HYGROSCOPICITY OF WOOD-CEMENT COMPOSITES CONTAINING STABILISED ALTERNATIVE RAW MATERIAL

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Abstract

This paper presents research on the hygroscopicity of wood-cement composites containing a by-product of cement-bonded particleboard production. The behaviour and properties of wood-cement composites were analysed with respect to variable air humidity. The intention was to assess the suitability of the alternative raw material used in terms of volumetric changes. Emphasis was also placed on the verification of basic performance properties.

Keywords

Wood-cement, composite, material, cement-bonded, particleboard

1 INTRODUCTION

Wood-cement composite materials are often used in the construction industry for a variety of purposes, including formwork, ceilings, flooring systems, roofs, facade cladding, fire protection applications and railing infill. Due to their advantageous combination of properties such as strength, durability, fire resistance, etc., wood-cement composites are quite popular. These composite materials are exposed to moisture in structures during normal use. The fluctuating relative humidity of the ambient air can have an impact on such materials, mainly causing dimensional or volumetric changes to the wood chips contained in the cement matrix. Wood is a hygroscopic material with considerable sorption dynamics. This leads, among other things, to the generation of pressure which affects the surrounding cement matrix and changes the overall weight and dimensions of the composite. These changes significantly affect the material's properties and possibly its functionality in the structure.

Wood is composed of cellulose, hemicellulose, lignin and potentially other small substances. Some of the constituents of wood may adversely affect its properties and thus the properties of wood-cement composite to some extent see Fig. 1.
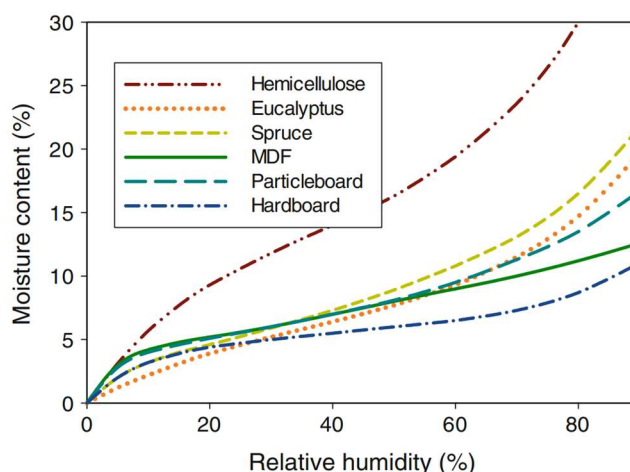

Fig. 1 Sorption isotherms of hemicellulose, wood and particleboard [1].

It is therefore necessary to modify the composition of wood or stabilise its properties. The stabilisation process, which is also called mineralisation, irreversibly changes the chemical structure of the wood. The main objective is to remove hemicellulose, change the structure of cellulose or depolymerise long-chain hydrocarbons and lignin.

Hemicellulose is considered to be the most problematic component of wood with respect to the combination of cement matrix and wood chips. This wood component is able to absorb more water than the cement matrix and also negatively affects the maturation of the cement matrix (via the retardation of hydration reactions). Mineralisation enables the negative effect of hemicellulose to be eliminated or minimised to a tolerable level. In relation to hygroscopicity, wood and wood composite materials are susceptible to changes in weight and volume. The graph Fig. 1 above shows the variation in moisture content (weight changes) of several materials, wood species and wood components. The curves show the amount of water that hemicellulose is able to absorb compared to, for example, spruce or cement-bonded particleboard. Thus, the importance of removing hemicellulose from wood to limit its water sorption capacity (whether in the liquid or gaseous state) is evident.

The structure of wood is made up of cells, mainly cell walls and lumens. When absolutely dry, there is no water in the structure. If water begins to enter the cell structure of the wood, it is stored in the cell walls. Once the cell walls are fully saturated (approximately 30% moisture – depending on the wood species) the cell wall saturation limit (FSP) is reached (see. Fig 2). The behaviour at FSP is mainly influenced by the presence of amorphous cellulose and hemicellulose, which bind chemically to water molecules. When the FSP region is exceeded, water is freely deposited in the intercellular region – the lumen. As the humidity decreases, water will first be removed from the lumen [2], [3].
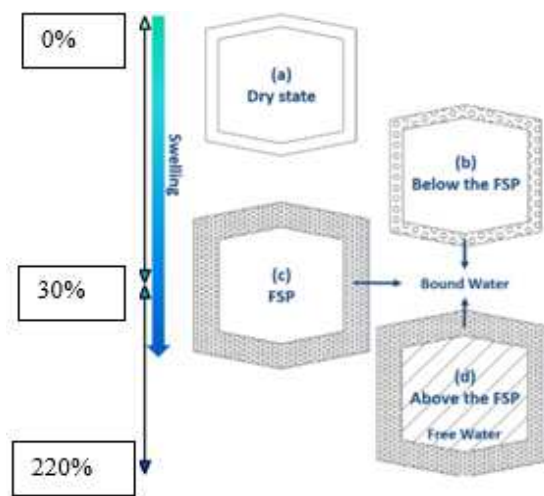

Fig. 2 Water absorption in wood [3].

