CEMENT-BONDED PLYWOOD (CBPLY)

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ABSTRACT

The use of wood composites for interior design is especially limited by the formaldehyde emission and flammability of the material. Plywood, the world wide most significant wood-based panel, is mostly made by formaldehyde-based amino resins (e.g. UF and PF resins). Without expensive additives or coatings, plywood can't comply with many emission standards and fire protection limits. In this study, formaldehyde-free Ordinary Portland cement (OPC) is presented as a binder for wood veneers. OPC is widely available, inexpensive and is in use in various industries, including the wood-based panel industry (e.g. cement-bonded particle boards = CBPB). The bending properties, formaldehyde emission, and flammability of the laboratory manufactured cement-bonded plywood (CBPly) were tested. The results indicate that the formaldehyde emission and the flammability of plywood bonded by OPC were much lower than those of plywood bonded by formaldehyde-based resin. The bending properties of CBPly can't compete with those of organic bonded plywood, yet. However, the bending values of CBPly clearly exceed those of CBPB. The new product CBPly combines the advantages of organic-bonded plywood (e.g. high strength, low density) and CBPB (e.g. low formaldehyde emission, high fire resistance). With these properties, CBPly is expected to be increasingly used in markets that are difficult or inaccessible for organic-bonded plywood and CBPB.

KEYWORDS:

Cement-bonded plywood, Cement-bonded particle board, Formaldehyde emission, Flammability, Ordinary Portland cement

INTRODUCTION

In Europe, the building industry consumes more raw materials than any other industry. The manufacture of construction products is responsible for approximately 5 % of the total energy consumption and for the corresponding climate-related emissions (Julin 2010). A high proportion of construction is based on non-renewable resources. In respect of climate change, great quantities of CO_2 can be cut down by the use of wood as a building material. The building stock is dominated by multi-storey buildings from 3 to 10 floors. Up to now, far less than 5 % of the new multi-storey buildings are wood-based constructions (Fadai et al. 2012).

Nevertheless, wood-based construction materials have disadvantages. First and foremost, the fire behaviour restricts the use as a building material. Wood-based composites have been contributing to fire hazards resulting in numerous injuries and fatalities due to their inherent flammability. Therefore, improving the fire protection of wood-based composites plays a major role for their possible future applications. Fire protection of building materials is an important criterion, first of all to meet the existing building regulations and standards, second of all to contribute to a sense of security,

Another problem of wood-based materials, especially particle boards and plywood, is the use of formaldehyde containing adhesives. Formaldehyde was classified in the EU as "suspected of causing cancer" until in June 2014 the EU classified it as "may cause cancer" on the basis of new findings. For the use as construction material, wood-based materials have to meet the emission levels from different formaldehyde emission standards and regulations all over the world (e.g. CARB, JAS, EN).

These barriers can be overcome by the use of an inorganic binder instead of formaldehyde-based amino resins. The best examples are cement-bonded particleboards. Wood-cement composites are commonly referred to as being incombustible (Topf 1989; Moslemi 1993; Yu et al. 2016). The resistance to fire of wood-cement composites such as CBPB is attributed to the lower content of organic matter and the crystal water in the binder. The use of a formaldehyde free binder reduces the formaldehyde emission to the level of natural wood or just slightly higher, like Roffael (2012) stated.

In this study, the manufacture and properties of cement-bonded plywood (CBPly) were investigated. The motivation of the development was to create a lightweight wood-cement composite for wood-based internal constructions or interiors with a high content of renewable resources (wood veneer) by using Ordinary Portland cement (OPC) as formaldehyde-free and incombustible binder.

