Long-term durability of cement-bonded particleboards with modified composition by waste dust

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Abstract

This paper presents research on long-term behaviour of cement-bonded particleboards exposed to adverse conditions. The boards were subjected to frosting / defrosting cycles, up to 300 cycles. Specifically, 100, 200, 300 cycles were performed at the age of 28 days, 6 months, 12 months, 18 months and 24 months. Compositoin of the particleboards was modified by by-product, which has its origin in production of cement-bonded particleboards. Dust from cutting and grinding of the particleboards was used in amount of 7% as a partial substituent of cement (6%) and spruce chips (1%). The goal of presented research is the assessing the effect of adverse conditions at different age of cement-bonded particleboards (with modified composition), when attention is paid to mechanical properties and microstructure, respectively. Bending strength, modulus of elasticity in bending, transverse tensile strength perpendicular to the plane of the board and microstructure (SEM) were studied with respect to the changes in time (up to 2 years).

Keywords: *Cement-bonded particleboards, modification, composition, alternative raw material, properties, microstructure, long-term, durability, frost, development in time.*

Introduction

Cement-bonded particleboards are a globally widespread building material, with the production of the domestic producer reaching approximately 55 thousand m^3 of boards per year. These boards are characterized by very good durability. The creation of by-products is a typical part of the industrial production of building materials and components. These by-products very often have no further use and therefore have to be landfilled. One of the by-products created during production of cement-bonded particleboards is the dust from their formatting. This fine-grained particulate substance is produced in quantities of around 7 to 7.5 tonnes per year. With regard to the composition of the cement-bonded particleboards, there is a possibility of adding this unused by-product, suitably treated, back to the production of the boards. Each time the composition of the material is modified its properties change. Therefore, it is always necessary to assess and analyse the behaviour of the material in detail when carrying out any modification. Cement-bonded particleboards are no exception, as evidenced by many studies and research papers published to date. The authors discuss various aspects of the production of cement-bonded particleboards using various types of alternative raw materials, including the very important durability [1-8].

The aim of the research presented here was assessing long-term behaviour of cement-bonded particleboards with modified composition. The composition of the boards was modified by dust from the formatting of these boards. Basic characteristics including microstructure were monitored at six-month intervals. The analysis of the properties and behaviour of the particleboards were carried out over a period of 2 years. This time interval is sufficient for objective assessing the durability of the particleboards. The behaviour prediction and estimating the durability of cement-bonded particleboards in a real structure when exposed to adverse effects can be formulated by the mentioned procedure. A typical such influence is the cyclic freezing and thawing in the presence of water, which is characteristic of temperate climatic conditions.

Materials and Methods

Materials

Composition of the cement-bonded particleboards corresponds to standard boards produced commercially. These particleboards contain (in volume) Portland cement CEM I 42.5 R (25%) according to EN 197-1[9], spruce chips (63%), aluminium sulphate (Al_2 $[SO_4]$ $_3$), sodium water glass (total 2%), water (10%). Composition was modified by waste from formatting the particleboards in amount of 7%. Two following types of the cement-bonded particleboards were tested:

- Reference boards DR – standard composition of the cement-bonded particleboards, i.e. cement, spruce chips, water and hydration admixtures.
- Modified boards DP – standard composition of the cement-bonded particleboards was modified by dust, which is produced during trimming and grinding of these boards, in amount of 7% (partial substitution of 6% cement and 1% chips was carried out).

A detailed analysis of the dust generated during the machining of cement-bonded particleboards was presented by Melichar and Bydzovsky [10]. In the cited study, the authors present a comprehensive set of all relevant properties and behaviour of dust in terms of its use in cementitious composites. The results and findings of the authors 10 clearly demonstrate the high potential, suitability and compatibility of cement-bonded particleboard processing dust for the manufacture of cement composites. Also significant is the fact that the wood chips contained in the dust are already mineralised and therefore show better properties than primary spruce chips.

Figure 1: Structure of the dust in detail, picture from optical microscope

Due to the environmental situation, the dust with a grain size of up to 2 mm was applied. Dust is an inert particulate substance with no active contribution to the forming structure of the new composite. The possibilities of replacing the primary raw materials of cement-bonded particleboards in quantities of 6, 8 and 10% were verified and evaluated in the laboratory. The production, testing of properties and microstructure was carried out in the laboratories of Brno University of Technology, Faculty of Civil Engineering, Institute of Technology of Building Materials and Components. The tests were carried out in accordance with technical standards [11-15]. Based on the results and findings amount of 7% was selected as an optimal possibility for the real production with minimal impact on the decrease of especially the utility properties of the particleboards.

Subsequently, cement-bonded particleboards were fabricated directly on the production line of the domestic manufacturer CIDEM Hranice, a.s. Boards with a thickness of 12 mm were manufactured. Test specimens with dimensions of 290 mm × 50 mm × 12 mm and 50 mm × 50 mm × 12 mm were made from fabricated boards for the determination of strength characteristics, modulus of elasticity and density with emphasis on long-term durability (resistance to frost influence, evolution over time) including subsequent microstructure assessment. In order to obtain the average value, including the deviation (absolute error) and the coefficient of variation (relative error) of each parameter, six test specimens were tested. Three test specimens were made in the longitudinal direction of the production line and three test specimens in the transverse direction, i.e. perpendicular to the direction of the cement-bonded particleboard production line.

