The stabilized waste dust as a constituent modifying properties of wood-cement composites

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Abstract

The research presented in this paper deals with the effect of stabilized waste dust (from cement-bonded particleboard processing) on the properties of wood-cement composites. The attention was paid to sorption characteristics and mechanical properties. The goal of the research presented was to study the properties and behaviour of wood-cement composites containing an alternative raw material once stabilised. To evaluate this aspect, composites of modified composition (filler and matrix - based on Portland and mixed cement, substitution with waste dust) were exposed to variable relative humidity ranging from 0 to 96% (increase/decrease in 10% increments). Specimens were always exposed to a given humidity (0, 10, 20, etc.) for a period of time sufficient to stabilize their weight. Absorption and then desorption took place. After the exposure to moisture was completed, the bending strength and modulus of elasticity in bending, tensile strength perpendicular to the plane of the board were tested. In this way, the effect of stabilization of spruce chips in terms of the different matrix composition of the materials was indirectly analyzed in a partial way. Sorption isotherms demonstrate the different behaviour of the materials during varying ambient air humidity. The composition of the wood-cement composites affecting the stabilization of the spruce chips (contained in the composites), among others. In case of the physical and mechanical properties a slight increase was observed.

Key words: *Stabilization; Waste; Dust; Wood; Cement; Material; Substitution; Properties; Sorption; Isotherm; Modification*

Introduction

Wood-cement composites are made up of spruce chips and cement. Commonly these materials (board shape) are used, in the construction industry as flooring systems, facade cladding, roofing, fire protection applications, soffits, lost formwork, railing infills and more. Wood-cement composites are quite popular due to their favourable combination of performance properties (strength, durability, fire resistance, etc.). In construction, these composite materials are generally exposed to moisture. Variable humidity can then have a negative effect on the properties of the wood component of these composites. When moisture content fluctuates, the dimensions and weight of the wood chips change. This leads to pressure being exerted on the surrounding cement matrix and an overall change in the dimensions and weight of the composite. The volumetric changes in the composite material are significant both in terms of the effect on its properties and with regard to its functionality within the structural unit. Wood consists of cellulose, hemicellulose, lignin and possibly other minor components. Some of the wood constituents may to some extent adversely affect the properties of the wood (see Figure 1) and thus the cementitious chipboard composite. It is therefore appropriate to adjust the properties or to stabilise the wood composition. Stabilization, sometimes also mineralization, irreversibly changes the structure and chemical composition of the wood. The primary objective is usually the removal of hemicellulose, followed by a change in the structure of cellulose or depolymerisation of long-chain hydrocarbons and lignin. Hemicellulose is problematic not only in terms of absorption of increased amounts of water, but also because of its negative effect during the maturation of the cement matrix. There are several types of mineralisation, for example: mechanical, chemical, thermal, hydrothermal and biological. The main objective is to improve the resistance to water absorption and to increase the dimensional stability of the wood. Wood and composite materials containing wood are subject to volumetric (dimensional) and mass changes related to hygroscopicity. The changes in moisture content (mass changes) of selected wood masses, materials and components are illustrated in the following figure (see Figure 2). It can be seen from the curves that spruce can show moisture content (weight) changes of up to 15-20 %, which is not insignificant in terms of, for example, large-scale facade panels.

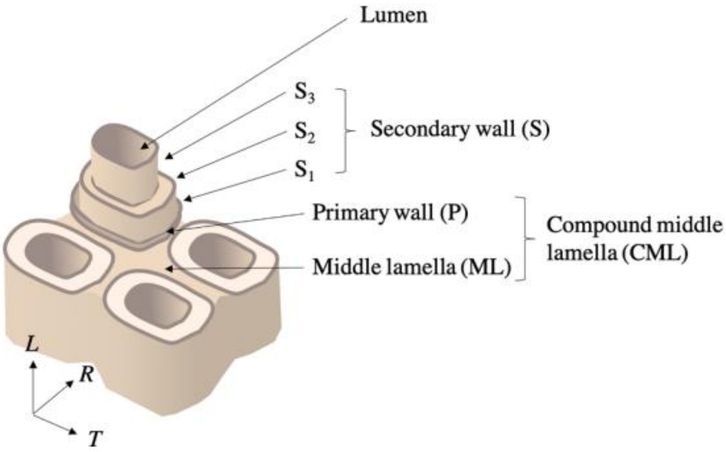

Figure 1: Wood cell structure[1]

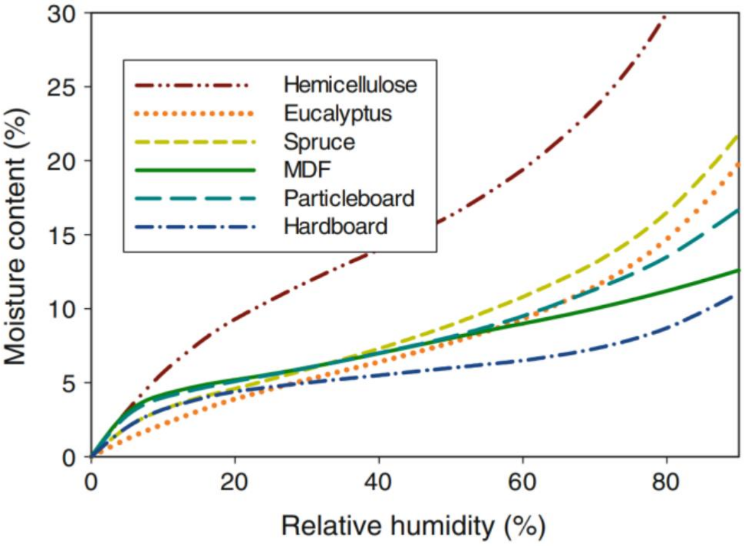

Figure 2: Sorption isotherms of hemicellulose, selected wood species and particleboard[2,3,4,5,6,7,8]