Irreversible changes (e.g. in dimensions or volume) can be observed due to the saturation of the material with water (in liquid and gaseous state) and its subsequent drying. This phenomenon is called hysteresis.
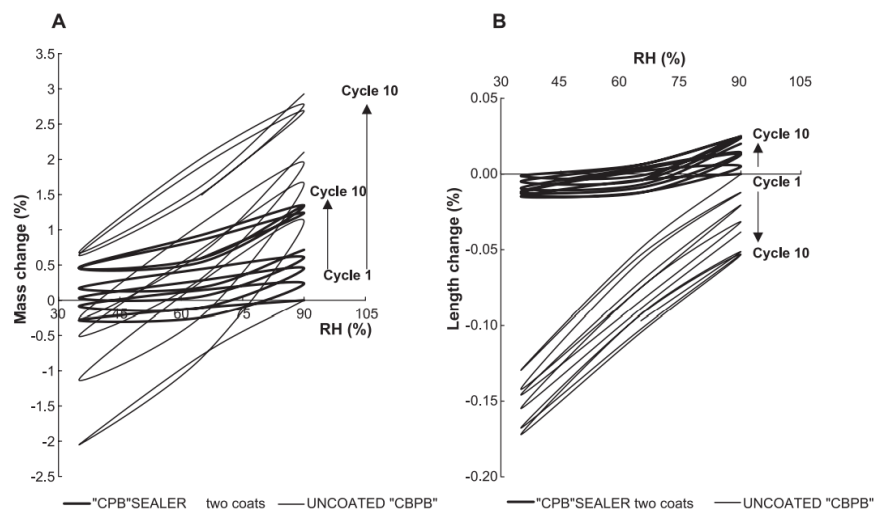

Fig. 3 The hysteresis phenomenon in uncoated and coated CBPB (cement-bonded particleboards) in terms of mass changes (A) and length changes (B) [4].

From the graph above Fig. 3 it can be seen that during absorption and subsequent desorption the curves do not follow the same path and do not return to the same starting point. This results in an irreversible volume change. During cycling, the hysteresis effect increases until the steady state point is reached. In practice, this effect can be reduced by limiting water ingress into the wood structure (e.g. via mineralisation or coating). By stabilising the wood structure, hysteresis can also be partially eliminated.

The following figure see Fig. 4 shows a diagram of the production of cement-bonded particleboards. The production processed can be summarised in several points. Processing of wooden logs into chips. Mixing of the chips with cement, hydrating additives and water. Batching on the lay-up line. Pressing at 20 N/mm^2 to 1/3 of the spreading thickness. Treatment of the slabs in a steam chamber for 8 hours at 60 °C and 95% relative humidity. This achieves the handling strengths. After curing, the boards are placed in an air-conditioning chamber for 7 days. They are then dried to a maximum moisture content of 9% and formatted to the required size.
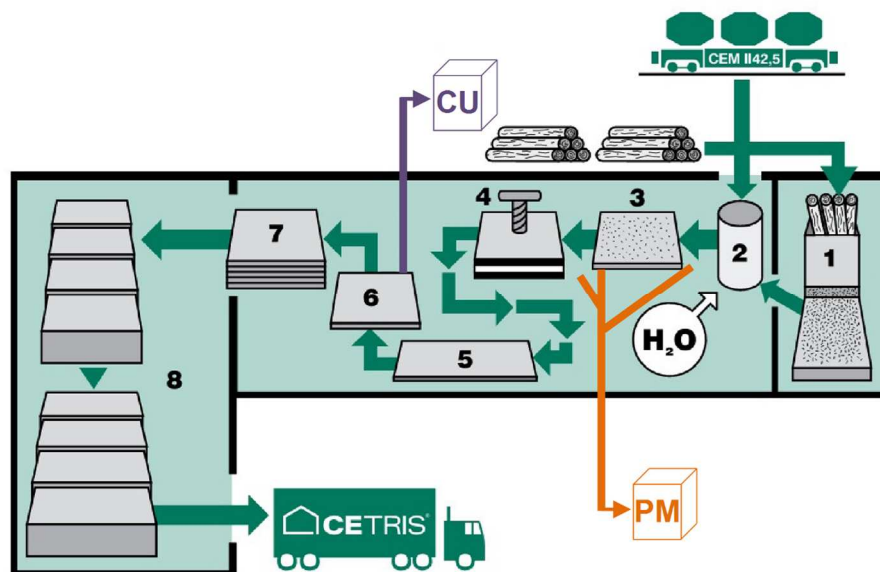