Methods

The intention of the research was evaluating the long-term durability of cement-bonded particleboards of composition modified by waste dust. Therefore, the test specimens were stored in a climate chamber with a relative humidity of (75 ± 3) % and a temperature of (20 ± 2) %. The reason for this was to ensure the hydration of the cement and at the same time the volumetric stability of the spruce chips throughout the storage of the test bodies. The chips would show greater volume changes in presence of higher humidity and thus, among other things, cause pressure on the adjacent cement matrix. This phenomenon could then result in possible deteriorating the structure of the particleboards. Conversely, lower humidity is not conducive to promoting hydration reactions of the cement matrix. Before each parameter determination, the test specimens were tempered in accordance with the requirements of the relevant technical standard, i.e. at a relative humidity of (65 ± 5) % and a temperature of (20 ± 2) %.

The development of material characteristics over a period of 2 years was evaluated. Emphasis was placed on effect of modification on properties of the cement-bonded particleboards. Testing was carried out at the 28 days, and then at six-month intervals, i.e. after 6 months, 12 months, 18 months and 24 months. After reaching the required age, the test specimens were exposed to an alternating freezing/thawing environment in the presence of water in accordance with the requirements of EN 1328 [15]. 100, 200 and 300 freeze/thaw cycles were carried out. This procedure made it possible to assess how the frost resistance develops with increasing particleboard age over a longer time.

The dried test specimens were weighed using KERN PCB 1000-2 scales with readability of 0.01 g and the dimensions were measured with a digital caliper KINEX 600/100 mm with a resolution of 0.01 mm. Density of the particleboards was determined and rounded to the nearest 10 kg/m^3 from the measured values. Strength and modulus of elasticity were tested on a Testometric M350-20CT device with a 20kN load cell and accuracy of ± 0.5% of reading down to 1/1000 of the load cell capacity. Testing and determination of bending strength and modulus of elasticity in bending were performed in accordance with EN 310[11] (test specimens with dimensions 290 mm × 50 mm × 12 mm). Transverse tensile strength perpendicular to the plane of the board was tested and determined in accordance with EN 319[12] (test specimens with dimensions 50 mm × 50 mm × 12 mm). During all mechanical tests, the load was applied at a constant velocity so that the maximum, i.e. failure of the test specimen, was reached within (60±30) s. Frost resistance was tested and determined in accordance with technical standard EN 1328 [15]. This technical standard specifies the design of frost resistance on test specimens for the determination of bending strength. For the purpose of the research, the specimens were also subjected to freezing and thawing cycles to determine the tensile strength perpendicular to the plane of the board. The standard requires 50 freeze/thaw cycles to be performed. However, for the purposes of research and long-term durability assessment, the boards were subjected to up to 300 cycles in a freezing device. The microstructure of the particleboards was analysed by TESCAN MIRA3 XMU scanning electron microscope with resolution 1.2 nm at 30 kV (with EDX). Emphasis was put on board microstructure aged 24 months in climate chamber (20 °C temperature and 75% relative humidity) – both tested types of the particleboards (reference and modified).

Results and discussion

Physical and mechanical parameters

The density (Figure 2) of all tested boards exceeds 1,000 kg/m^3, which is in accordance with the requirements of EN 634-2 [13]. The average values of the both board types are very similar and in range from ca 1,230 kg/m^3 to 1,370 kg/m^3. In terms of the development of density over time, a slight increase in the values is noticeable, i.e. up to 5%. As the number of freeze/thaw cycles increases, a decrease in density is predominantly evident. Based on the results obtained, it cannot be clearly decided whether DR or DP plates are more resistant to the effect of freezing with respect to density changes. The effect of modification was not very pronounced in the case of density, even in terms of the long-term evolution of this parameter over a 2-year period.

Interesting information on the behaviour of the particleboards due to exposure to adverse frost conditions is also provided by the determined deviations (error bars - Figure 2). It is evident that the deviation from the average density value increases with increasing number of cycles. This is related to the deterioration of the particleboard structure with regard to frost effect. The relative, i.e. percentage, deviations are expressed as a coefficient of variation in the following table (Table 1). The coefficient of variation values are in the order of a few percent. The lower coefficients of variation were mainly determined for the reference (DR) boards.

