

CEMENT AS AN INORGANIC BINDER FOR THE PRODUCTION OF FORMALDEHYDE-FREE BONDED PLYWOOD

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Abstract:

For the bonding of veneers into plywood, formaldehyde-containing amino resins are mainly used. The advantages of these adhesives are good properties (e.g. fast curing), high availability, acceptable price and a mature technology. The formaldehyde emission (FE) is the major disadvantage of these adhesives. The limit of FE for wood-based panels has been reduced more and more in recent years. With the decision of the European Union from 1 January 2016, formaldehyde was obligatorily classified as carcinogenic and mutagenic. The result of this decision is a further reduction of FE limits for manufacturing and use of wood-based panels. Without expensive adhesive systems or coatings, plywood and its production will not comply with these limits in the future.

Prospectively, the use of formaldehyde-containing adhesives will become uneconomical. For this reason, studies for bonding wood veneers with formaldehyde-free Portland cement were carried out. Ordinary Portland cement (OPC) is widely available, inexpensive and is in use in various industries including the wood-based panel industry (e.g. Cement-bonded particle board = CBPB). A new product called "cement-bonded plywood (CBPly)" combines the advantages of organically-bonded plywood (e.g. great strength, low density) and CBPB (e.g. low FE, high fire resistance).

In contrast to well-known cement-bonded composites based on wood particles (CBWC) like CBPB, cement-bonded wood-wool boards or wood-fibre-reinforced cement boards, the amount of wood is much higher in CBPly, since the cement is only located between the layers of wood (more specific information). The veneers ensure a high tensile strength of the material. This provides better bending properties compared to other particle-based CBCs. In addition to the increased strength, the handling and machinability is improved due to the lower density and lower cement content. Results from cone calorimeter tests indicate that if cement is also applied to the top veneers, the CBPly can be classified as Euroclass B (EN 13501-1).

Due to the advantageous properties of CBPly, markets can be developed that are difficult or inaccessible for organically-bonded plywood and CBPB. Especially the use in applications with high demands on fire resistance and low emissions are regarded.

Key words: cement-bonded plywood; cement-bonded particle board; spruce; flammability; formaldehyde emission.

INTRODUCTION

Ordinary Portland cement (OPC), the most common binder used in cement-bonded particleboards (CBPB), imparts some performance advantages to this type of wood-based panels. An obvious benefit is high resistance to fire, moisture and chemicals. The binder is also thought to be the main cause of the excellent dimensional stability of this product when compared to other wood-based panels. The disadvantages associated with the use of OPC as a binder include panel density (typically 1,250kg/m³) and low specific strength and stiffness. The high density is a result of the high cement amount which strongly affect the wearing of processing tools. Compared to resin-based binders, inorganic binders have about 1,000 times lower specific surface area (Ambrozy and Giertlová 2005). This means that inorganically-bonded wood-based panels have significantly higher binder content than resin-bonded ones. Typically, CBPBs consists of 60...70% OPC and 30...40% wood particles (dry mass). In other words, CBPB has a cement-wood (c/w) ratio of around 2. The resin content of organically-bonded wood-based panels is mainly in the range of 5 to 15%.

All attempts at lowering the c/w ratio of CBPB leads to a reduction of the mechanical and physical values, especially MOE, IB and TS (Musokotwane 1982, Soroushian et al. 2003, Papadopoulos 2008, Marzuki et al. 2011, Sotannde et al. 2012, Abdelrhman et al. 2015). According to van Elten (2006), the production of CBPB with wood strands offers the opportunity to lower the density without reducing the mechanical properties. Van Elten (2006) reported that the EltoBoard with a density of $1,100\text{kg/m}^3$ achieves a MOR of 20N/mm^2 (Paulitsch and Barbu, 2015). Dube and Scherfke (2008) compared particles of different length. With the use of 16mm-long particles, the density could be reduced by about 150kg/m^3 without decreasing the MOR and MOE, in contrast to CBPB with particles of 7mm average length. With a decrease in specific surface area, the adhesive content can be lowered. It is well known that the adhesive content of OSB is lower than for particleboards (Nishimura 2015). The adhesive content in a glue line of resin-bonded plywood is in the range of $100\ldots 200\text{g/m}^2$, which is about 10% of the wood's dry mass.