Fig. 4 Production diagram from CIDEM Hranice, a.s for cement-bonded particleboard: 1 – chipping; 2 – preparation of mixture; 3 – layering of boards; 4 – pressing; 5 – drying; 6 – formatting; 7 – storage; 8 – transport (violet CU – covered space for collecting cuttings from the formatting of particleboards; orange PM – covered space for storing the particle mixture) [5], [6].

The diagram Fig. 4 also shows where the by-product particulate mixture (denoted PM) is produced. It is evident that the phase where the PM is captured is an unhydrated and relatively fresh mixture of cement, chips and other additives. However, the PM mixture is captured into a hopper where it is stored, thereby gradually hydrating the cement. This also stabilises the spruce chips contained in the PM. The presence of sodium water glass also contributes to stabilisation.

2 INPUT RAW MATERIALS, DESIGNED MATERIALS AND EXPERIMENTAL METHODOLOGY

The cement particleboards used in this investigation were produced directly on an industrial production line by CIDEM Hranice, a.s. The composition of the recipe in weight percent consisted of 19% wood chips, 69% cement binder (Portland CEM I 42.5 R, or mixed cement CEM II 42.5 R), 10% water and 2% hydrating additives [7]. The R formulation was designed using recyclate to replace 4% cement and 4% wood chips.

Thus, the following types of slabs were produced and further analysed:

- Formulation P – standard reference formula based on Portland cement CEM I 42.5 R.
- Formulation B – formula based on mixed Portland cement CEM II 42.5 R.
- Formulation R – formula based on mixed Portland cement CEM II 42.5 R and recyclate (4% cement replacement and 4% spruce chips replacement).

The purpose of the research was to test the behaviour of modified wood-cement composites under air humidity fluctuations. More specifically, the focus was on the determination of absorption and desorption curves and their comparison with physical-mechanical properties.

For testing, the test procedure set out in the EN 318 technical standard was used, which requires the dimensions of the solids to be (300 ± 2) mm $\times$ (50 ± 2) mm $\times$ t. To render the measurements easier to interpret, the dimensions of the solids were modified to 350 mm $\times$ 150 mm $\times$ 12 mm. These dimensions better match those of actual cement-bonded particleboards used in real structures. For each set, 4 test specimens were prepared.

The measurement points for length and width were inspired by EN 318, which states that metal pins are to be glued to the ends of the test body at locations 25 mm from the ends. Due to the larger dimensions of the boards tested for this study, this distance is 300 mm for length and 100 mm for width. A dilatometer was used for the measurements, and the brass targets were fixed with Sikadur CF31 Rapid epoxy adhesive (see Fig 5).

EN 318 specifies the climatic conditions for testing test specimens for 3 levels of relative humidity. Specifically, at 30%, 65% and 85% relative humidity, and 20 °C. In order to fully plot the absorption and desorption curves, this interval was modified to cover the full range of air humidity variations, i.e. from 0% to 96%. Specifically, measurements were taken after a 10% change in relative humidity up to 90% and 96% respectively. The properties were measured after the mass had settled. This is achieved when the results of two consecutive weighings separated by an interval of 24 hours does not differ by more than 0.1% of the weight of the test specimen. Acclimatization to temperature and relative humidity was performed in a CTS C- 20/350 climatic test chamber.

Fig. 5 Determination of the mass and dimensions of test specimens during the absorption of air humidity (specimen removed from climate chamber).

The flexural modulus of elasticity and flexural strength were determined according to the EN 310 standard. The test specimens are loaded in the centre, placed on two supports. The distance between the centres of the supports is set to within 1 mm of 20 times the thickness of the plate + 50 mm. The loading shall be carried out at a constant feed rate during the test. The loading rate shall be adjusted so that the maximum load is reached within 60 ± 30 s [8].

The tensile strength in the plane of the board was determined according to the ČSN EN 319 standard. The test specimens must be square with a side length of 50 ± 1 mm. The test specimens are to be accurately cut with a 90° angle and the edges are to be straight and clean. The load shall be applied to the test piece until failure occurs in a direction perpendicular to the plane of the test piece, coincident with the plane of the plate. The loading rate shall be adjusted so that the maximum load is applied within 60 ± 30 seconds [2].

All properties were determined on 2 sets each with 4 test specimens for each type of slab (recipe) before and after storage in an environment with variable humidity.