Wood hysteresis is a phenomenon that occurs when moisture content changes. Wood is hygroscopic, which means that it can absorb and release moisture from the surrounding air. When the humidity in the environment changes, wood either gains or loses moisture until it reaches equilibrium. In practice, this results in an irreversible change in the volume and weight of the wood, see Figure 3. In cement-bonded particleboard, this phenomenon can be inferred as the release of residual compressive stresses within the wood structure resulting from the pressing process[9].One possibility to improve the stabilization of wood mass is to use alternative raw material that contains already stabilized wood mass. From this point of view, the use of the dust generated during the processing of cement-bonded particleboards seems to be very advantageous. This dust is captured in a part of the production line for the formatting of the boards and the sanding of their surface. It is a relatively fine particulate material, which is produced in the order of 7 000 t per year.

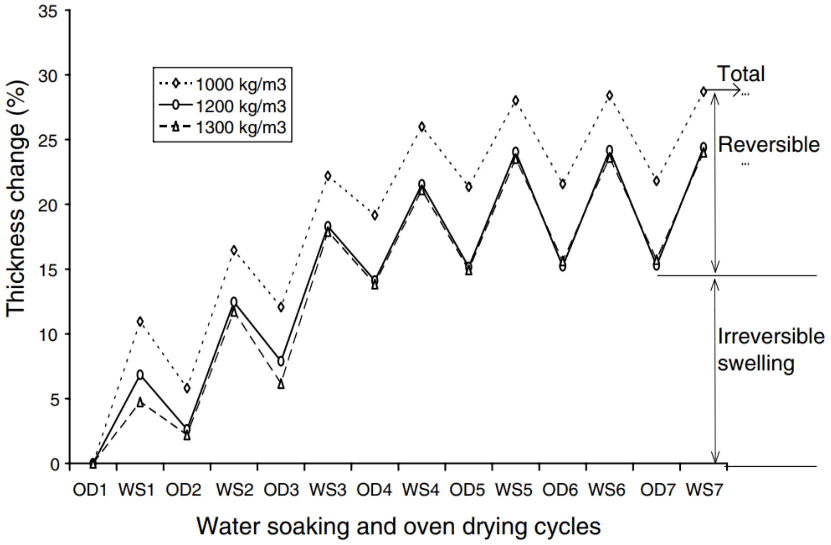

Figure 3: Thickness variation in water soaking and oven drying cycles for cement-bonded boards[10]

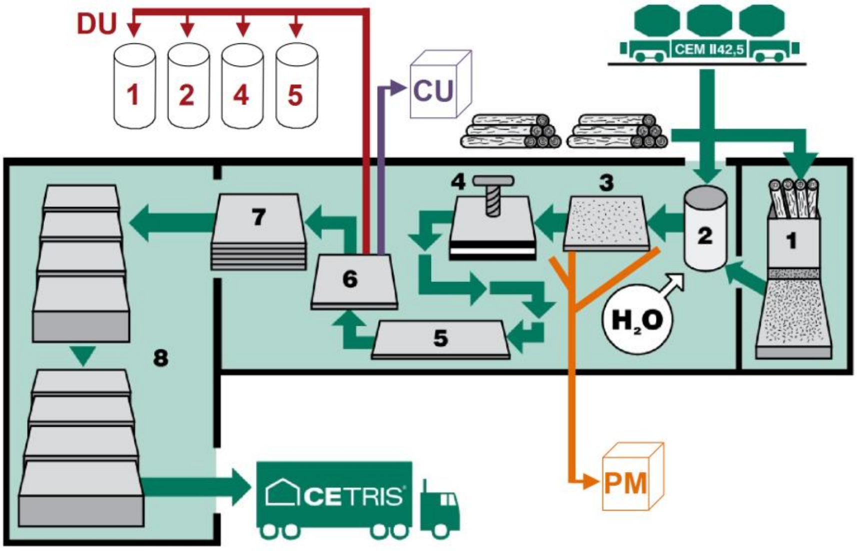

Figure 4: Schematic diagram of the production of cement-bonded particleboards CIDEM Hranice, a. s: 1 - emptying; 2 - mixture preparation; 3 - layering of boards; 4 - pressing; 5 - drying; 6 - formatting; 7 - storage; 8 - transport (red DU 1, 2, 4, 5 - dust collection; purple CU - area for collecting particleboard scraps; orange PM - area for storing particleboard mixture)[11]

The production can be summarised in several points. Treatment of wood logs into chips. Mixing the chips with CEM I 42.5 R Portland cement (or CEM II 42.5 R Portland mixed cement), hydrating additives and water. After mixing, the mixture is dosed onto the lay-up line. The top and bottom layers contain fine chips for a smoother surface, while the core layer contains coarser chips for better mechanical properties. This layered mixture is stamped onto steel plates, which are then transported to the press. The hydraulic press compresses the layered mixture to 1/3 of the spreading thickness. After compaction, the slabs are resealed in a steam chamber for 8 hours at a temperature of 60 °C and a relative humidity of 95 %. The handling strengths are thus achieved. After curing, they are placed in an air-conditioning chamber for 7 days. The boards are then dried to a maximum humidity of 9 % and formatted to the required size, or the surface and edges of the boards are machined (sanded), where the dust mentioned above is generated (see Figure 4 - DU 1-5).

A review of the literature (e.g., [22-28]) did not reveal that researchers have addressed the issue of recovery of dust from cement-bonded particleboard processing in terms of its reuse in the production of these boards with boards hygroscopicity assessment. The knowledge on this topic is studied only briefly by Russian scientists (CPBP waste applied in concrete)[13]. Therefore, the aim of this work was to assess the properties of cement-wood composites modified with waste dust and to investigate the effect of the behaviour under increasing and decreasing air humidity.