Using an inorganic binder like OPC in combination with veneers could help overcome the disadvantages in CBPB. A comparably lower cement content not only reduces the density (better handling and machinability), but also the higher amount of wood will increase the mechanical values. On the other hand, the use of cement will lead to a change in plywood properties. With a non-formaldehyde binder, the threshold values of formaldehyde emission (FE) will be met much more easily. Furthermore, the fire, moisture and chemical resistance will be increased, without using any other additives or surface treatments.

MATERIALS AND METHODS

For the production of cement-bonded plywood (CBPly), peeled veneers (500mmx500mm) from Norway spruce (*Picea abies* (L.) Karst) of 2.0mm thickness were used. As inorganic binder, OPC (CEM I 52,5R) and a combination of accelerators were chosen. The laboratory board production was performed by the following steps: (1) conditioning/watering of the veneers, (2) spraying of accelerators onto veneer surfaces, (3) the OPC paste ($200\text{g}_{\text{atro}}/\text{m}^2$) with a water-cement (w/c) ratio of 0.40 was troweled on both sides of the veneers, (4) lay-up of the veneer stacks between cauls in a clamping frame, (5) cold pressing by 3N/mm^2 and fixing of the clamps, (6) accelerated setting in a hardening chamber (6.5h / 65°C), (7) opening the clamps and storage for 14 days in a climate chamber for final setting. Finally, (8), the boards were dried (40°C / 14h) and conditioned (20°C / 65% rel. humidity) before testing.

To investigate the properties of CBPly in comparison to resin-bonded plywood and CBPB, different tests were performed: density (EN 323), bending strength (MOR) and bending stiffness (MOE) (EN 310), shear strength after 24h water immersion (EN 314-1), formaldehyde content and emission (ISO 12460-5, ISO 12460-3) and fire behavior (ISO 5660).

RESULTS AND DISCUSSION

Mechanical Properties

One of the most important parameters for the hydration of cement in a composite material like cement-bonded wood-based panels is the effective w/c ratio. From CBPB it is well known that, similar to lightweight concrete, the wood particles absorb a part of the mixing water that is needed for the cement hydration (Simatupang 1979). For CBPly, two options were possible to balance the lack of water: (1) adding more mixing water or (2) pre-wetting the wood. The first option was neglected after application trials of cement paste on veneers with different w/c ratios. A w/c ratio of 0.40 seemed to be most feasible. Three different veneer moisture contents (MC) were investigated (35%, 45%, 55%). The MC was adjusted by storing the veneers under water for different time periods. The lowest level was chosen because of the fiber saturation point (FSP) of wood at around 30%. Below the FSP, wood contains only bound water in the wood cell walls. It was supposed that only free water above the FSP will be squeezed out of the veneers by pressing.

Fig. 1 presents the MOR, MOE and shear strength summarized for three and five-layer CBPly with different veneer MCs. Trials with seven veneer layers exhibited a significant decrease of bending properties in contrast to three and five layers. A plausible explanation could be that the time slot for pre-hardening of the OPC before pressing was exceeded. For MOE and MOR, the same trend applies: with increasing veneer MC, the mean value decreases. However, no significant difference can be observed, with one exception: MOE of CBPly with a MC of 35% differs significantly from that with 55%. Similar findings were found for the shear strength. It is possible that, with a MC above 45%, the w/c ratio between the veneers was too high.