In addition, the microstructure was further analysed using a Keyence VHX-950F optical microscope, focusing on matrix compactness, possible chip disruption and the matrix/chip interfacial zone.

3 RESULTS

Absorption and desorption were caused by changes in relative humidity. In the following graphs Fig. 6, Fig. 7, Fig. 8, Fig. 9 and Fig. 10, only the average values for each set of bodies are always shown. The mass parameter showed the largest fluctuations Fig. 6, ranging up to about 18%. The best of the evaluated slabs are those marked with a P (Portland cement). On the other hand, the largest weight variation was observed for the slabs labelled R (recycled chips). It can be seen from the graph that the weight change increased with increasing relative humidity, especially from 80% relative humidity. It is also evident that the curve did not return to its original state upon desorption. This condition is referred to as hysteresis, during which some ambient water is absorbed into the structure of cement-bonded particleboards. The hysteresis phenomenon may also be caused by the partial release of stress resulting from the compression of the board. The maximum hysteresis value ranged from 2.2 to 3.2% [9].

Other parameters that were monitored and evaluated were the dimensional changes in the longitudinal Fig. 7 and transverse Fig. 8, direction of the boards, both on the reverse and facial surfaces. The linear changes determined on the length defined by the fixed targets at a distance of 300 mm were so similar for all boards that there is practically no difference between them. They range from 0.30 to 0.32%. The steepest increase was observed when the relative humidity increased above 80%. Hysteresis ranged from 0.02% (P slabs) to 0.03% (R slabs).

The change in the transverse direction of the board was measured on targets fixed at a distance of 100 mm from each other. The resulting values Fig. 8 show a similarity with the percentage change in the linear direction of the tested boards. The P boards, which showed a maximum increase of 0.29% in lateral dimension, are the best of those evaluated. In contrast, the R boards were the most affected by changes in relative humidity, i.e. 0.34%. The smallest hysteresis was observed for the P boards (0.02%), while the largest hysteresis was observed for the R boards (0.03%).
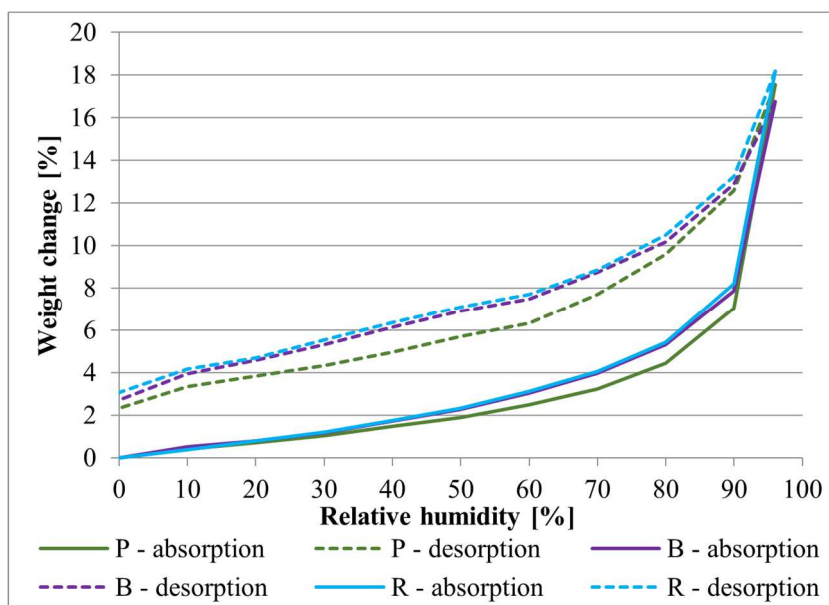

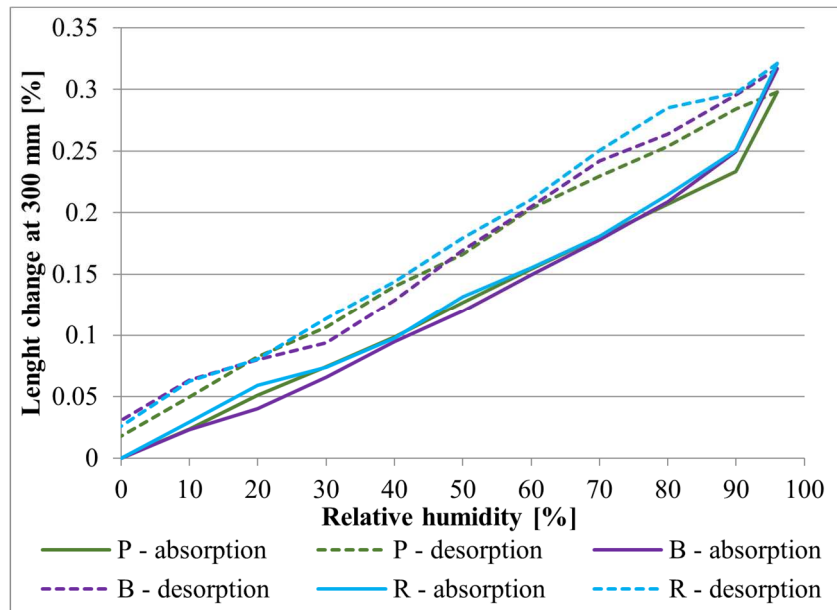Fig. 6 Absorption, desorption curves and hysteresis – mass change.