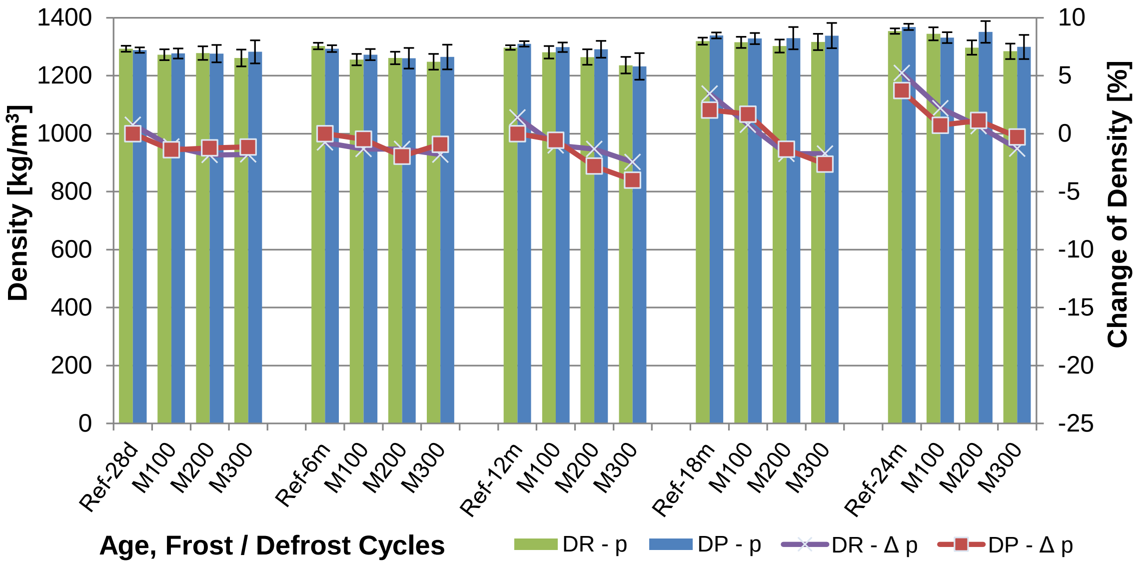

Figure 2: Comparison of cement-bonded particleboards density, red and violet curves represent decrease of density, black vertical bars represent deviations

Table 1: Coefficient of variation of density of the particleboards DR and DP

Age [days, months]	Density coefficient of variation – DR [%]				Density coefficient of variation – DP [%]			
	Cycles				Cycles			
	Ref	M100	M200	M300	Ref	M100	M200	M300
28 days	0.80	1.49	1.84	2.28	0.73	1.35	2.36	3.09
6 months	0.87	1.57	1.71	2.19	0.90	1.51	2.83	3.40
12 months	0.61	1.68	2.12	2.32	0.73	1.29	2.27	3.72
18 months	0.92	1.45	1.74	2.15	0.75	1.44	2.90	3.26
24 months	0.69	1.68	1.94	2.10	0.79	1.41	2.78	3.18

The bending strength (Figure 3) of the tested boards ranges from 12.9 N/mm^2 to 8.8 N/mm^2 (DR) and 12.7 N/mm^2 to 8.6 N/mm^2 (DP), respectively. The decrease in bending strength due to lower cement dosage in the boards corresponds to the results presented by Zhou et al. [16]. The minimum bending strength requirement of 9 N/mm^2 according to EN 634-2 [13] was met for boards without exposure to freezing cycles. Only some boards exposed to 300 freeze/thaw cycles showed strengths lower than 9 N/mm^2. Specifically, DR boards at 28 days and 6 months of age, and DP boards at 28 days of age. An adverse effect on the strength of the particleboards under cyclic exposure to moisture and temperature changes was also demonstrated by Miranda de Lima et al. [5]. A negative effect of water on the properties of the particleboards (when volume changes of chips occur) was also reported by Drdlova et al. [19]. During further maturation, all boards, even when subjected to 300 freeze/thaw cycles, reached a strength of at least 9 N/mm^2. With increasing age, a gradual increase in bending strength of about 1.1 N/mm^2 (DR) and 0.8 N/mm^2 (DP) was observed. Thus, by modifying the composition of the boards, the long-term strength increase was slightly slowed down. In terms of frost resistance, the two types of tested boards (DR and DP) can be evaluated very similarly. The resistance to the adverse conditions of cyclic freezing and thawing improves slightly with increasing age. The error bars (Figure 3) are much more pronounced than in the case of density. This fact indicates a higher variability or bending strengths dispersion due to adverse climatic conditions.