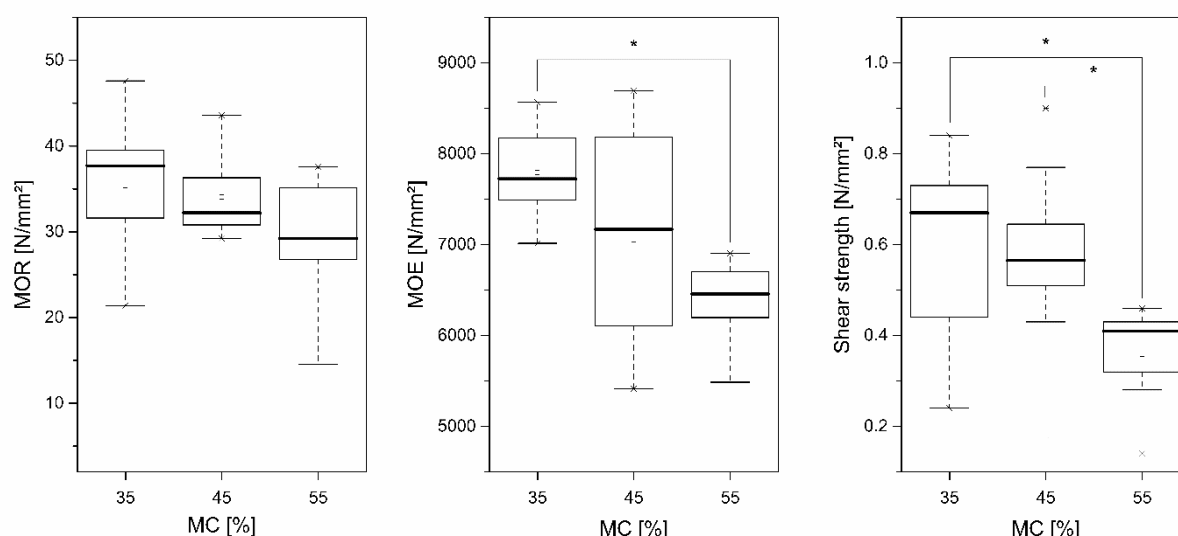


Fig. 1.

MOR, MOE and shear strength (after 24 h water immersion) as average of three and five-layer CBPly with different veneer MC (N = 10).

In contrast to lightweight concrete, cement-bonded wood-based panels are compacted by a high pressure of 2...4N/mm². By compression, the water is pressed out of the veneers and the w/c ratio exceeds the theoretical optimum of 0.40 for the cement hydration. In this case, the excess of water leads to the formation of capillary pores. This will result in a decreased strength of the hydrated cement. Press trials with different water-loaded veneers and pressing power revealed that the water release increases with increasing MC as expected, but not with higher pressing power. The effective w/c ratio is a combination of the water content of the cement paste, the water pressed out from the veneers and the water that the veneers absorb from the cement paste.

Further investigations were carried out with different veneer thickness, pressing power, hydration temperature and pre-treatments of the veneers. Fig. 2 presents the current specific bending properties of CBPly in comparison to organically-bonded plywood (characteristic strength according to DIN 20000-1) and CBPB (requirements according to EN 634-2). Due to the lower c/w ratio of CBPly (0.6), the boards have a much lower density (approx. 750kg·m⁻³) in contrast to CBPB (approx. 1,250kg·m⁻³), with a c/w ratio of 2.0. At 600kg·m⁻³, the density of plywood is naturally lower. The specific strength and stiffness indicate that, at the same weight of the boards, the bending properties of CBPly are close to those of plywood and much higher than those of CBPB. The difference of CBPly can be explained by the tensile strength of the material combination. Spruce has a tensile strength of 80...90N·mm⁻² and a MOE of 10,000N·mm⁻². Cement stone in contrast has values around 4...15N·mm⁻², respectively 5...20N·mm⁻². The high MOE of the veneers has a very positive effect on the composite bending stiffness. Therefore, the gap between the MOE of CBPly and plywood (10%) is tremendously lower than for the MOR (40%). In addition to the low strength of the cement, the wood strength has probably been lowered by the alkaline degradation of the veneers (Govin et al. 2005, Ishikura et al. 2010). This leads to a more brittle wood structure.