Fig. 7 Absorption, desorption curves and hysteresis – changes determined by the dilatometer in the length direction.
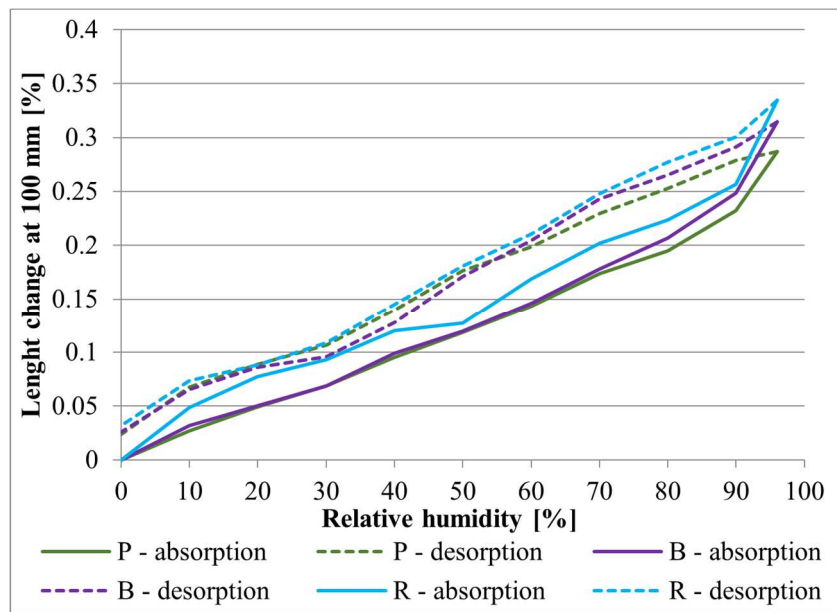

Fig. 8 Absorption, desorption curves and hysteresis – changes determined by the dilatometer in the width direction.

The next parameter investigated was thickness see Fig. 9. In terms of dimensional changes, thickness showed the most significant differences. An essential reason for this is the orientation of the chips in the cement-bonded particleboards. The orientation of the radial and tangential direction of the chips is predominantly perpendicular to the plane of the board, which may explain why the largest dimensional changes were in the thickness direction. These changes are described and investigated by the authors in [6] and [10].

The largest observed differences in thickness occurred at between 90% and 96% relative humidity. The thickness change was the worst for the R boards (1.5%) and the best for the reference boards, P (1.3%). The hysteresis effect for thickness compared to the other dimensional changes was approximately three times greater.
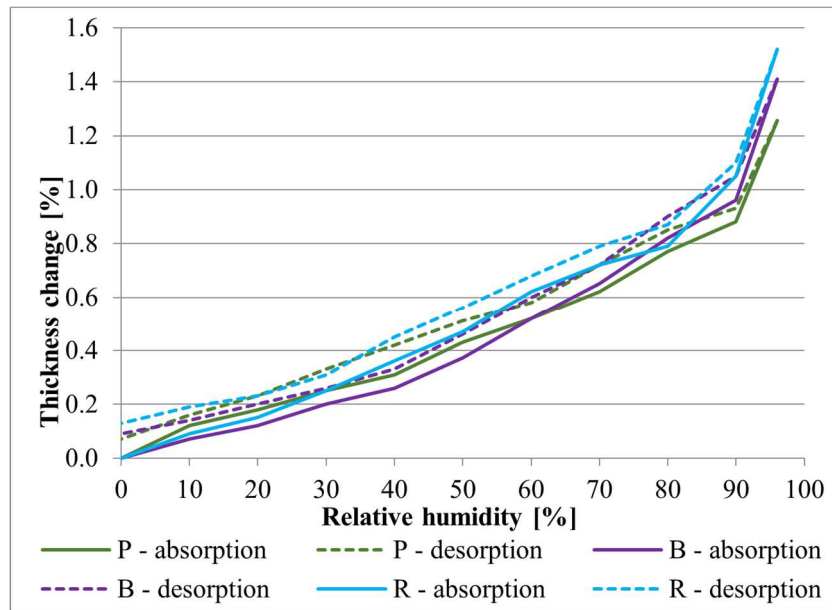
Fig. 9 Absorption, desorption curves and hysteresis – changes determined by a micrometer in the thickness direction.