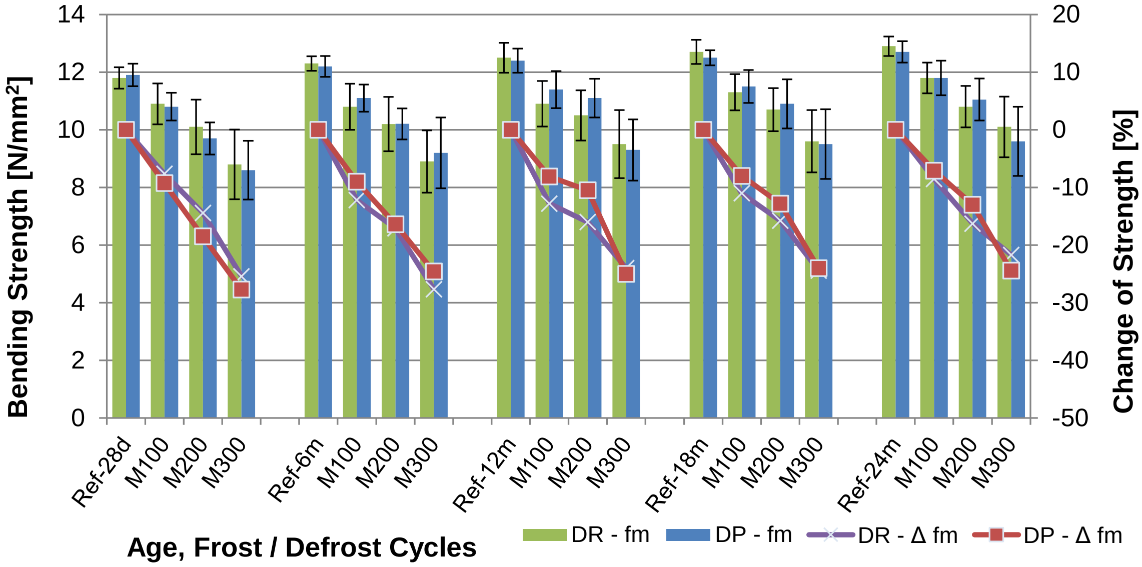

Figure 3: Comparison of cement-bonded particleboards bending strength, red and violet curves represent decrease of strength, black vertical bars represent deviations

Table 2: Coefficient of variation of bending strength of the particleboards DR and DP

Age [days, months]	Bending strength coefficient of variation – DR [%]				Bending strength coefficient of variation – DP [%]			
	Cycles				Cycles			
	Ref	M100	M200	M300	Ref	M100	M200	M300
28 days	3.14	6.51	9.41	13.75	3.28	4.44	5.77	11.86
6 months	2.03	7.41	9.22	12.13	2.95	4.23	5.29	13.37
12 months	4.16	7.25	8.29	12.42	3.39	5.62	6.04	11.40
18 months	3.31	5.58	7.01	11.25	2.08	4.96	7.80	12.74
24 months	2.64	4.50	6.67	10.39	2.93	5.07	6.60	12.46

The coefficients of variation (Table 2) of the boards before exposure to freeze/thaw cycles range from ca 2% to 4%, whereas after 300 cycles these coefficients reach values from ca 10% to 14%. Thus, it is evident that the degradation of the board structure due to exposure to adverse conditions will have a more pronounced effect on the bending strengths (rather than the densities). DR boards are slightly better in this respect. Comparing the results and findings of Fuwape et al. [17] , it is evident that DR and DP boards are characterized by very low variability. In fact, Fuwape et al. report values for cement-bonded particleboards of modified composition corresponding to a coefficient of variation ca 25%.

The modulus of elasticity in bending (Figure 4) of the tested boards ranges from 8,021 N/mm^2 to 5,213 N/mm^2 (DR) and 7,965 N/mm^2 to 4,872 N/mm^2 (DP), respectively. The requirement for a minimum modulus of 4,500 N/mm^2 according to EN 634-213 was met in all cases even plates subjected to 300 freeze/thaw cycles. A gradual increase in modulus of approx. 767 N/mm^2 (DR) and 817 N/mm^2 (DP) was observed with increasing age. The increase in stiffness and bending strength with increasing age is supported by the results of Vu et al. [18]. The slowing of the modulus increase was not confirmed as in the case of bending strength due to modification of the board composition. The DR boards performed slightly better in terms of frost resistance, which is particularly obvious after 300 freezing cycles. It is also evident that the resistance to the adverse freeze conditions improves slightly with increasing age.

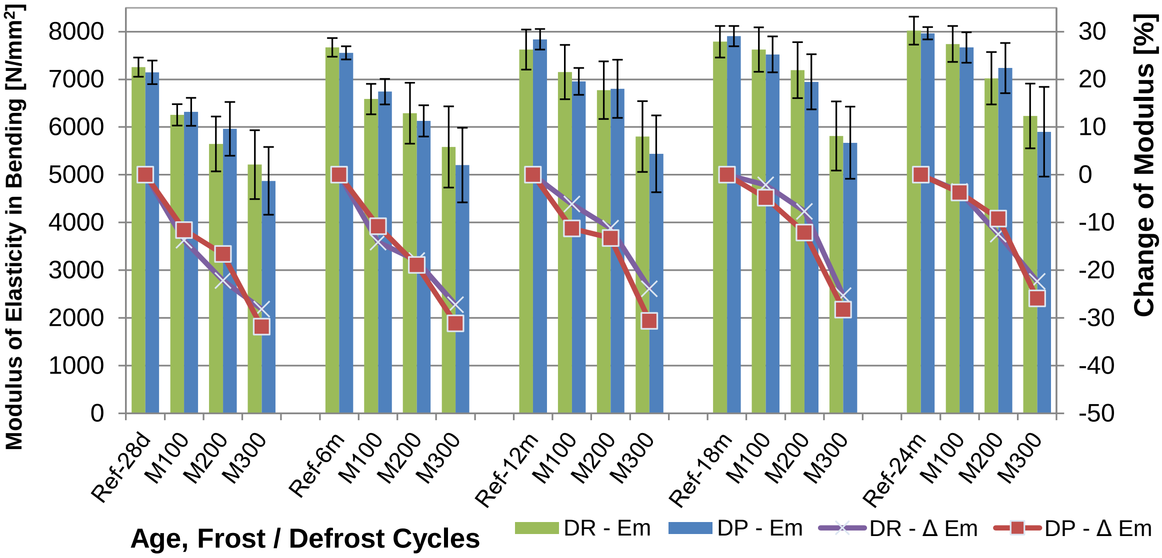

Figure 4: Comparison of cement-bonded particleboards modulus of elasticity in bending, red and violet curves represent decrease of modulus, black vertical bars represent deviations