Experimental part

The cement-bonded particleboards for the experiments were manufactured on the industrial production line by CIDEM Hranice, a.s. The reference formulations consisted of 63 % wood in the form of chips, 25 % Portland cement or mixed cement (CEM I 42.5 R and CEM II 42.5 R), 10 % water and 2 % hydrating additives. Furthermore, a formulation was proposed with the addition of dust generated during the processing of the cement-bonded particleboard. For this recipe, Portland mixed cement was substituted at 6 % and spruce chips were substituted at 2 %. The following formulations were proposed for the research:

- Recipe P – standard reference formula based on Portland cement CEM I 42.5 R;
- Recipe B – recipe based on mixed Portland cement CEM II 42.5 R;
- Recipe B/D – formula based on mixed cement (Portland slag) of strength class 42.5 R and dust from the processing of cement particleboards (6% cement replacement and 2% spruce chip replacement).

Publications [14, 15] delve into the properties and composition of dust produced during the processing of cement-bonded particleboard.

The intention of the research presented here was to assess the behaviour of the modified boards under changes in ambient relative humidity. Specifically, it involved the determination of absorption and desorption curves during the increase and decrease of humidity with subsequent comparison of the physical and mechanical properties (before and after exposure to humidity). In this way, the effect on the stabilisation properties in terms of moisture fluctuations was also indirectly verified.

The test procedure for the hygroscopicity verification was inspired by the technical standard EN 318, which defines test bodies with dimensions of (300 ± 2) mm × (50 ± 2) mm × t. For the purpose of the experiment, the procedure was modified by using test bodies with dimensions better characterising the actual cement-bonded particleboards used in building structures. The cement-bonded particleboard composites were fabricated with dimensions of 350 mm × 150 mm × 12 mm. From each recipe, 4 solids were prepared for each parameter studied.

EN 318 specifies the conditions for determining adsorption in the relative humidity range of 65 % to 85 % and desorption in the range of 65 % to 30 %. These limits have been modified to provide a more detailed description and understanding of the behaviour of the boards over a wider range of relative humidity changes. Specifically, testing was carried out at intervals of 10 % relative humidity change, ranging from 0 % (dried bodies) to 90 % and 96 %, respectively. From the values thus determined (dimensions, masses, etc.), sorption isotherms were generated for each parameter monitored. For each change in relative humidity, the properties were determined after the mass of the test pieces had stabilised. The condition of the test body is considered to be steady state if the mass does not vary by more than 0.1 % after 24 hours (2 consecutive determinations).

Measurements of volume changes were made with a mechanical dilatometer using brass targets with conical holes for the placement of the dilatometer tips. The targets were fixed with Sikadur CF31 adhesive at precisely measured locations at a distance of 300 mm for the distance in the length direction and 100 mm for the distance in the width direction of the body. The measurement accuracy was 0.001 mm.

The modulus of elasticity in bending and the bending strength are determined by loading the test body at its centre, supported on two supports. The spacing of the supports is calculated as 20 times the thickness + 50 mm. It should be emphasized that for the tests of bulk mass, strength and modulus of elasticity, the test bodies according to EN 310, i.e. 290×50 mm, were used. The loading rate was adjusted to give a maximum load within 60 ± 30 s.[16]

The determination of the tensile strength perpendicular to the plane of the board is determined with the load applied to the test body until failure in a direction perpendicular to the plane of the body, coincident with the plane of the board. The tensile strength perpendicular to the plane shall be determined from the maximum force applied to the surface of the test piece. The test piece shall be square in shape with a side length of 50 ± 1 mm. The loading rate shall be adjusted to produce a maximum load within 60 ± 30 s.[17]

The density was determined according to EN 323 as the ratio of the mass of the test body to its volume, both measurements being made at the same moisture content. A sliding scale with an accuracy of 0.01 mm was used for length and width measurements. Thickness measurements were made using a micrometer with an accuracy of 0,001 mm. The weight was measured with an accuracy of 0.01 g.[17]

Microstructure was analysed by an optical and scanning electron microscope, i.e. Keyence VHX-950F and scanning electron microscope TESCAN MIRA3 XMU with resolution 1.2 to 1.5 nm at 30 kV in SE mode and 2 nm at 30 kV in BSE mode.

Results and discussion

Changes in relative humidity resulted in absorption and desorption, with the most significant changes in the mass parameter, i.e. up to approximately 18%. The results indicate that the effect of composition is not negligible in terms of hygroscopicity. The P slabs, i.e. the reference slabs based on Portland cement, are the best evaluated. On the other hand, the most significant change in weight due to varying relative humidity was observed for slabs containing dust particles from the processing of cement-bonded particleboards (B/D). The graph (see Fig. 5) also shows that the highest weight increase occurred at relative humidity of 80 % or more. The trends of the sorption curves are similar, but differences can be noticed, which is characterized by hysteresis, where a certain amount of water is bound from the air moisture into the structure of the cement-bonded particleboards (ranging from 2.3 % to 3.1 %), and even on drying this moisture is not degraded. The standard deviation ranged from 0.002 to 0.229 % for boards P, 0.009 to 0.360 % for boards B and 0.012 to 0.525 % for boards B/D.

Another parameter monitored and evaluated was the dimensional changes in the longitudinal direction of the boards on the sections defined by brass targets spaced 300 mm apart, both on the reverse and face faces. In the following graph (see Fig. 6) only the average values for each set are shown. The P boards, i.e. 0.30 %, are the best to evaluate with the maximum change in the linear direction. On the other hand, the B/D boards, i.e. 0.33 %, were the most subject to changes in relative humidity. The sorption curves are relatively smooth, except for the increase from 90 % to 96 %. Here, a steeper expansion in the longitudinal direction is noticeable for all formulations. The standard deviation ranged from 0.003 – 0.013 % for P boards, 0.005 – 0.025 % for B boards and 0.004 – 0.032 % for B/D boards.