MATERIAL AND METHODS

Fig. 1 presents the resources needed for the production of CBPly. As renewable raw material peeled veneers (500 mm x 500 mm) from Norway spruce (*Picea abies* (L.) Karst) of 2.0 mm thickness were used. As inorganic binder, OPC (CEM I 52.5R (ft)) and a combination of accelerators (aluminum sulfate, calcium hydroxide and sodium silicate) were chosen. By a two-sided application of the additives and the cement paste (200 $g_{adry} \cdot m^{-2}$), CBPly consisted of the following dry composition of resources:

- Wood:	65 %
- Cement:	30 %
- Additives:	5 %

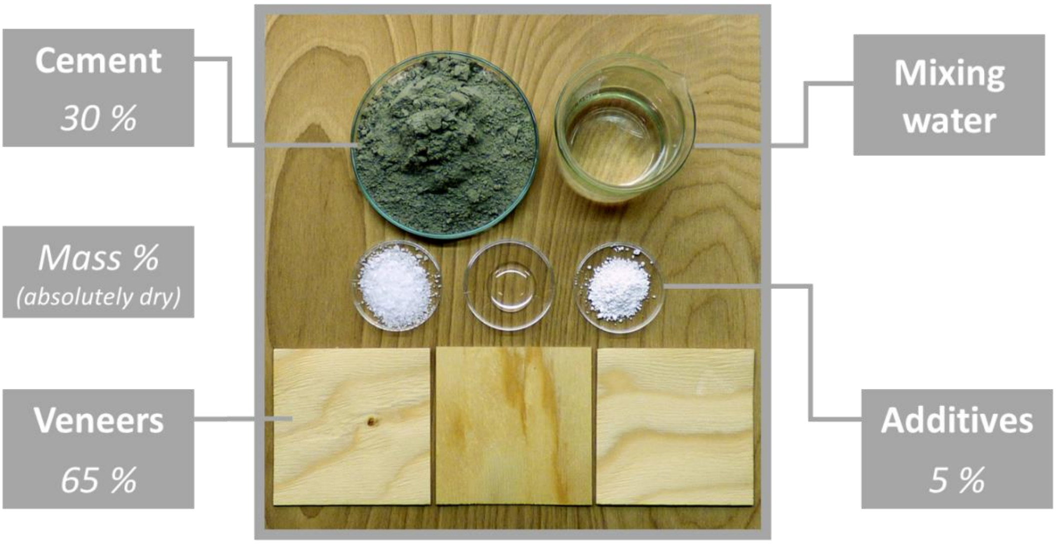

Figure 1 - Resources used fort he production of cement-bonded plywood

The amount of water needed for the cement paste depends on the moisture content of the veneers, the chosen water-cement ratio of the cement paste, and the target moisture content (MC) of the composite during hardening. Pull-out tests of veneer strips from cement blocks (according to Frybort et al. 2010) revealed the best bonding behavior with a wood-cement ratio of 0.40. Additionally, this cement paste showed a comparably good workability regarding the application onto the veneer surface. Regarding the initial MC of the veneers, an advantageous bonding behavior was found for veneer MC of 30 %. At the so called fiber saturation point, the veneer doesn’t absorb much water from the cement paste. Furthermore, only a small part of water is pressed out of the veneers while pressing. The wood-cement ratio remains almost unchanged and can be controlled easily.

The laboratory board production was performed by the steps shown in Fig. 2: (1) conditioning/watering of the veneers, (2) spraying of accelerators on to veneer surfaces, (3) troweling the OPC paste on both sides of the veneers, (4) laying-up of the veneer stacks between cauls in a clamping frame, (5) cold pressing by 3 $N \cdot mm^{-2}$

and fixing of the clamps, (6) accelerated setting in a hardening chamber (6.5 h / 65 °C), (7) opening the clamps and storaging for 14 days in a climate chamber for final setting. Finally (8), drying of the boards (40 °C / 14 h) and conditioning (20 °C / 65 % rel. humidity) before testing.