Table 3: Coefficient of variation of modulus of elasticity of the particleboards DR and DP

Age [days, months]	Modulus of elasticity coefficient of variation – DR [%]				Modulus of elasticity coefficient of variation – DP [%]			
	Cycles				Cycles			
	Ref	**M100**	**M200**	**M300**	**Ref**	**M100**	**M200**	**M300**
28 days	2.77	3.60	10.15	13.83	3.47	4.64	9.46	14.54
6 months	2.54	4.87	10.14	15.26	1.82	3.95	5.32	15.07
12 months	5.52	7.94	8.90	12.77	2.77	4.03	8.96	14.81
18 months	4.22	6.13	8.16	12.47	2.69	5.03	8.33	13.34
24 months	3.64	4.84	7.82	10.88	1.64	4.16	7.27	15.96

The coefficients of variation (Table 3) of the boards before exposure to freeze/thaw cycles range from ca 2.5% to 5.5%, whereas after 300 cycles the coefficients of variation reach values from approx. 11% to 16%. It is therefore evident that the degradation of the board structure due to frost exposure will have a more pronounced effect on the elastic modulus, than in the case of bending strength and density. DR particleboards reach better resistance in this respect.

The tensile strength perpendicular to the plane of the board (Figure 5) ranges from 1.16 N/mm^2 to 0.55 N/mm^2 (DR) and 1.13 N/mm^2 to 0.50 N/mm^2 (DP), respectively. The requirement for a minimum tensile strength of 0.5 N/mm^2 according to EN 634-2 [13] was met in all cases even boards subjected to 300 freeze/thaw cycles. A gradual increase in tensile strength of approximately 0.26 N/mm^2 (DR) and 0.27 N/mm^2 (DP) was observed with increasing age. The slowing down of the increase in tensile strength was not confirmed as in the case of bending strength due to the different composition of the boards. The DR plates performed slightly better in terms of frost resistance, which is particularly evident after 300 freezing cycles. The resistance (tensile strength) to the adverse conditions of cyclic freezing and thawing improves slightly with increasing age.

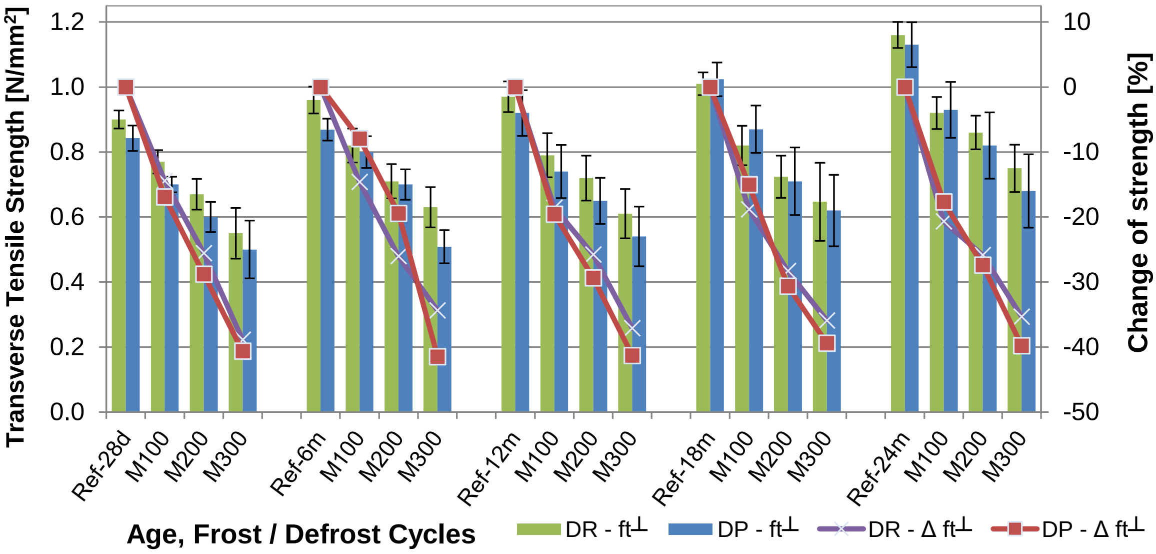

Figure 5: Comparison of cement-bonded particleboards transverse tensile strength perpendicular to the plane of the board, red and violet curves represent decrease of strength, black vertical bars represent deviations

Table 4: Coefficient of variation of transverse tensile strength perpendicular to the plane of the board – particleboards DR and DP