The volume changes reached a maximum value at a relative humidity of 96% see Fig. 10. The volume changes ranged from 1.8% to 2.2%. Hysteresis ranged from approximately 0.09% to 0.18%. The reference boards labelled P were the most resistant to volume changes. In contrast, the R boards using an alternative raw material containing partially stabilised chips were the least resistant to volume changes.

The most resistant to volume and weight changes under relative humidity was formulation P. Conversely, formulation R was the most subject to change. The largest differences compared to all measured parameters were observed in the weight measurements. Hysteresis was recorded for all formulations – P, B and R, namely 0.09, 0.12 and 0.18% for volume change and 2.2, 2.7 and 3.2% for weight change, respectively.
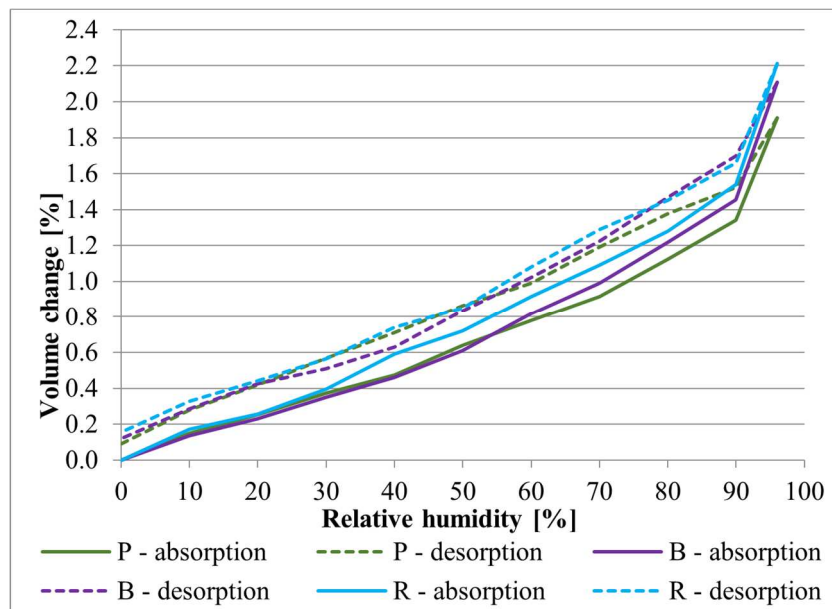

Fig. 10 Absorption, desorption curves and hysteresis – volume changes.

From the results, it is evident that there was a single-digit percentual increase in the parameters due to the effect of air humidity. The resulting parameters were influenced by composition, amount of modifying additives, matrix and type of chips. Although the worst parameters were recorded for formulation R, their properties did not differ compared to the other formulations.

The bending strength requirement of EN 634-2 [11] was met for all test specimens. All specimens showed bending strengths of ≥ 9 N/mm^2 (see Fig. 11), modulus of elasticity values of ≥ 4500 N/mm^2 (see Fig. 12) and tensile strengths perpendicular to the board plane of ≥ 0.5 N/mm^2 (see Fig. 13). All boards exceeded the tensile strength value by approximately 100% compared to the value required by the relevant standard.
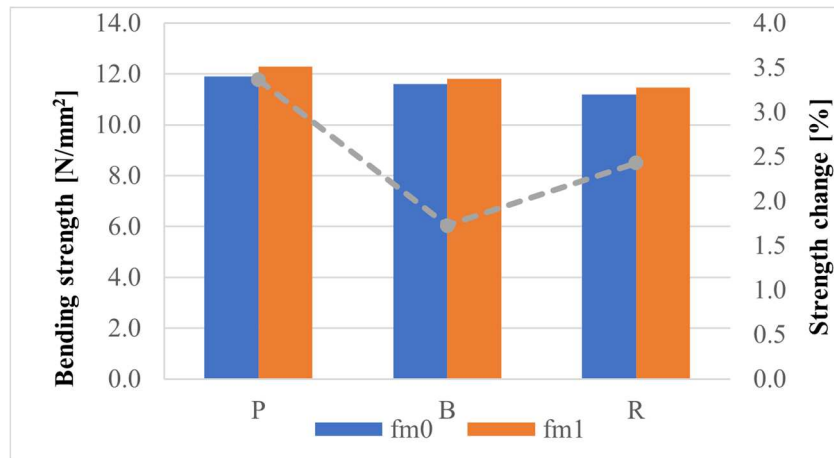