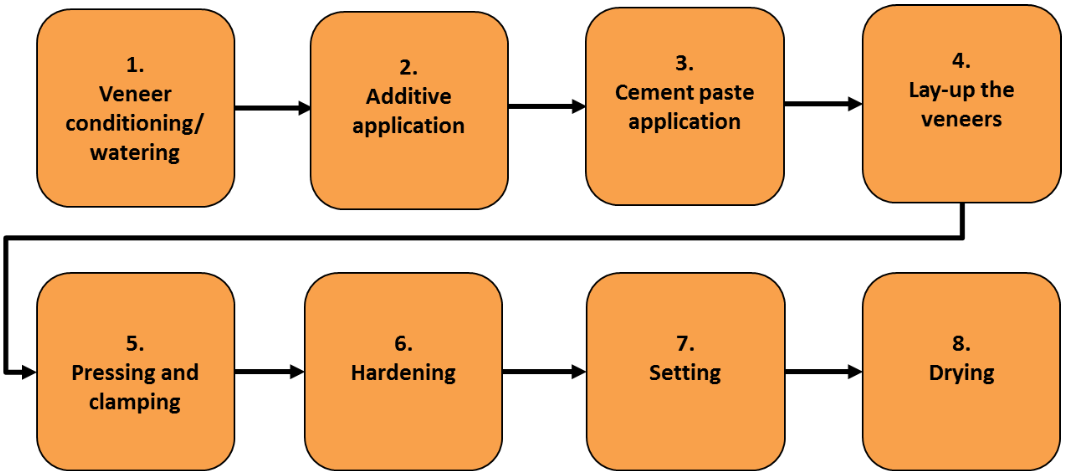

Figure 2 - Procedure of laboratory production of cement-bonded plywood

To investigate the properties of CBPly in comparison to resin-bonded plywood and CBPB different tests were performed: density (EN 323), bending strength (modulus of rupture = MOR) and bending stiffness (modulus of elasticity = MOE) (EN 310), formaldehyde content and emission (ISO 12460-5; ISO 12460-3) and fire behavior (ISO 5660).

RESULTS AND DISCUSSION

Bending properties

Typically, CBPB consists of 65…75 dry mass % OPC and 25…35 dry mass % wood particles (Wenderdel and Krug 2013). In other words: the cement-wood ratio is about 2.30. Because of the high density of OPC (3,000 kg·m^{-3}), CBPBs have a density of about 1,250 kg·m^{-3}. Some companies also sell boards with a density up to 1,650 kg·m^{-3}. Due to the linear relationship between board density and properties (e.g. MOR, internal bond) the CBPB meet the standards much easier (Badejo 1988; Dube and Scherfke 2007). However, the high density restrains the handling, the logistic and the workability. In contrast, organic-bonded plywood is a light-weight material (550 kg·m^{-3}), with a low adhesive content of about 5…10 % (Dunky and Niemz 2002).

To compare CBPly with well-known wood-based panels, an industrial CBPB with a density of 1,400 kg·m^{-3} and melamine urea formaldehyde (MUF) bonded plywood (600 kg·m^{-3}) were used as references. The laboratory manufactured CBPly had an average density of 750 kg·m^{-3}, with a cement/wood-ratio of 0.60.

Figure 3 presents the specific MOR and MOE of CBPly (mean MOR = 49 N·mm^{-2}; mean MOE = 7,150 N·mm^{-2}, σ = 750 kg·m^{-3}), in contrast to CBPB (requirements according to EN 634-2; MOR = 9 N·mm^{-2}; MOE = 4,500 N·mm^{-2}, σ = 1,000 kg·m^{-3}) and plywood (requirements according to DIN 20000-1; MOR = 50 N·mm^{-2}; MOE = 7,333 N·mm^{-2}, σ = 600 kg·m^{-3}). At the same density, the bending properties of CBPly were about 20 % lower than for plywood and 53 % (MOE), 86 % (MOR) higher than for CBPB, respectively. The differences between CBPly and the other two materials can be explained by the tensile strength of the composite raw materials. Norway spruce has a tensile strength of 80…90 N·mm^{-2}. For cement stone the value is only about 4…15 N·mm^{-2}. On the one hand, the considerable higher wood content of CBPly (70 %) in comparison to CBPB (30 %) leads to an increasing MOR. That effect is well known from CBPB. With increasing cement-wood-ratio the MOR decreases due to the higher brittleness of the matrix (Moslemi and Pfister 1987; Marzuki et al. 2011). On the other hand the cement stone leads to a lower MOR in contrast to plywood. Next to the lower MOR of the cement stone, alkaline degradation of the wood structure by the cement is a reason of lower strength (Govin et al. 2005; Ishikura et al. 2010). However, cement is a more rigid material than wood. Therefore, an increasing in cement-wood ratio results in higher MOE (Moslemi and Pfister 1987; Marzuki et al. 2011). This could be an explanation for the smaller difference of the MOE between CBPly and CBPB.