Age [days, months]	Transverse Tensile strength coefficient of variation – DR [%]				Transverse Tensile strength coefficient of variation – DP[%]			
	Cycles				Cycles			
	Ref	M100	M200	M300	Ref	M100	M200	M300
28 days	3.47	4.64	9.46	14.54	4.63	3.47	7.74	17.80
6 months	1.82	3.95	5.32	15.07	3.91	6.08	6.71	10.03
12 months	2.77	4.03	8.96	14.81	7.61	11.08	10.92	17.04
18 months	2.69	5.03	8.33	13.34	5.08	8.39	14.65	17.74
24 months	1.64	4.16	7.27	15.96	6.12	9.25	12.44	16.62

The coefficients of variation (Table 4) of the boards before exposure to freeze/thaw cycles range from ca 1.6% to 6.1%, whereas after 300 cycles the coefficients of variation reach values from about 10% to 17.7%. Thus, it is evident that the board structure deterioration due to adverse conditions exposure has a more pronounced effect on the modulus of elasticity (than in the case of bending strength and density). DR boards can be better evaluated in this respect. By comparing all the parameters determined, it can be concluded that the tensile strength perpendicular to the plane of the board is the most subject to degradation due to the action of adverse effects. This is indicated by the highest decreases in this strength with increasing number of freeze/thaw cycles and by the highest coefficients of variation. This is due to the anisotropy of the cement-bonded particleboards. The swelling and shrinkage in the thickness direction is the greatest when contact with water and temperature changes occur. Orientation of the spruce chips and manufacturing process are major cause. The particleboards are pressed and subjected to heat treatment during their production. In this way, tension is brought into the boards in the thickness direction. During contact with water, the volumetric changes in the chips cause the stresses are released in the thickness direction. When the release of this stress occur, the wood chips then exert pressure on the surrounding cement matrix. This fact is confirmed, for example, by the findings of Rowell et al. [20]. When the cohesive value of the matrix is exceeded due to this pressure, the structure of the boards gradually fails, which is most evident when the tensile strength is tested perpendicular to the plane of the board.

Microstructure

Microstructure analysis revealed that the cement matrix of the particleboards is compact and the crystalline phases are extensively developed with no structural defects. The microstructure images of the particleboards at 24 months of age before and after 300 freeze cycles are shown below (Figure 6 to 9). The interface between the cement matrix and spruce chips is compact in the case of the boards not subjected to freeze/thaw cycles. In the case of all analysed boards, it is evident that both crystalline and amorphous phases of the cement matrix grow into the surface layers of the cellular structure of the chips. The differences between the reference and the adversely stressed boards are mainly evident by the identified cracks.

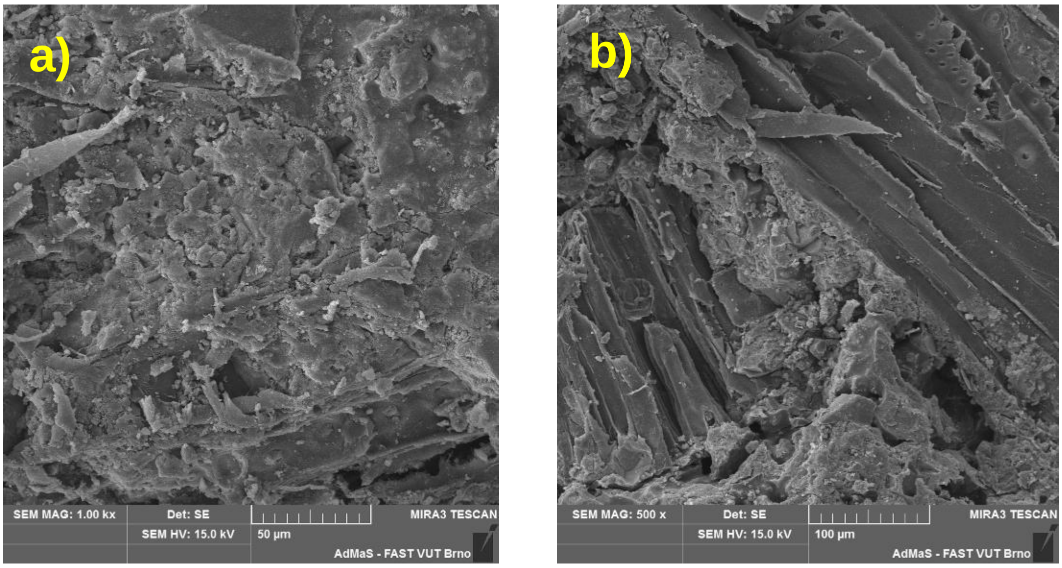

Figure 6: SEM pictures of DR Ref-24m board; a) microstructure of cement matrix, b) detail of interfacial transition zone