Dimensional changes in the transverse direction of the boards on the sections defined by brass targets spaced 100 mm apart on both the reverse and face surfaces were also considered. In the following graph (see Fig. 7) only the average values for each set are shown. The trends of the curves evaluated demonstrate the similarity of the linear changes of the tested boards in the transverse direction. The Po boards, i.e. 0.29 %, are the best with the maximum change in the transverse direction. On the other hand, the B/D boards showed the highest change in relative humidity, i.e. 0.35 %. The standard deviation ranged from 0.001 – 0.007 % for P boards, 0.003 – 0.010 % for B boards and 0.005 – 0.013 % for B/D boards.

The dimensional changes in the thickness direction are the highest (see Fig. 8). In terms of dimensional changes and their relative differences, the orientation of the spruce chips in the cement-bonded particleboards is important. This is described quite clearly in [20]. The authors present images which show the orientation of the radial and tangential direction of the chips to be predominantly perpendicular to the plane of the board, which may justify the greatest dimensional changes in the thickness direction. Significant dimensional or volumetric changes of wood in the radial and tangential direction were investigated and found by the authors in [12, 20]. The standard deviation ranged for P boards 0.002 – 0.006 %, B boards 0.003 – 0.007 % and B/D boards 0.002 – 0.009 %.

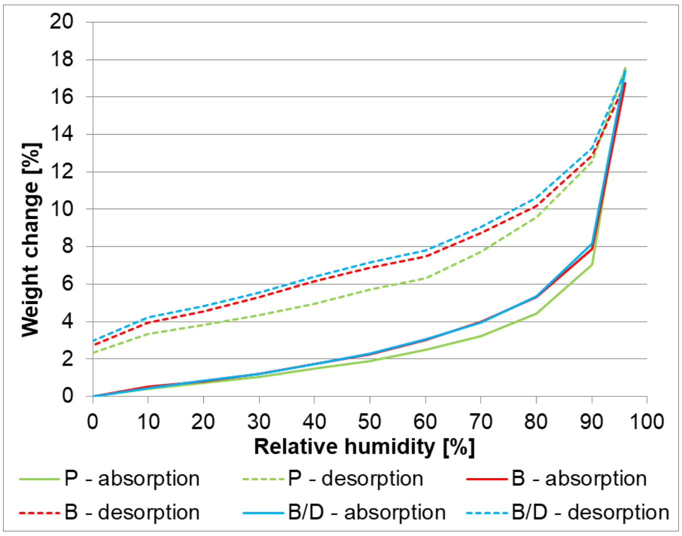

Figure 5: Absorption, desorption curves and hysteresis - mass change

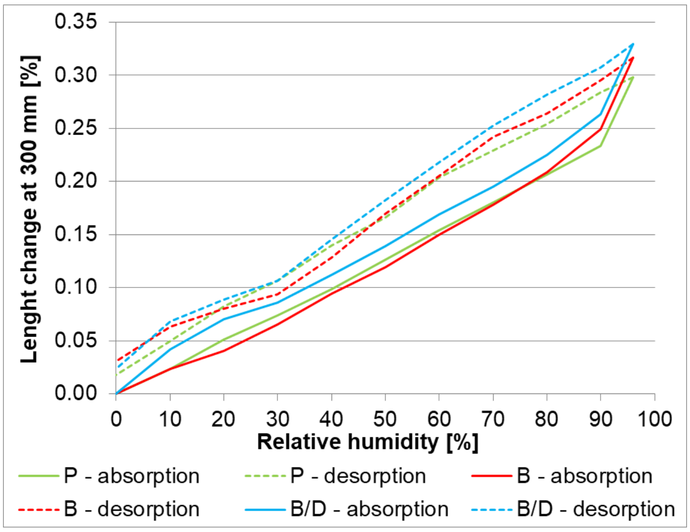

Figure 6:Absorption, desorption curves and hysteresis - changes determined by the dilatometer in the length direction

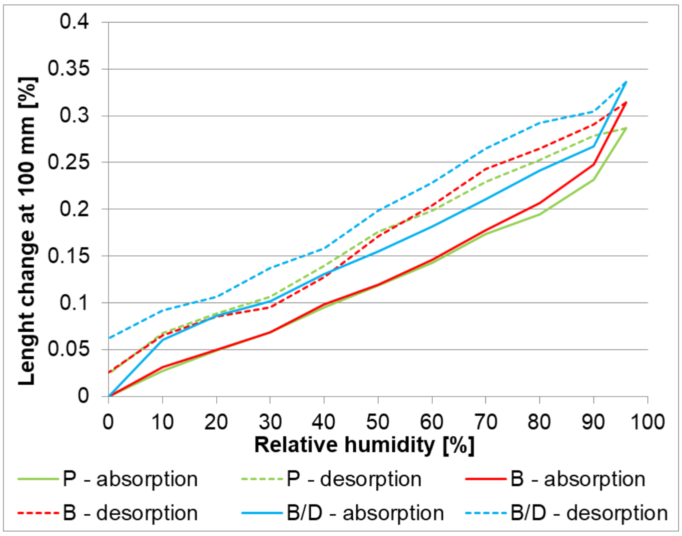

Figure 7: Absorption, desorption curves and hysteresis - changes determined by the dilatometer in the width direction