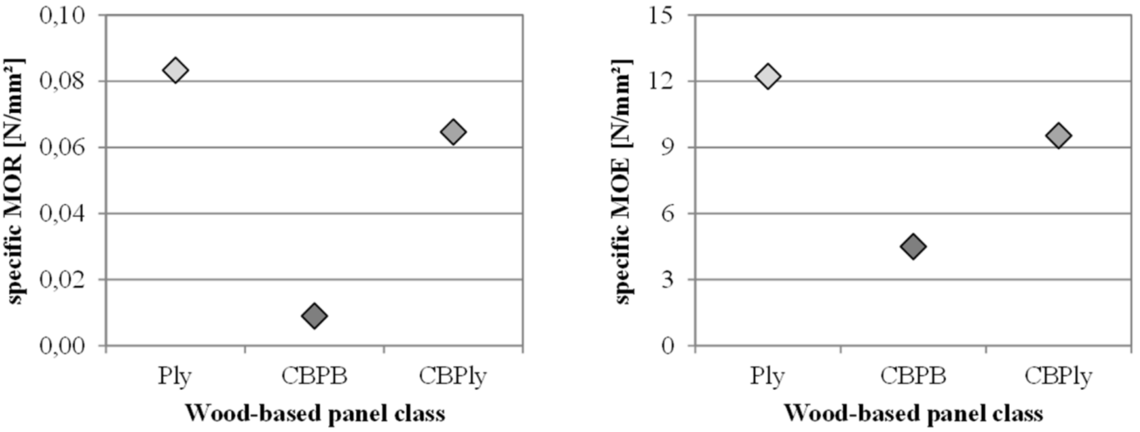

Figure 3 - Specific bending strength and flexural modulus of elasticity from CBPB, organic-bonded plywood (Ply) and cement-bonded plywood (CBPly)

Formaldehyde emission

To evaluate the formaldehyde emission, CBPly was investigated in comparison to melamine-urea-formaldehyde- (MUF-) bonded plywood by gas analysis and 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 (Figure 4). For gas analysis, no values for CBPly were detected (detection limit 0.2 mg/m²h). The formaldehyde content of CBPly with 0.13 mg/100g$_{board}$ is clearly below the value of E1 (8.0 mg/100g$_{board}$). In contrast, the MUF-bonded plywood exceeds booth thresholds marginally. The gas analysis value is 0.3 mg/100g$_{board}$ higher, and the perforator value is 0.67 mg/100g$_{board}$ higher than the limits of the standard requirements.

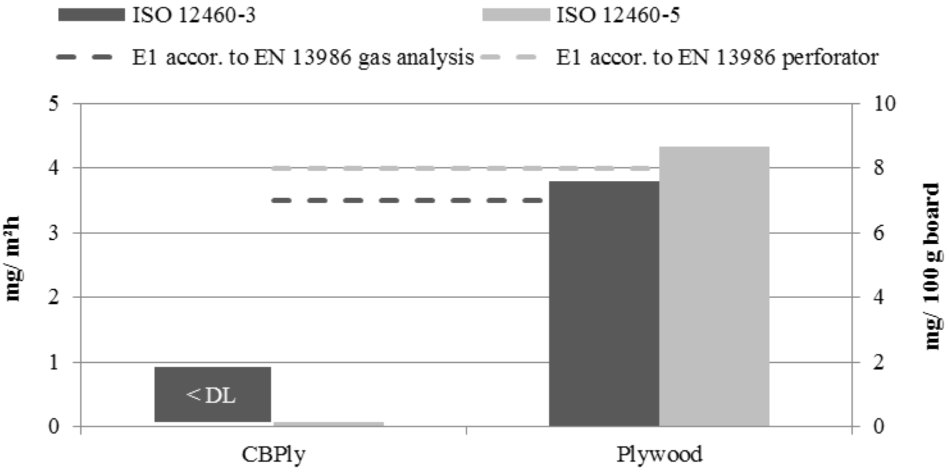

Figure 4- Formaldehyde emission and content of MUF-bonded- and cement-bonded plywood (N = 3; DL…detection limit)