Fig. 11 Bending strength before and after exposure of the boards to changes in humidity.
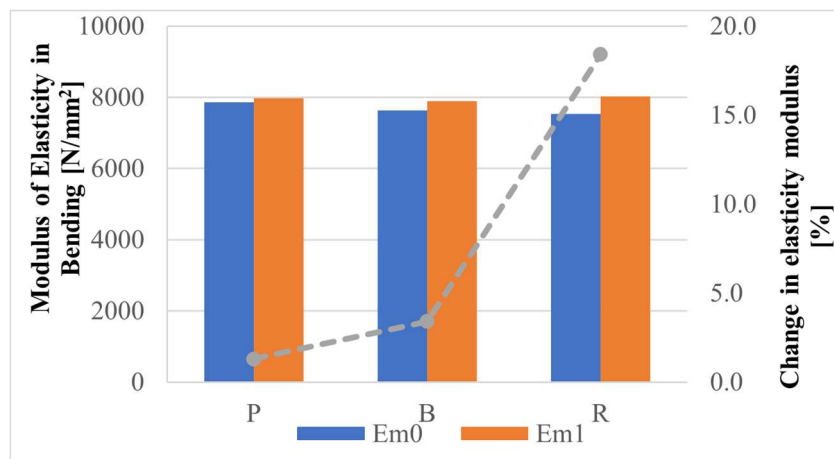

Fig. 12 Modulus of elasticity in bending before and after exposure of the boards to changes in humidity.
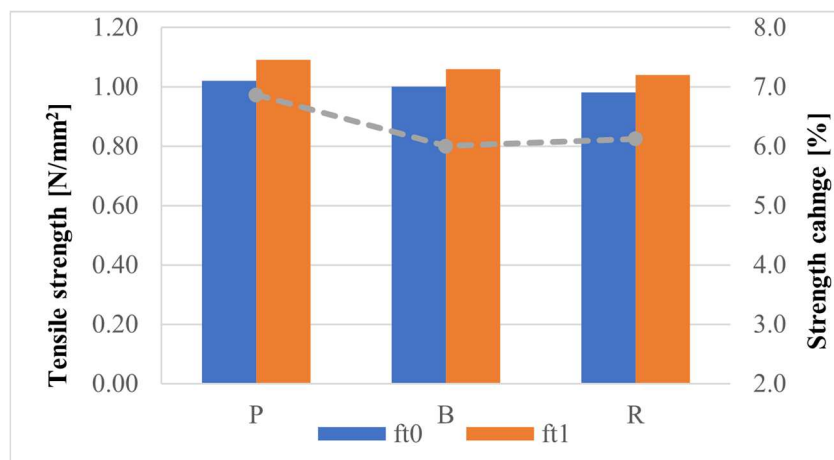

Fig. 13 Tensile strength perpendicular to the plane of the board before and after exposure of the boards to moisture changes.

4. DISCUSSION

The results indicate that the composition of cement-bonded particleboards will affect their hygroscopicity, which is related to the behaviour of such boards and to changes in their properties, especially volume changes under varying ambient relative humidity.

The exposure of the boards to different relative humidities of the ambient air resulted in a change in their parameters. The additional supply of water helped the cement matrix in continued hydration, which had a positive effect on the strengthening of the matrix structure and hence the development of the properties of the cement-bonded particleboard.

The following images show the typical microstructure of wood-cement composites before and after exposure to variable relative humidity Fig. 14 and Fig. 15. The microstructure analysis was focused on the evaluation of the cement matrix structure, especially around the spruce chips, i.e. the matrix/chip interfacial zone. Of course, the structure of the phases (matrix and chips) themselves was also monitored.