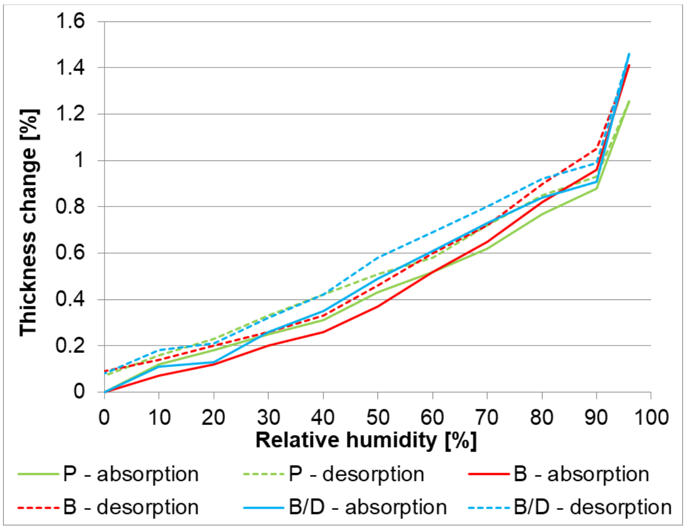

Figure 8: Absorption, desorption curves and hysteresis - changes determined with a micrometer in the thickness direction

For all tested formulations, the greatest change occurs between 90 % and 96 % relative humidity, with the maximum thickness change determined to be 1.5% (formulation B/D). Again, the reference slab P is the best, i.e. a change of 1.3 %. However, it can be seen that the differences are not so noticeable compared to the other dimensional changes. The hysteresis effect was approximately twice as pronounced for the thickness compared to the other dimensional changes evaluated.

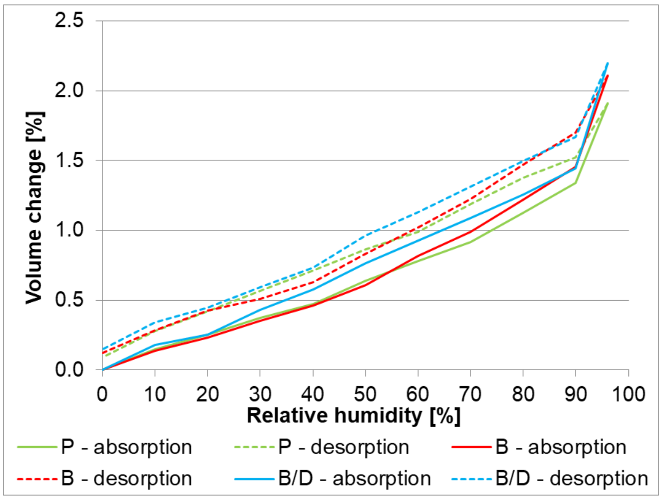

Figure 9: Absorption, desorption curves and hysteresis - volume changes

The sorption isotherms characterising the volume changes (see Fig. 9) reach a maximum when the boards are exposed to a relative humidity of 96 %. The maximum expansion changes range from 1.9 % to 2.3 %, with hysteresis not exceeding 0.18 %. It is clear from the curves that the reference boards, i.e. P, are the most resistant to changes in relative humidity. The most significant volume changes can be observed for the formulation using B/D dust. The replacement of cement by dust particles has the most significant negative effect on the behaviour of the slabs under variable moisture conditions. The standard deviation ranged from 0.002 – 0.020 % for P boards, 0.005 – 0.032 % for B boards and 0.007 – 0.037 % for B/D boards.

The results indicate that the composition of cement-bonded particleboards can significantly affect their hygroscopicity, which is related to the behaviour of the boards and changes in their properties, especially volume changes under varying ambient relative humidity. The most resistant to volume and weight changes is the standard Portland cement-based particleboard (formulation P). Conversely, boards containing cement-based particleboard dust particles as substitutes for the primary components of the mix are the most subject to changes. The most significant changes were observed in the case of weight (compared to the changes in individual dimensions and volume). Wood hysteresis was observed for all formulations - P, B and B/D and was around 0.09, 0.12 and 0.15 % volume change and weight change was around 2.3, 2.7 and 3 % for individual formulations. The composition of the mixture for the production of cement-bonded particleboards has an influence on, among other things, the stabilisation of the spruce chips, which was evident when testing the hygroscopicity of the boards.

Exposure of the board to moisture resulted in an increase in parameters. (Fig. 10 – Fig. 12) 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. Furthermore, during the saturation of the spruce chips with water, the expansion of the chips and, to some extent, the release of residual stresses introduced during the manufacture of the slabs[9], which may have contributed to the densification and strengthening of the slab structure. Importantly, the strength limit of the residual stress release was not exceeded. In such a case, there would be a decrease in the parameters that would be most evident in the flakiness, which characterizes the tensile strength perpendicular to the plane of the boards.

The standard deviation was affected by the different type of matrix. The standard deviation for flexural strength was in the range of 0.52 – 0.74 N/mm^2 (0.46 – 0.55 N/mm^2 – after exposure) for the P boards, 0.65 – 0.82 N/mm^2 (0.51 – 0.62 N/mm^2 – after exposure) for the B boards and 0.86 – 1.02 N/mm^2 (0.76 – 0.93 N/mm^2 – after exposure) for the B/D boards. For the flexural modulus, the standard deviation for boards P was in the range 460 – 680 N/mm^2 (420 – 650 N/mm^2 – after exposure), for boards B 520 – 780 (500 – 710 N/mm^2 – after exposure) and for boards B/D 750 - 920 N/mm^2 (660 - 820 N/mm^2 – after exposure). The friability values were in the range of 0.05 – 0.08 N/mm^2 (0.05 – 0.07 N/mm^2 – after exposure) for boards P, 0.04 – 0.09 N/mm^2 (0.04 – 0.08 N/mm^2 – after exposure) for boards B and 0.08 – 0.12 N/mm^2 (0.07 – 0.11 N/mm^2 – after exposure) for boards B/D.