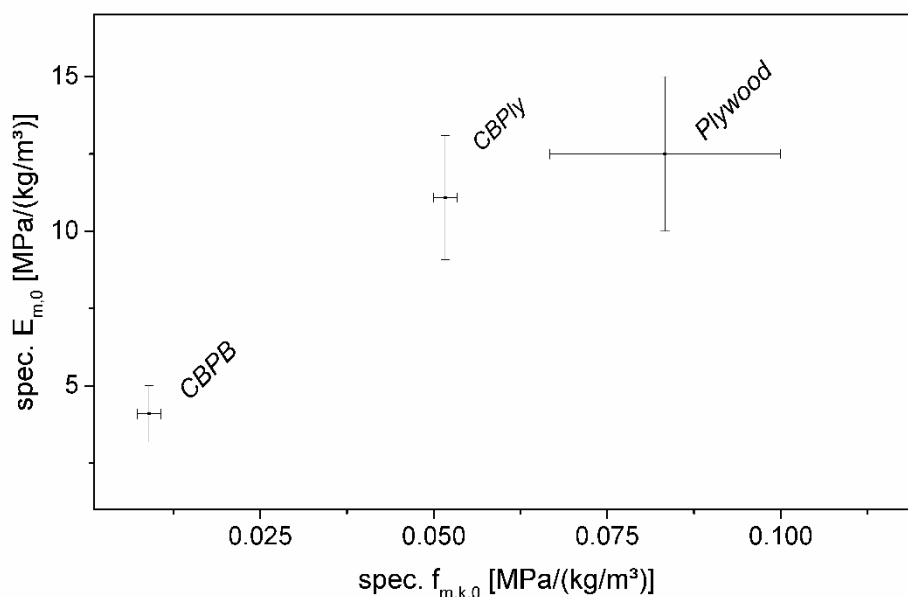


Fig. 2.

Specific strength plotted against specific stiffness of CBPly, CBPB and Plywood.

Formaldehyde emission

To evaluate the FE, CBPly was investigated in comparison to melamine-urea-formaldehyde-bonded (MUF) plywood by gas analysis and the perforator method. After ISO-standards, the perforator method is not required, but it is a standard analysis according to GOST 27678-88.

As expected, the formaldehyde content as well as the emission of MUF-bonded plywood is much higher than that of the cement-bonded plywood (Fig. 3). For gas analysis, no values for CBPly were detected (detection limit 0.2mg/m²h). The formaldehyde content of CBPly, at 0.13mg/100g_{board}, is clearly below the value of E1 (8.0mg/100g_{board}). In contrast, the MUF-bonded plywood exceeds both thresholds marginally. The gas analysis value is 0.3mg/100g_{board} higher and the perforator value is 0.67mg/100g_{board} higher than the standard requirements.

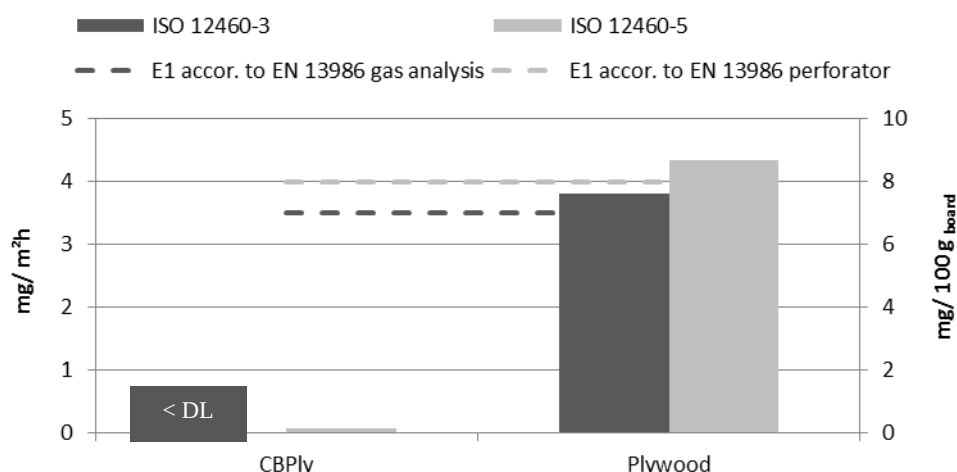


Fig. 3.

Formaldehyde emission and content of MUF-bonded and cement-bonded plywood (N = 3; DL...detection limit).

Roffael (2012) measured an FE of 2mg/m²h for CBPB. This value is higher than that of native wood (Boehme 2000). The investigated CBPly had a much lower c/w ratio (0.6) than CBPB (2.0). This and the fact that the wood particles in CBPB are completely embedded in a cement matrix reduce the alkaline effect of the cement in relation to the specific wood surface in CBPly.