The analysis of the reference board P shows that the structure of the cement matrix interacts very well with the spruce chips. From the image on the left Fig. 14 it is evident that micro-cracks are already formed during production, especially in the area of contact between the matrix and the wood chips. The width of these cracks is then increased due to moisture fluctuations, as can be seen in the image on the right see Fig. 15. This change is due in some measure to the partial relaxation of stress after exposure to moisture. The source of this imposed stress is the board manufacturing process (the pressing stage), and such stresses are generally then gradually released when the material is exposed to environmental influences. However, observation of the microstructure shows that only a slight widening of the crack widths has occurred. This phenomenon does not necessarily have a negative effect on performance, as confirmed by the results for the mechanical parameters (strength and modulus of elasticity). The influence of the ageing matrix is predominant here, and, in contrast, the observed parameters are improving despite the increase in crack width.
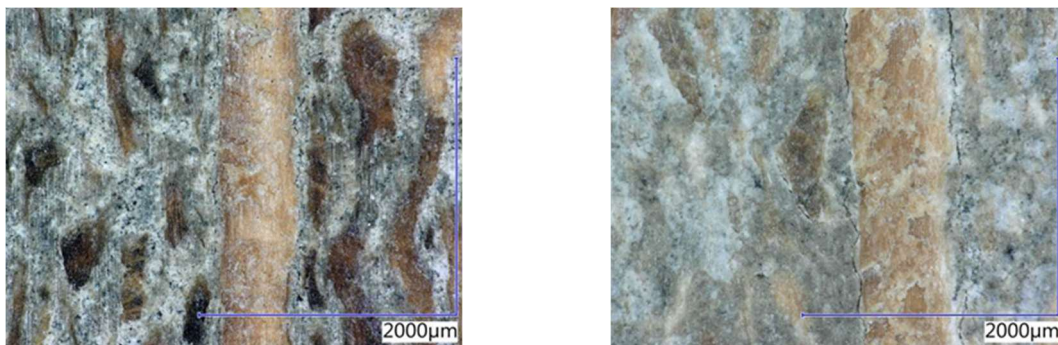

Fig. 14 Microstructure of board P before (left) and after (right) exposure to ambient moisture.

A slight increase in crack width can also be observed in the case of the modified boards (type R), as can be seen in the following images Fig. 15. Similar conclusions can therefore be drawn, i.e. most of the cracks were formed in the vicinity of the chips and the width of these cracks was slightly widened by the action of moisture without a significant negative effect on the performance of the boards.
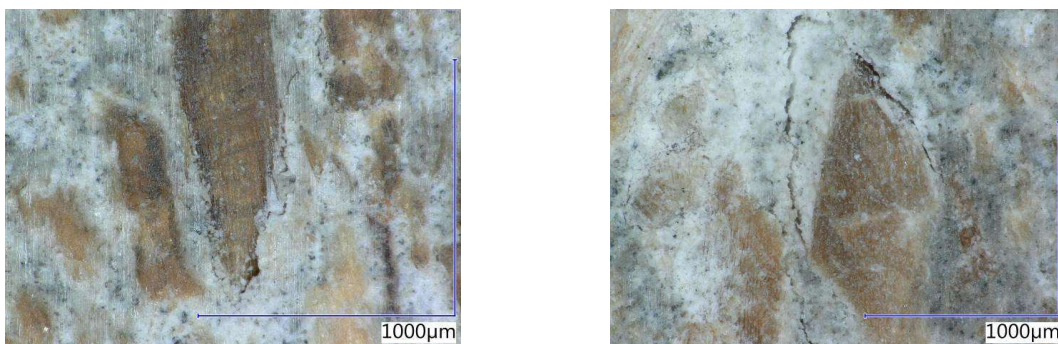

Fig. 15 Microstructure of board R before (left) and after (right) exposure to ambient moisture.

5. CONCLUSION

The results show that the composition of cement-bonded particleboards affects their hygroscopicity and influences their properties, with the boards being affected by volumetric changes in particular. The composition of the matrix of the cement-bonded particleboards also affects, among other things, the stabilisation of the spruce chips they contain.

The resulting sorption isotherms were characterised by different trajectories during the increase and decrease of relative humidity. Each point on the sorption curves was determined after the mass had stabilised. The results and findings indicate the following:

- The cement-bonded particleboard with Portland cement (formulation P) resisted the volume and weight changes best.
- The particleboard containing particle mix (a by-product of particleboard production; formulation R) is less resistant to volume and weight changes.
- Thickness was the most significantly (of the dimensional parameters studied) affected by changes due to moisture fluctuations, with the largest percentage changes, i.e. up to 1.5%.
- Weight changes of up to 18% were detected.
- The hysteresis was around 0.1% of the volume change and approximately coincided with the results of other authors [12].
- In terms of differences in the composition of the board formulations, rather minor differences were observed, which is a positive finding with respect to the potential suitability of the PM particulate mixture for further use in the production of wood-cement composites (which would achieve savings in terms of primary raw materials – cement, spruce chips, as well as the elimination of the by-product that represents waste when not used).

From a comprehensive evaluation and comparison of all the data, it can be concluded that differences in the compositions of mixtures for the production of wood-cement composites (cement-bonded particleboards) have a partial effect on the stabilisation of the spruce chips contained in such mixtures. Further research will have to focus on the verification of other essential parameters, such as the long-term development of strength and durability, and the study of the cyclic effect of water fluctuations in the gaseous and liquid state.

Acknowledgements

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