No dependence of the change in parameters due to air humidity on the composition of the boards was observed, with parameter increases in the order of one percent. The parameters were subject to changes due to the type and amount of modifying components, matrix and chips. Although the B/D formulation showed the worst performance, the variation in properties was not significant compared to the reference formulation.

The bending strength requirement of EN 634-2[21] was met for all types and environments of installation, i.e. all test bodies exhibited a bending strength ≥ 9 N/mm^2. Similarly, the bending modulus requirement was met, specifically for class 1, where the boards exhibited values ≥ 4500 N/mm^2. For the tensile strength perpendicular to the plane of the slab, EN 634-2 specifies a requirement for values ≥ 0.5 N/mm^2, which was also met. The tested slabs exhibited significantly high tensile strength values, as the minimum requirement of EN 634-2 was exceeded by approximately 100 %.

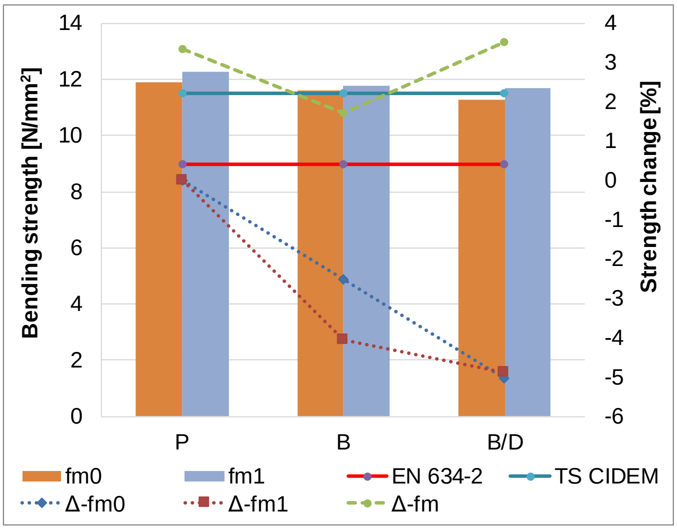

Figure 10: Bending strength

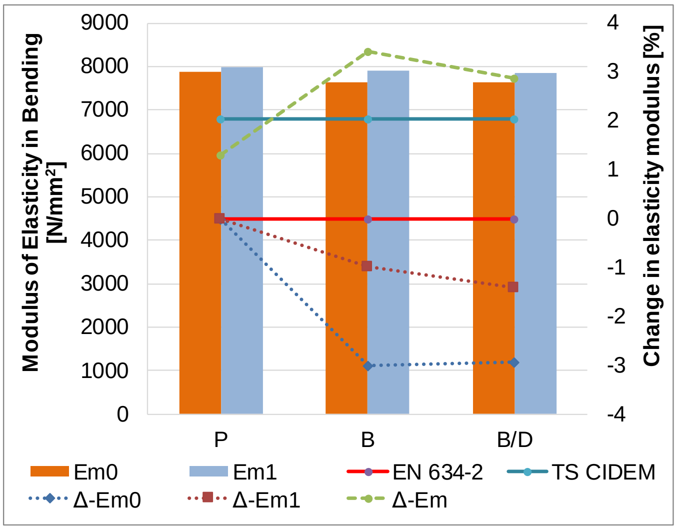

Figure 11: Modulus of elasticity in bending

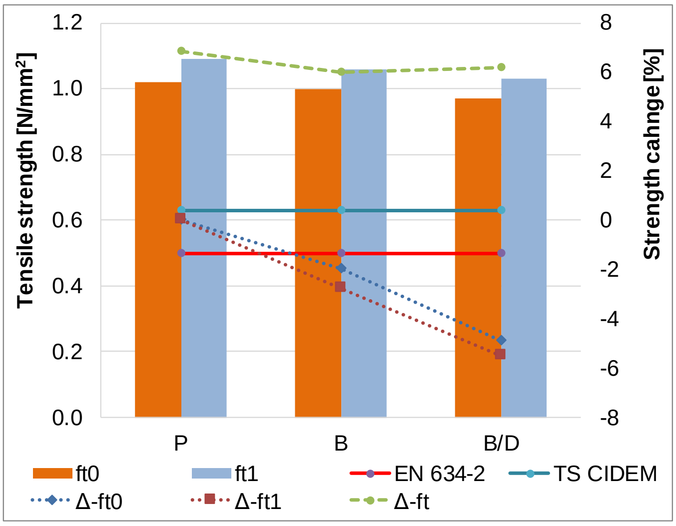

Figure 12: Tensile strength perpendicular to the plane of the boards

Analysis of the structure by optical microscopy confirms that the structure of wood-cement composites is compact, even in the case of modified materials (see Fig. 13 and Fig. 14). Based on the evaluation of the images, it is evident that small micro-cracks are already visible in the structure of the materials from the manufacturing process. However, in the context of the strength characteristics, it is evident that these minor disturbances have no effect on the final properties. It is also significant that these small insignificant disturbances have been identified in the structure of both the reference and modified materials. It is also clear from the progression of the identified cracks that these disturbances occur randomly in the matrix and also in the interfacial transit zone of the cement matrix and spruce chips (after referred to as ITZ). Leachates or crystallized salts (most likely mainly based on calcium ions) were observed on the surface of the masses saturated with air humidity and subsequently dried. Detailed analysis of these leachates will be the subject of following-up research. Even though the hysteresis phenomenon was observed (for all dimensions), the wood-cement masses contained microcracks after drying and subsequent tempering.