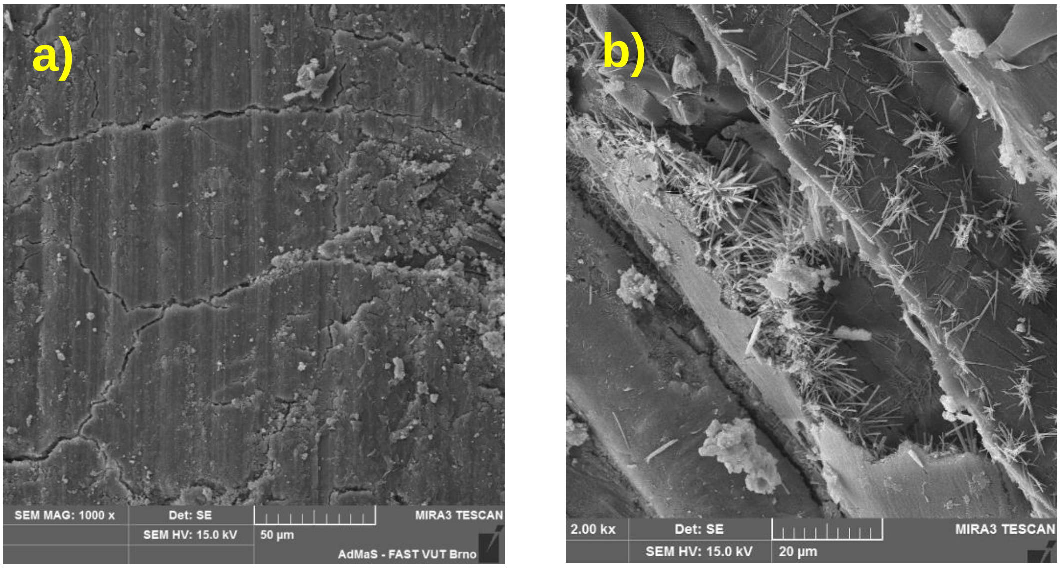

Figure 7: SEM pictures of DR 24m M300 board; a) microstructure of cement matrix under spruce chip, b) detail of interfacial transition zone

Microscopic cracks are in the area where spruce chips were present in the cement matrix (DR boards) (Figure 7a). This is indicates matrix degradation, which relates, among other things, to volumetric changes in the adjacent spruce chip. The volumetric changes in the chips are due to the alternating effects of positive and negative temperatures combined with the presence of water. The crystalline phases of the cement matrix in the cellular structure of the spruce chips can be seen in Figure 7b. Microscopic cracks in the chip with widths of a few μm were also identified at this location. Considering the microstructure of the dust-modified particleboards, i.e. DP, it is clear that the matrix of the reference test specimens is compact with a well-developed and compact crystalline structure (Figure 8, 9). This is supported by the results of the determined mechanical parameters, where negligible differences were observed between DR and DP particleboards. Synergic interaction of wood chips in the cement matrix is obvious. Such as in the case of DR, exposure to freezing cycles resulted in degradation of the structure on a microscopic scale. However, the identified failures (cracks) are rather local character without affecting the evolution of the matrix structure. Minor defects were also identified in the ITZ between the spruce chips and the cement matrix (Figure 9b).

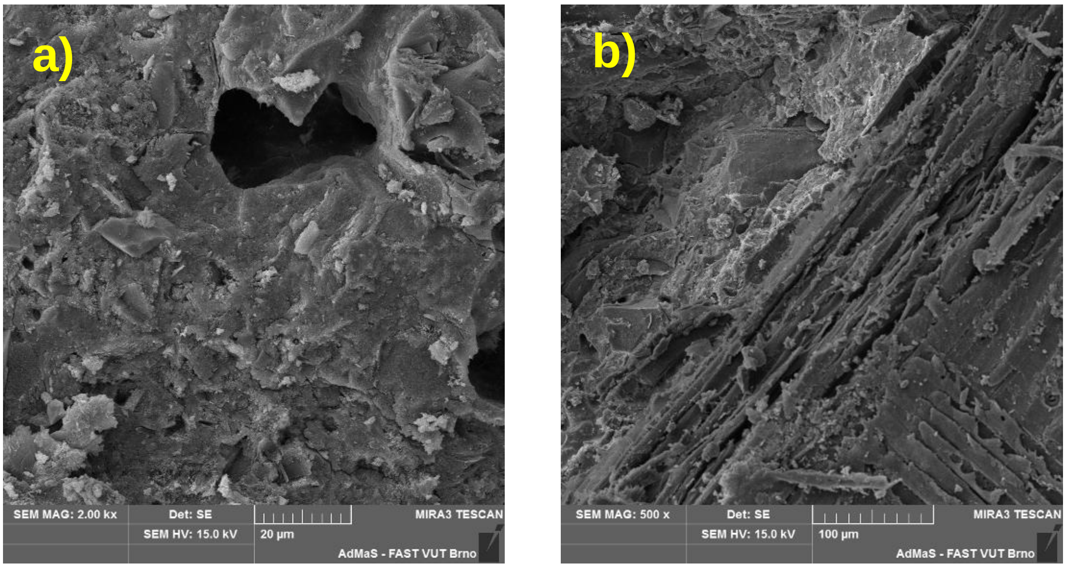

Figure 8: SEM pictures of DP Ref-24m board; a) microstructure of cement matrix, b) detail of interfacial transition zone