Roffael (2012) measured a formaldehyde emission of 2 mg/m²h for CBPB. This value is higher than of native wood (Boehme 2000). According to Roffael (2012), monosaccharides of the wood are isomerized, reduced to products of a small C-number, and oxidized by the alkalinity of the cement. The investigated CBPly had a much lower cement-wood ratio of 0.6 than CBPB (cement-wood = 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 flame-resistant, which corresponds to the European fire performance class (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 flame-resistant plywood without adding extra flame retardants.

The flammability was examined with the cone calorimeter method according to ISO 5660-1 by a heat flux of 50 $kW{\cdot}m^{-2}$. Three samples (100 mm x 100 mm x thickness) of five and seven layer MUF-bonded (reference 1) and cement-bonded plywood (board thickness: 9 mm and 12 mm, respectively 11 and 15 mm) and an industrial CBPB (reference 2) of 18 mm thickness were tested.

Figure 4 shows the thermal heat release (THR) as a function of time, depending on the number of layers. As expected, CBPB has the lowest THR. The wood particles are completely covered by cement. That protects the wood from burning. Only when the concentration of volatile extractives reaches a critical value, the combustion starts and releases heat of combustion. In the charts of figure 5, the maximum heat release of the first 300 sec of CBPly is below that of plywood. The maximum heat releases for CBPly and plywood are rarely influenced by the number of layers. The first sharp peak of the heat release is primarily due to the combustion of the veneers. The curves of CBPly exhibit no shortened ignition time and also a large second peak. The latter is probably attributed to the destruction of char residue created by the combustion of the wood veneers.

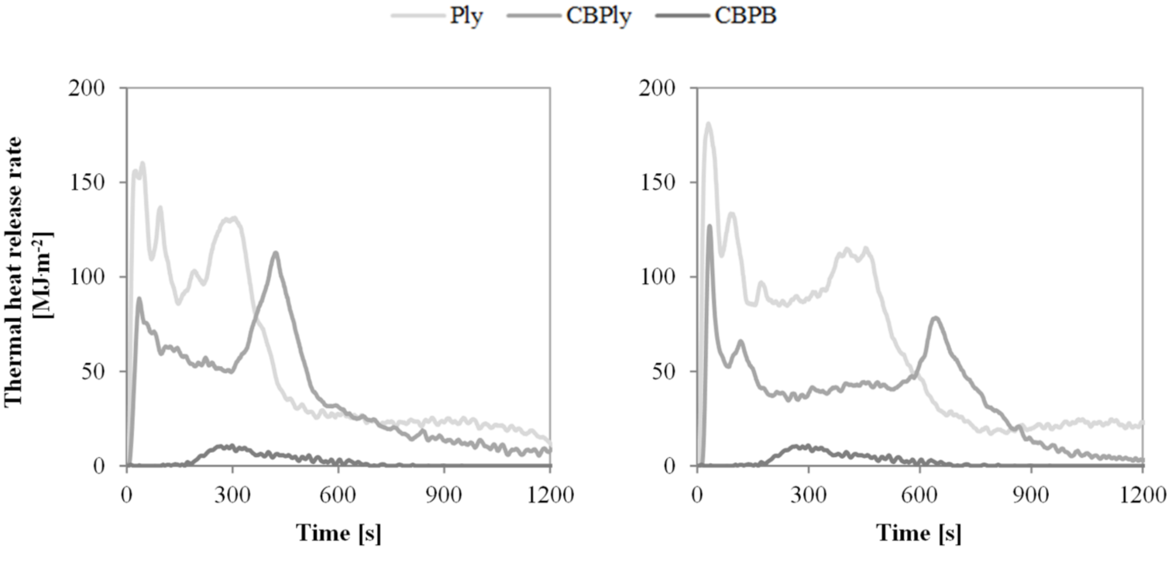

Figure 5- Thermal heat release rate of 18 mm thick CBPB, 5layer (left) and 7layer (right) MUF-bonded plywood and cement-bonded Plywood (CBPly) tested with the cone calorimeter method (N = 2)

