small thickness.

3.2. Equilibrium moisture content

The measured values of equilibrium moisture of materials at six different degrees of relative moisture are specified in Table 2. The table shows the mean values in % and the coefficients of variation in brackets, also in %.

| Material | 15% | 35% | 50% | 65% | 85% | 100% |
|----------|-----|-----|-----|-----|-----|------|
| OSB      | 2.39| 4.68| 6.18| 8.24| 12.56| 20.11|
|          | (4.91)| (1.73) | (1.61) | (1.32) | (2.68) | (6.35) |
| PB       | 2.60| 5.22| 6.58| 8.34| 12.05| 19.14|
|          | (3.69) | (2.31) | (2.96) | (1.26) | (1.75) | (4.56) |
| PW       | 2.38| 5.54| 7.11| 9.00| 12.63| 21.85|
|          | (4.16) | (3.12) | (1.88) | (2.44) | (2.32) | (2.63) |

All of the tested materials have significantly lower equilibrium moisture than solid wood under the same conditions. Therefore, the equilibrium moisture results were compared to a control sample of spruce wood that was subjected to the same conditions. The equilibrium moisture of solid spruce wood was only 11.68% at 20 °C and 65% relative air humidity at a density of 559 kg/m$^3$. It is commonly stated in professional literature that the equilibrium moisture of wood-based materials is about 2% lower than that of wood [9]. However, in this experimental measurement, it was found that the equilibrium moisture content of particleboard and OSB is lower by more than 3% at 65% relative humidity compared to wood.

Furthermore, the OSB equilibrium moisture is higher than the particleboard equilibrium moisture at the two highest moisture levels, even if a higher temperature was used during OSB pressing. This is likely due to a smaller coating of paraffin.

The highest equilibrium moisture was achieved by plywood due to the large proportion of solid wood in the form of veneers.

The moisture sorption is shown in Figure 5.
Fig. 5. Dependence between relative air humidity and equilibrium moisture content of materials.

Third degree polynomials were used to graphically depict the profiles of the measured equilibrium moisture values. The moisture sorption is very similar for all of the tested materials. The highest equilibrium moisture was achieved by plywood, but compared to the other OSBs, this difference is less than 10%. Adversely, the changes in thickness swelling are quite significant, see Tab. 3 and Fig. 6.

3.3. Thickness swelling

Table No. 3 shows average thickness swelling values in %. The numbers in brackets represent coefficients of variation, also in %.

| Material | Relative humidity |
|----------|------------------|
|          | 15%   | 35%   | 50%   | 65%   | 85%   | 100%  |
| OSB      | 0.61  | 1.58  | 2.24  | 4.09  | 8.52  | 15.32 |
|          | (24.65)| (18.28)| (10.26)| (13.35)| (13.85)| (11.08)|
| PB       | 0.71  | 1.84  | 2.27  | 3.35  | 5.63  | 11.24 |
|          | (14.07)| (8.42)  | (5.72)  | (6.52)  | (2.77)  | (4.96)  |
| PW       | 0.38  | 1.69  | 1.75  | 2.20  | 3.89  | 7.22  |
|          | (19.61)| (7.26)  | (7.96)  | (7.87)  | (6.76)  | (5.40)  |

Fig. 6. Thickness swelling of the tested materials.
The moisture sorption is very similar for all the studied materials up to a relative humidity of 40%. However, at a higher relative humidity, the differences between the materials start to increase. OSBs achieved the highest thickness swelling, where 15% was the maximum thickness swelling value. Particleboard had less swelling (11.2%) and plywood (7.2%) had the least. As the proportion of nonrecoverable thickness swelling has a greater impact on material properties than overall thickness changes, nonrecoverable thickness changes were analysed in more detail.

3.4. Nonrecoverable thickness swelling

Non-linear regression was used to estimate the relationship between equilibrium moisture content and nonrecoverable thickness swelling. The outputs from the regression analysis are shown in Fig. No. 7.

![Graph showing the relationship between equilibrium moisture content and nonrecoverable thickness swelling.](image)

**Fig. 7.** Relationship between equilibrium moisture content and nonrecoverable thickness changes.

It was found that at low equilibrium moisture, the proportion of nonrecoverable thickness swelling increases very slowly, almost linearly. However, since equilibrium moisture is about 8% for OSB, and about 12% for plywood and fibreboard, the proportion of nonrecoverable swelling is increasing rapidly. The profile of this dependence is best described by the exponential fit. Due to the natural variability of the tested materials, the calculated exponential equation has a relatively close dependence with a determination coefficient exceeding 85% for OSB and 77 and 72% for plywood and particleboard.

The smallest proportion of nonrecoverable thickness swelling is achieved by plywood, which contains only 11 bonded joints per 12 mm thickness. Due to its construction, its thickness swelling consists mainly of recoverable solid wood swelling and the nonrecoverable changes are very small.

Several factors have contributed to a greater proportion of nonrecoverable thickness swelling of OSB versus particleboard. On the one hand, OSB is made of larger flat strands which, when their moisture changes, cause greater shear stress and result in greater stress on the bonded joint and also cause greater unevenness in the density profile. Furthermore, the OSBs are compressed at pressures exceeding 3 MPa, while particleboard at only about a third of the pressure. Due to the larger OSB strands that are more difficult to from and the greater pressure, more residual tension is already accumulated in the OSBs. Wood strands have a greater tendency to straighten, leading to greater overall thickness changes, as well as a higher proportion of nonrecoverable thickness swelling.
4. Conclusions
According to Eurocode 5, all of the tested materials belong to Use Class 2, where it is stated that the “relative humidity of the surrounding air only exceeds 85% for a few weeks per year”. Although this concerns use for protected applications, Eurocode 5 permits short-term exposure of water to these construction materials. It arises from the investigation that for the deterioration of their properties, the important thing is the equilibrium moisture content that the materials achieved, as nonrecoverable thickness changes are strongly dependent on the equilibrium moisture content of the materials.

The equilibrium moisture content that the materials achieve is affected by the amount of paraffin and their density profile. For short-term washing with water, higher-density surface layers may be advantageous, as they slow moisture penetration into the material. On the other hand, higher density of the surface layers appears to be unsuitable for exposure to high air humidity. OSB has the highest nonrecoverable thickness swelling values and has the non-uniform vertical density profile.

Neither a significant increase in relative humidity above the limit of 85%, nor washing with water may be problematic for the proper function and use of materials. However, this increase of humidity must only be short-term, wherein the equilibrium moisture content of materials is not over-increased. On the contrary, even a very slight increase in relative humidity above 85% can have a negative impact on the properties of the tested materials if it is long-term. The higher moisture exposure time depends on the way the materials are applied. In a laboratory experiment, unprotected materials that were accessible to moisture from all sides except the lower edge achieved an equilibrium moisture content of about 12% after 5 days of increasing relative humidity from 65% to 85%.

The results also show that it is particularly important to ensure that the long-term use of tested materials in structures does not increase their equilibrium moisture content by more than 12%, when the proportion of nonrecoverable thickness swelling begins to increase rapidly.

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