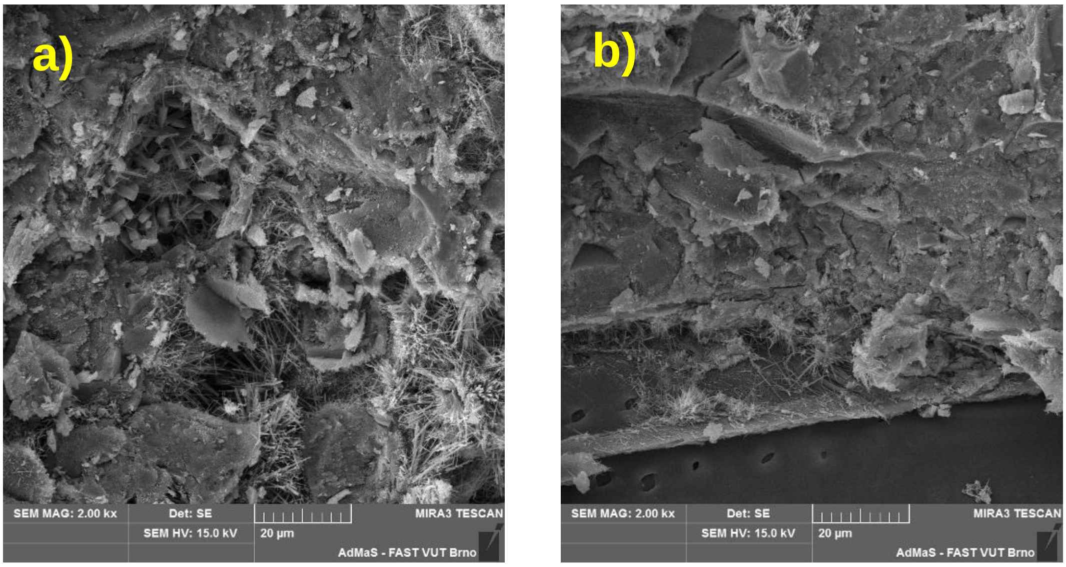

Figure 9: SEM pictures of DP 24m M300 board; a) microstructure of cement matrix under spruce chip, b) detail of interfacial transition zone

Conclusions

Based on the results obtained and the findings concluded in the scope of long-term durability of cement-bonded particleboards of modified composition, the following can be stated:

- Waste dust from formatting the cement-bonded particleboards can be used for their re-production in amount of 7% as substituent of cement (6%) and spruce chips (1%). This way could save circa 2,600 tons of cement and 140 tons of spruce chips per year in production of cement-bonded particleboards.
- Effect of the composition modification on mechanical properties and microstructure including their development in time is negligible.
- Particleboards modified by waste dust meet requirements of technical standard EN 634-2 (density, strength characteristics, modulus of elasticity and frost resistance).
- In terms of long-term development, there is a slight improvement in frost resistance. Boards subjected to 300 freeze/thaw cycles reach a bending strength of at least 9 N/mm^2 after 2 years maturing.
- Microstructure analysis showed very good interactions between the spruce chips and the cement matrix, even after exposure to 300 freeze/thaw cycles. Identified microscopic failures were rather local.
- The crystalline phases of the cement matrix penetrated into the surface parts of the cellular structure of the spruce chips over a period of 2 years. This has the effect of forming a more compact ITZ structure between the chips and the adjacent matrix. It is therefore evident that in the long term the interaction between the spruce chips and the cement matrix in the cement-bonded particleboards improves. The ITZ has a relatively significant effect on, among other things, the durability of cement-bonded particleboards and therefore an improvement in this respect can be predicted with time.
- For further research, it would be interesting to study the durability under other adverse conditions such as temperature shocks, CO_2, SO_2 etc.

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Dlouhodobá trvanlivost cementotřískových desek modifikovaného složení odpadním prachem

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Souhrn

Článek prezentuje výzkum zaměřený na dlouhodobé chování cementotřískových desek vystavených nepříznivým vlivům. Desky byly podrobeny zmrazovacím / rozmrazovacím cyklům, do 300 cyklů. Konkrétně bylo realizováno 100, 200 a 300 cyklů, a to ve stáří desek 28 dní, 6 měsíců, 12 měsíců, 18 měsíců a 24 měsíců. Složení desek bylo modifikováno vedlejším produktem vznikajícím při opracování právě cementotřískových desek. Prach z formátování a broušení cementotřískových desek byl použit v množství 7 % jako parciální náhrada cementu (6 %) a smrkových třísek (1 %).

Cílem prezentovaného výzkumu je posouzení vlivu nepříznivých podmínek v rozdílném stáří cementotřískových desek (modifikovaného složení), kdy je pozornost věnována mechanickým vlastnostem, resp. mikrostruktuře. Byla analyzována pevnost v ohybu, modul pružnosti v ohybu, pevnost v tahu kolmo na rovinu desky a mikrostruktura (rastrovací elektronová mikroskopie) s ohledem na změny v čase (do 2 let).

Klíčová slova: *Cementotřísková deska, modifikace, složení, alternativní surovina, vlastnosti, mikrostruktura, dlouhodobý, trvanlivost, mráz, vývoj v čase.*