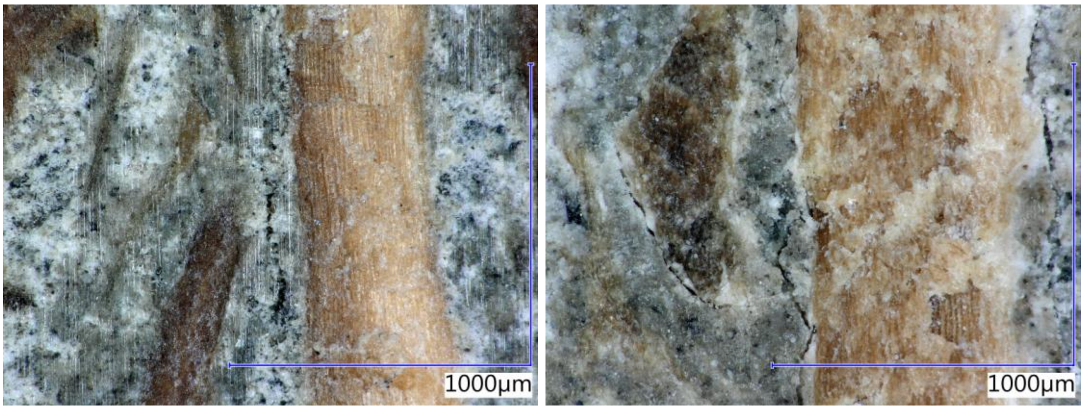

Figure 13: Microstructure of reference material P - before (left) and after (right) exposure in an environment of variable relative humidity

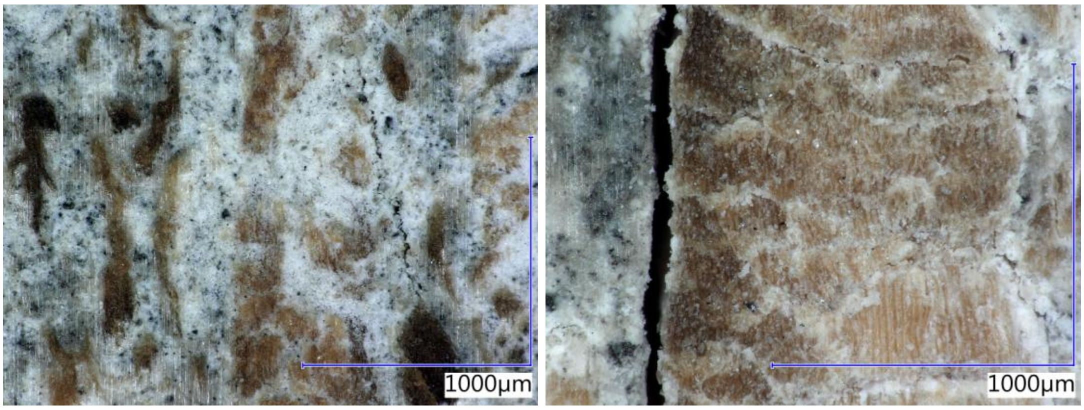

Figure 14: Microstructure of the modified B/D material - before (left) and after (right) exposure in an environment of variable relative humidity

The following images show the microstructure of selected types of wood-cement materials tested (see Fig. 15 and Fig. 16). In the microstructure analysis, attention was focused on the compactness of the cement matrix, even around the spruce chips. The interlocking of the cellular structure of the chips with the cement matrix and the penetration of hydration products into the spruce chips were also evaluated, as well as the evolution of the structure due to exposure to increasing relative humidity. The microstructure assessment showed that the tested wood-cement composites are characterised by a compact structure. The cement matrix interacts very well with the spruce chips. It is important that the exposure of the boards to elevated humidity results in additional hydration of the cement. The dust is compatible with its origin and interacts very well in the structure of the analysed masses. In the figure below (see Fig. 16), a detail of the compact structure can be seen when dust particles are used as an alternative binder and filler component. The structure of the B/D boards also appears to be dense and compact. This structure appears denser due to the effect of moisture, as confirmed by microscopic images. The dust particles (from the processing of the cement-bonded particleboards) are compatible with the cement matrix or the raw material mix for the production of wood-cementitious materials. This is confirmed, among other things, by the fact that the ITZ of the cement matrix and the waste dust cannot be clearly identified.

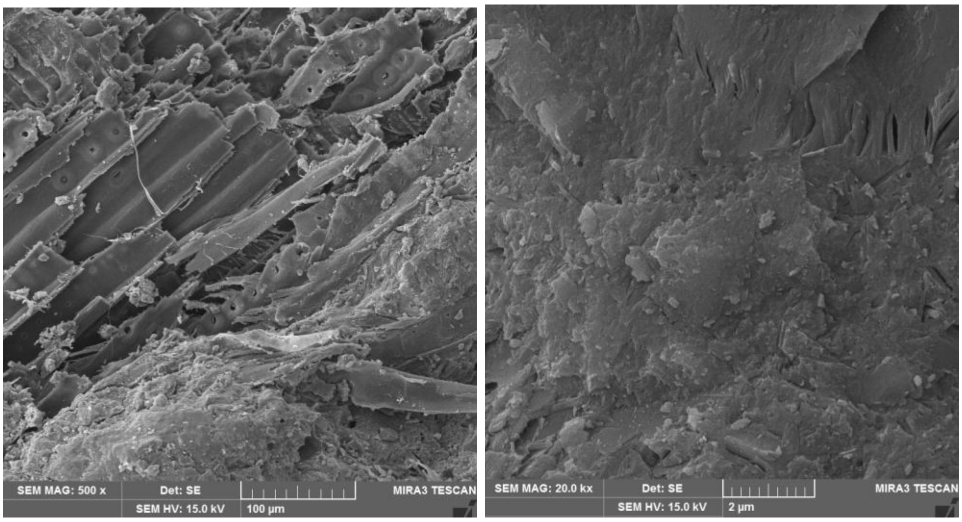

Figure 15: Microstructure of boards B before (left) and after (right) exposure to variable ambient relative humidity