Figure 6 shows the damage of the three different wood-based panels in case of the flammability test. From plywood, only the ash remained. In contrast, the residue of CBPly is about 30 mass-% and of CBPB 90 mass-%. The mass loss of CBPly corresponds with the mass based wood content. The wood content of the industrial CBPB is unknown, but from experience it must be in the range of 25 to 35 mass-%. In addition to the reduction of THR and total mass loss (TML), also the smoke production rate (SPR) of CBPly is lower as for plywood. CBPB showed no detectable smoke production. In contrast to cement, the most state of the art fire retardants for wood and wood-based panels cause a higher level of incomplete combustion and thereby an increase in smoke production.

Figure 6 - Specimens before (left) and after (right) cone calorimeter method of 18 mm thick CBOB (top), seven layer MUF-bonded plywood (middle) and seven layer cement-bonded plywood (bottom)

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 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 from Steen-Hansen and Kristoffersen the Euroclass was correctly predicted for 92.4 % of all the 184 cases.

To calculate the Euroclass for CBPB, CBPly and plywood according to Steen-Hansen and Kristoffersen (2007), the values of Table 1 were used.

Table 1 - Results of cone calorimeter test of MUF-bonded plywood (Ply) cement-bonded plywood (CBPly) and cement-bonded particle board CBPB (THR…total heat release, TML…total mass loss, SPR…smoke production rate)

Layer / Thickness	5		7		18 mm
Material	Ply	CBPly	Ply	CBPly	CBPB
THR [MJ·m^{-2}]	64.8	48.4	80.3	43.2	1.4
TML [%]	100.0	70.0	100.0	70.0	9.2
SPR [m^{2}·s^{-1}]	170.5	137.5	295.0	31.0	…
Density [kg·m^{-3}]	465.0	739.0	480.0	745.0	1400.00
Euroclass	D	B	D	B	B

The highest calculated value according to the equations of Steen-Hansen and Kristoffersen (2007) identifies the corresponding Euroclass of the material. Therefore, the tested plywood is classified as Euroclass D and CBPly and CBPB as Euroclass B. It must be recognized, that no calculation for Euroclass A exists. Otherwise, the very low THR and TML of the tested CBPB enable the opportunity for classification as A2. Comparing to other publications, the THR and the TML of CBPly fits very well to the investigation of Yu et al. (2016). They analyzed CBPB with different cement-wood ratios by cone calorimetry. CBPB with a very low cement-wood ratio of 0.50 (800 kg·m^{-3}) had a THR of around 52 MJ·m^{-2} and a TML of 57 %.

CONCLUSION

By laboratory production of plywood with OPC binder, the suitability of inorganic binders for bonding layers of wood to wood-based panels was demonstrated. The properties of the new wood-based panel CBPly represent a combination of the well-known materials plywood and CBPB: formaldehyde emission 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 to emission and fire resistance can be extended.

Compared to common plywood, the named advantages can be achieved without using other chemicals (e. g. flame retardants, coatings). Compared to CBPB, for the production of CBPly a significantly lower cement content is needed (30…40 %). From this it follows that on the one hand, the handling and machinability is significantly facilitated, which makes the product accessible to a larger market. On the other hand, by saving energy-intensive produced OPC, the carbon dioxide emission can be reduced.

In conclusion, a low-cost, formaldehyde-free and high flame retardant inorganic binder for plywood was developed. OPC might offer a valuable binder to be applied in the plywood manufacturing industry and could replace the formaldehyde-based adhesives.

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