Fire behavior

CBPB are classified as hardly flammable, which corresponds to the Euroclass B-s1d0 (EN 13501-1). Plywood in general is inflammable and is classified as Euroclass D-s2 d0. The use of cement as bonding agent for veneers aimed to produce hardly flammable plywood without adding a flame retardant.

The flammability was examined with the cone calorimeter method according to ISO 5660-1 by a heat flux of 25 and 50 kW·m⁻². Three samples of five- and seven-layer MUF-bonded and cement-bonded plywood were tested.

Fig. 4 presents the heat release as a function of time depending on the heat flux and number of layers. In the four charts of figure 4, the maximum heat release of CBPly is always below that of plywood. At a heat flux of 25 kW·m⁻² (a1 and b1), the heat release of CBPly is continuously lower than for plywood. The maximum heat release for CBPly and plywood hardly depends on the number of layers. The influence of the heat flux is much higher. The curves of CBPly with five and seven layers are looking quite similar at a heat flux of 25 kW·m⁻². The ignition starts later than for plywood because of the cementitious protection layer. The first sharp peak of heat release is primarily due to the combustion of the veneers. For CBPly the peak is much smaller, because the burn-off is hindered by the cement layers, whereas the curves of CBPly at a heat flux of 50 kW·m⁻² (a2 and b2) exhibit a similar ignition time and a large second peak. The latter can probably be attributed to the destruction of char residue created by the combustion of the wood veneers.

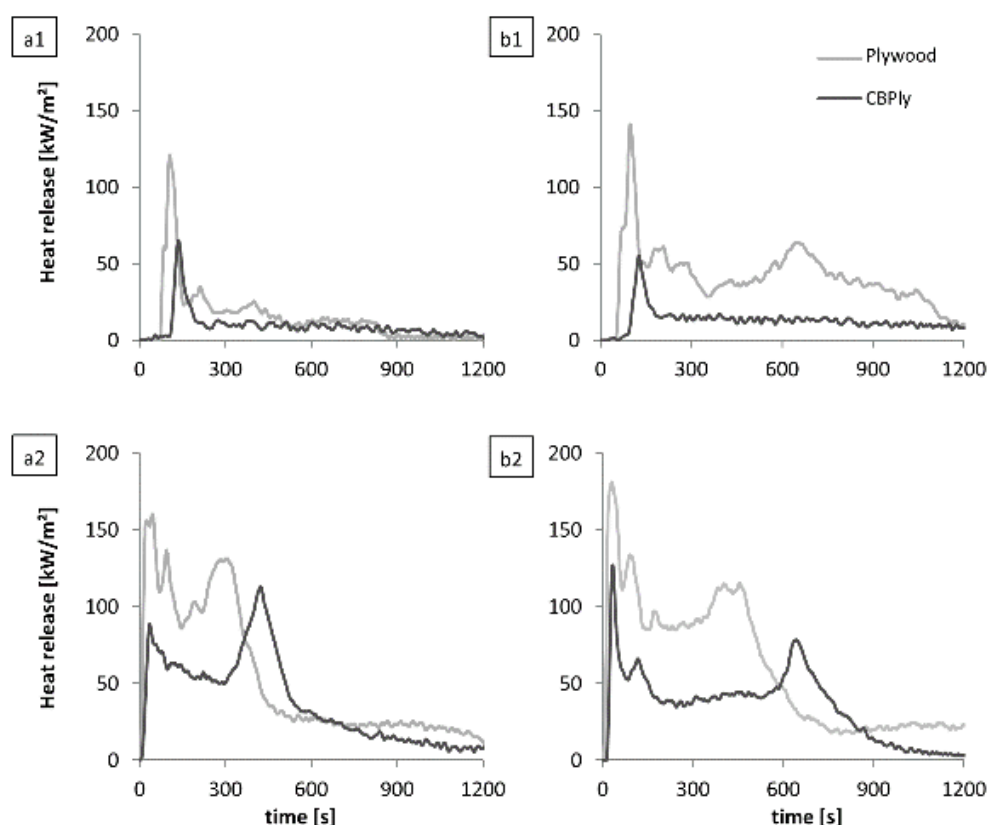


Fig. 4.

