Impact of Wetting/Oven-Drying Cycles on the Mechanical and Physical Properties of Birch Plywood

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Abstract. The objective of this study was to explore some physical and mechanical properties and the dimensional stability of birch (Betula sp.) nine-ply veneers glued with phenol-formaldehyde (PF) after 10 cycles of soaking/oven-drying. The properties to be determined were bending strength (BS), modulus of elasticity in bending (MOE), Janka hardness (JH) and thickness swelling (TS), which were tested according to the European Standards (EN). An analytical equation was used for approximation of the change in the physical and mechanical properties of the samples depending on the number of cycles. It was shown that the values of the studied properties were affected most by the first soaking and drying cycles after which BS and MOE decreased continuously while the values of JH and TS stabilized. After 10 cycles the final values of BS, MOE, JH and TS accounted for 75-81%, 95%, 82% and 98.5% of the initial values, respectively.

1. Introduction
Plywood is an original engineered wood product made by bonding several softwood or hardwood plies. Plywood is a multi-used structural material in the manufacture of conventional construction (engineered flooring) and industrial products (even high-risk gasholder). The important factors that affect the physical and mechanical properties of plywood are tree species, density of wood, number of plies, type of adhesive, thickness of veneers and technological parameters of manufacturing [1,2,3,4].

Various test methods were applied in accordance with the European Standards (EN); bending strength (BS) and modulus of elasticity in bending (MOE) were determined according to the face grain orientation of the first plies; Janka hardness (JH) and thickness swelling (TS) were determined as well. Changes in BS, MOE, JH, TS at different soaking/oven-drying cycles were investigated in a Master’s thesis of Sooru, Kasepuu [5, 6].

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The basic method consists in soaking specimens in water at room temperature for 24 h, drying 48 h in a ventilated drying box at 65±1 °C for a certain number of cycles and testing (immediately after pre-treatment with cold water and after drying) using the computer-controlled mechanically actuated universal test machine INSTRON 3369. After these procedures the output of data and the analysis of the obtained results take place. The sensitivity of the measured data is studied and the expanded uncertainties of the computed mean values are presented.

An analytical expression was used to approximate the experimental data for the investigated BS, MOE and JH depending on the number of soaking/oven-drying cycles.

2. Experimental procedure and methods

Three nine-ply plywood panels, birch (Betula sp) veneers, of 3000×1500×12 mm³, made by UPM-Kymmene Otepää, Estonia, were used. Engineered hardwood plywood panels are commonly glued with phenol - formaldehyde resin (PF) as the wood adhesive.

Test samples for MOE and MOR were cut from each of the panels in the parallel (major axis) and perpendicular (minor axis) directions to the face grain (parallel and perpendicular samples) [7]. Experiments were conducted in 11 series (minimum number of samples in a series being twelve). The samples were tested using the computer-controlled mechanically actuated universal testing machine Instron 3369. Deflection for calculating the modulus of elasticity was measured by an optical gauge (Advanced Video Extensometer 2663-821).

MOE and BS were found by three-point bending on the basis of dried samples and on the basis of samples pre-treated with cold water in accordance with the EN (figure 1) [8].

![Figure 1](image-url)

*Figure 1.* (a) A photo of the three-point bending test and of the Advanced Video Extensometer 2663-821 in the upper right-hand corner; (b) schematic view of the three-point bending test; location of the testing area for determining static hardness and thickness swelling.
The BS was calculated by the following formula (see EN [8])

\[ f_m = \frac{3F_{\text{max}}l_1}{2bt^2}, \]  

(1)

where \( F_{\text{max}} \) is the maximum load, N; \( l_1 \) is the length between the supports, (240 mm); \( b \) is the width of the sample, (50±1 mm); \( t \) is the thickness of the sample, (12 mm).

MOE was determined by the following formula (see EN [8])

\[ E_m = \frac{l_1(F_2 - F_1)}{4bt^3(a_2 - a_1)}, \]  

(2)

where \( F_1 \) and \( F_2 \) are 10% and 40% of the maximum bending force, respectively; \( a_1, a_2 \) are deflections according to the loads \( F_1, F_2 \), respectively (see figure 2b).

Moisture content in the test samples after a soaking time of 24 h determined according to EN [9] was about 40%. The samples were dried (48h) to a moisture content of about 8% in a ventilated drying box at 65±1 °C. The JH was determined in the middle of the end area 50×50 mm\(^2\) of the samples before the bending test in accordance with ISO Standard [10] (see figure 1b). All investigated properties were determined at both moisture content values.

Thickness swelling of the samples was determined according to EN [11] before the bending test at the cross section for which hardness was determined (see figure 1b).

Calculation of the uncertainty of the measurements was done in accordance with EN [7].

The following linear-fractional function was used to approximate the obtained experimental data for the studied properties depending on the number of the soaking/oven-drying cycles [12]

\[ Y(x) = \frac{d(Y_i - Y_f)}{cx + d} + Y_f, \]  

(3)

where \( Y_i, Y_f \) are the calculated initial \((x = 0)\) and final values of the studied properties, \( x \) is the number of cycles, and \( c \) and \( d \) are constants.
The formula allowed predicting to some degree the mechanical and physical properties of the specimens when their values after applying a small number of soaking/oven-drying cycles were known.