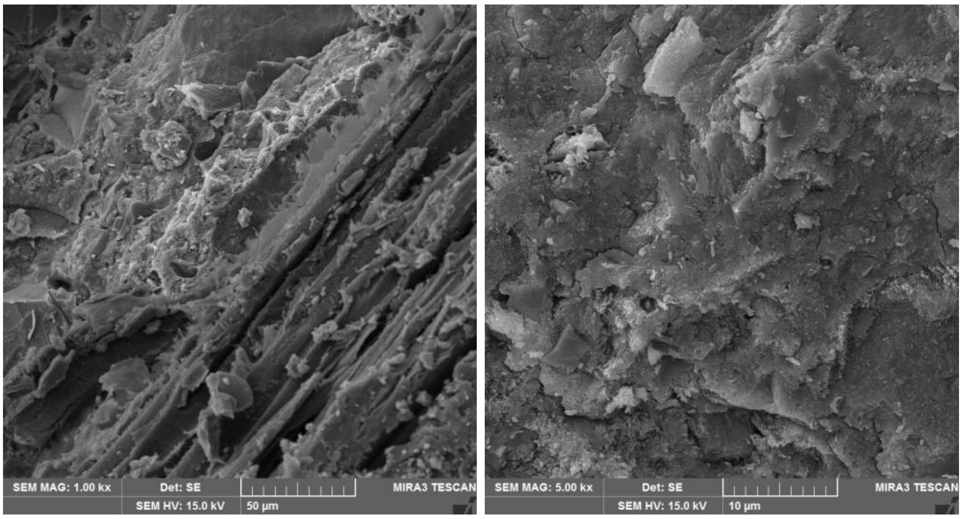

Figure 16: B/D boards microstructure before (left) and after (right) exposure to variable ambient relative humidity

Conclusion

It can be concluded that the composition of wood-cement composites influences their properties and behaviour. Changes in hygroscopic behaviour and physical properties are influenced to a significant extent by the use of a stabilised alternative raw material (waste dust from cement-bonded particleboard processing). Similarly, the composition of the cement-bonded particleboard matrix also has an influence on the stabilisation of the spruce chips contained, among other things. The course of the sorption isotherms showed a different behaviour of the analysed masses during the gradual increase and decrease of the ambient air humidity. The boards were always exposed to a given level of moisture for a period of time sufficient to allow their mass to stabilise. The results determined and the observations made confirm the following:

- The best resistance to volume and weight changes is provided by the commonly manufactured Portland cement-based particleboard (formulation P).
- Slabs containing dust particles as a substitute for the primary binder and partially for the filler of the mix are the most susceptible to changes.
- The most significant changes were observed in the case of weight (compared to changes in individual dimensions and volume).
- The differences between the different formulations are not significant, which roughly corresponds to the compatibility and the amount of raw materials in the mixture for the production of cement-bonded particleboards.
- The hysteresis value in the case of volume change is slightly lower compared to the results presented by other authors. It should be noted, however, that these were slabs with a higher content of alternative ingredients and often with lower quality ingredients.
- The composition of the mixture for the production of cement-bonded particleboards has an influence on the stabilization of spruce chips, which was evident in the hygroscopicity testing of the boards.

For further research, it appears that the optimisation of the dust dosage would be a good option, whereby a higher amount of this alternative ingredient (as a substitute for cement or Portland clinker) could be dosed into the mix for the production of cement particleboard. One way of achieving this is by mechanical or mechanochemical modification of the dust composition. Such modification of the dust could activate it in terms of its participation in the hydration reactions of the cement binder. In the event of such an intervention in the composition of the cement-bonded particleboard, it is also possible that the behaviour of the particleboards with regard to their hygroscopicity would be different, which would also need to be verified. The study of the influence of dust particles in terms of hygroscopicity in cement-bonded particleboards in the long term is also very interesting and relevant.

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Stabilizovaný odpadní prach jako složka modifikující vlastnosti dřevo-cementových kompozitů

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Souhrn

Výzkum prezentovaný v článku se zabývá vlivem stabilizovaného odpadního prachu (z opracování cementotřískových desek) na vlastnosti dřevo-cementových kompozitů. Pozornost byla zaměřena na sorpční charakteristiky a mechanické vlastnosti. Cílem prezentovaného výzkumu bylo studium vlastnosti a chování dřevo-cementových kompozitů obsahujících již jednou stabilizovanou alternativní surovinu. Pro hodnocení tohoto aspektu byly kompozity modifikovaného složení (plnivo i matrice – na bázi portlandského a směsného cementu, substituce odpadním prachem) vystaveny proměnlivé relativní vlhkosti vzduchu v rozmezí 0 až 96 % (zvyšování/pokles po 10 %). Dané vlhkosti (0, 10, 20, atd.) byla vždy zkušební tělesa vystavena po takovou dobu, aby došlo k ustálení jejich hmotnosti. Nejprve probíhala absorpce a následně desorpce. Po ukončení expozice (proměnlivé vlhkosti) byla testována pevnost a modul pružnosti v ohybu, pevnost v tahu kolmo na rovinu desky. Tímto způsobem byl parciálně nepřímo analyzován vliv stabilizace smrkových třísek z hlediska rozdílného složení matrice kompozitů. Sorpční izotermy prokazují rozdílné chování materiálů během proměnlivé okolní vzdušené vlhkosti. Složení směsi dřevo-cementových kompozitů ovlivňuje mimo jiné i stabilizaci smrkových třísek (v nich obsažených). V rámci fyzikálních a mechanických vlastností byl zaznamenán mírný nárůst.

***Klíčová slova**: Stabilizace; Odpad; Prach; Dřevo; Cement; Materiál; Substituce; Vlastnosti; Sorpce; Izoterma; Modifikace*