Heat release of five-layer (a) and seven-layer (b) MUF-bonded plywood and CBPly tested with a radiation power of 25kW (1) and 50kW (2) (N = 2).

In the European classification system described in EN 13501-1, the medium-scale single burning item (SBI) test is a central method. Fire testing in the SBI is relatively time-consuming and expensive. The cone calorimeter test and the SBI test are both based on the same principles for measuring heat release rate (HRR) and smoke production rate (SPR). It is therefore not unlikely that correlations between these methods exist. Steen-Hansen and Kristoffersen (2007) established equations for the classification of wood-based panels to Euroclass B, C or D. They compared the results of cone calorimetry on different wood-based panels with SBI values. In the analysis, the Euroclass was correctly predicted for 92.4% of all the 184 cases.

To calculate the Euroclass for CBPly and plywood according to Steen-Hansen and Kristoffersen (2007), the values of Table 1 with a heat release of 50 kW·m⁻² were used.

Table 1

Results of cone calorimeter test of MUF-bonded plywood (Ply) and cement-bonded plywood (CBPly) (THR...total heat release, TML...total mass loss)

Radiation power	25 kW·m ⁻²				50 kW·m ⁻²			
	5		7		5		7	
Layer								
Material	Ply	CBPly	Ply	CBPly	Ply	CBPly	Ply	CBPly
THR [MJ·m ⁻²]	20.1	12.6	57.1	15.3	64.8	48.4	80.3	43.2
TML [%]	100.0	62.7	94.8	58.8	100.0	70.0	100.0	70.0
Density [kg·m ⁻³]	465.0	739.0	480.0	745.0	465.0	739.0	480.0	745.0

Table 2 shows the calculated values according to the equations of Steen-Hansen and Kristoffersen (2007). The highest value influences the classification in the corresponding Euroclass. Therefore, the tested plywood is classified as Euroclass D and CBPly as Euroclass B.

The total heat release (THR) and the total mass loss (TML) of CBPly fit very well the investigation of Yu et al. (2016). They analyzed CBPB with different c/w ratios by cone calorimetry. CBPB with a very low c/w ratio of 0.50 (655kg·m⁻³) had a THR of around 52% and a TML of 57%. By inserting the values into the equations of Table 2, CBPB is also classified as Euroclass B.

Table 2

Calculation of Euroclass of MUF-bonded plywood (Ply) and cement-bonded plywood (CBPly) from cone calorimeter test results (THR...total heat release, TML...total mass loss, ρ ...density)

Euro-class	Equations according to Steen-Hansen and Kristoffersen (2007)	Plywood		CBPly	
		5 layer	7 layer	5 layer	7 layer
B	$= -0.503THR + 0.100\rho + 2.040TML - 86.177$	131.8	125.4	106.2	109.4
C	$= -0.313THR + 0.071\rho + 1.767TML - 66.596$	122.9	119.0	94.4	96.5
D	$= -0.468THR + 0.098\rho + 2.268TML - 105.250$	136.8	131.0	103.3	106.3

CONCLUSION

By laboratory production of plywood with OPC binder, the suitability of inorganic binders for bonding layers of wood into wood-based panels was demonstrated. The properties of the new wood-based panel CBPly represent a combination of the properties of the well-known materials plywood and CBPB: FE of less than 0.2 mg/100g_{board}, high fire resistance, good handling and machinability, and a classification as F20/E70 (EN 636) for fiber-parallel bending. Thereby, the scope of application for plywood with special requirements, for example for emission and fire resistance, can be extended, without the use of expensive additives or coatings.

Future investigations should pay attention especially to the improvement of the bonding behavior. By e.g. minimizing the alkalinity damage of the wood, prevention of cement inhibition by wood extractives, mechanical anchoring between the cement and the veneers, and reducing the swelling and shrinkage of the veneers during the whole process, it should be possible to meet the requirements of plywood bonding quality according to EN 314-2.

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