The initial and final values of the properties and constants should be determined so that the measured experimental data are approximated in the best way by minimizing the square of error (least squares regression). This problem was solved by using the program Mathcad 15.0 with the regression function \( \text{genfit}(v_x, v_y, v_g, F) \).

3. Results and discussion

The obtained values with the expanded uncertainty of BS, MOE, JH and TS are presented in figures 3a, 4a, 5a and 6a, respectively. All experimental data were approximated by formula 3. In figures 3b, 4b, 5b the mean values for one cycle are presented. The gradient of the studied properties was larger after the first soaking/oven-drying cycle. After the first soaking cycle, BS at moisture content 40% accounted for 50% and 63% of the values determined for the dry samples (8%) for the major axis and for the minor axis, respectively. The corresponding values for MOE were 57% and 61%, respectively. BS and MOE of the test samples decreased significantly after first soaking/oven-drying cycle, which is affected by the drying temperature and exposure time [13,14]. Also the first grain flaws appear in the surface of plywood. Thereafter BS and MOE decreased continuously with the increasing number of cycles, while JH and TS stabilized. After ten soaking/oven-drying cycles, the initial values of BS and MOE decreased significantly while the decrease was greater for MOE than for BS. The values of BS and MOE for the samples of major axis were clearly higher (ranking from 1.35 to 1.70) than those for the samples of minor axis. Evidently, this result is caused by the fact that the load direction of the load apparatus was perpendicular to the face grain direction of the samples of major axis, while it was parallel to the face grain direction of the samples of minor axis. In the face main grain flaws occurred after 2-3 soaking/oven-drying cycles. The flexural properties (MOE) of the samples of major axis were better than those of the samples of minor axis.

![Figure 3](image_url)

**Figure 3.** Dependence of BS on the number of soaking/oven-drying cycles: bar charts with expanded uncertainty.
Figure 4. Dependence of BS on the number of soaking/oven-drying cycles: mean values of the experimental data, the curves of approximation, calculated initial and final values of BS at moisture content in test samples 8% - 40% were: $f_{m,i} = 91.6 \text{ N/mm}^2$, $f_{m,f} = 45.4 \text{ N/mm}^2$ and $f_{m,i} = 74.3 \text{ N/mm}^2$, $f_{m,f} = 37.8 \text{ N/mm}^2$, $f_{m,i} = 67.8 \text{ N/mm}^2$, $f_{m,f} = 42.8 \text{ N/mm}^2$ and $f_{m,i} = 50.6 \text{ N/mm}^2$, for the major axis and for the minor axis, respectively.

Figure 5. Dependence of MOE on the number of soaking/oven-drying cycles: a) bar charts with expanded uncertainty.
Figure 6. Dependence of MOE on the number of soaking/oven-drying cycles: a) bar chart with expanded uncertainty; b) mean values of the experimental data; the curves of approximation, calculated initial and final values of MOE at moisture content in test samples 8% - 40% were: $E_{m,i} = 9539 \text{ N/mm}^2$, $E_{m,f} = 9105 \text{ N/mm}^2$ and $E_{m,i} = 5662 \text{ N/mm}^2$, $E_{m,f} = 5369 \text{ N/mm}^2$; $E_{m,i} = 5479 \text{ N/mm}^2$, $E_{m,f} = 5071 \text{ N/mm}^2$ and $E_{m,i} = 3475 \text{ N/mm}^2$, $E_{m,f} = 3370 \text{ N/mm}^2$, for the major axis and for the minor axis, respectively.

Figure 7. Dependence of JH on the number of soaking/oven-drying cycles: a) bar chart with expanded uncertainty; b) mean values of the experimental data; the curves of approximation, calculated initial and final values of JH at moisture content in samples were $H_{bc,i} = 56.7 \text{ N/mm}^2$ and $H_{bc,f} = 46.4 \text{ N/mm}^2$; $c = 0.037$; $d = 0.005$.

The experimental data of all properties fluctuated to a great extent and we can see that the proposed formula (3) approximated the experimental data satisfactorily.

The TS of the board did not change significantly after two soaking/oven-drying cycles, i.e. 8%. This has been observed in the case of wood. Swelling in wood takes place below the saturation point of fibre (about 30%) at which the total amount of water is present within cell wall [15] and, regardless of the number of soaking/oven-drying cycles, the dimensions do not change. Decrease of the dimensions of the test samples may be caused by the weight loss already after first soaking/oven-drying cycle [13]. This kind of a phenomenon was observed to a certain extent in our experiments in the case of BS, MOE, JH and TS.
4. Conclusions
The final mean values determined at a moisture content of 8% after ten soaking/oven-drying cycles were 95% for MOE (for both axes); 81% for BS for the major axis and 75% for the minor axis; 82% for JH and 98.5% for TS of the respective initial values.

After the first soaking (moisture content 40%), the values of BS accounted for 50% for the samples of the major axis and 63% for the samples of the minor axis; for MOE, 57% for the samples of the major axis and 61% for the samples of the minor axis and for TS, 106% of the values obtained for the dry samples (moisture content 8%).

The proposed analytical function approximated satisfactorily the experimental data of BS, MOE and JH, depending on the number of soaking/oven-drying cycles.

The presented analysis is restricted to the data obtained from the above-described experiments.

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