Some Physico-mechanical Characteristics of Uncoated OSB ECO-products Made from Scots Pine (*Pinus sylvestris* L.) and Bonded with pMDI Resin

Mohamed Z. M. Salem,[a,b,*] Martin Böhm,[b] Přemysl Šedivka,[b] Ramadan A. Nasser,[a] Hayssam M. Ali,[c,d] Wael A. A. Abo Elgat [e]

Some mechanical and physical properties and the formaldehyde content of uncoated oriented strand boards (OSBs) that were made from Scots pine (*Pinus sylvestris* L.), manufactured with different thicknesses, and bonded with polymeric methylene di(phenyl isocyanate) (pMDI) resin were evaluated. All of the mechanical and physical properties were affected significantly by the OSB type (3 and 4) and thickness of the panels, except for the thickness swelling after 24 h and measured formaldehyde content. The measured mechanical and physical properties of the OSB panels satisfied the standard requirements. The densities of the panels ranged from 554.2 kg/m^3 to 580.2 kg/m^3 and from 573.8 kg/m^3 to 610.7 kg/m^3 for OSB/3 and OSB/4, respectively, which met the standard requirements. The measured mechanical and physical properties of the OSB/4 panels were higher than those of the OSB/3 panels, but there were no differences in the thickness swelling after 24 h and measured formaldehyde content. Low formaldehyde contents were found for OSB/3 (0.00 mg/100 g and 0.29 mg/100 g) and OSB/4 (0.18 mg/100 g and 0.47 mg/100 g).

Keywords: Formaldehyde content; OSB; pMDI; Physico-mechanical characteristics; Scots pine

*Contact information: a: Forestry and Wood Technology Department, Faculty of Agriculture (EL-Shatby), Alexandria University, Alexandria, Egypt; b: Department of Wood Products and Wood Constructions, Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Prague, Czech Republic; c: Botany and Microbiology Department, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia; d: Timber Trees Research Department, Sabahia Horticulture Research Station, Horticulture Research Institute, Agriculture Research Center, Alexandria, Egypt; e: High Institute of Tourism, Hotel Management and Restoration, Alexandria, Egypt; * Corresponding author: zidan_forest@yahoo.com*

INTRODUCTION

Oriented strand board (OSB) is a wood-based composite made from wood strands. The surface area of the strands, as well as the elements of other particulates, is not completely covered with resin. It is a commodity product that is subject to market fluctuation (Conrad *et al.* 2004). Oriented strand board has been designed and developed to be more stable (Barbuta *et al.* 2012) and have a high bending modulus of elasticity in the parallel direction, close to that of Baltic birch plywood (BBP) in its strongest direction (Barbuta *et al.* 2011). Oriented strand board has been used to manufacture engineered wood flooring prototypes (Barbuta *et al.* 2012). More information about the technological development of OSB in North America and China are listed in the review article written by Jin *et al.* (2016).

Several resins, such as urea formaldehyde (UF), melamine-urea formaldehyde, polyvinyl acetate (PVA), phenol formaldehyde (PF), polyurethane (PUR), and emulsion polymer isocyanate, have been used to manufacture wood-based panels (Risholm-Sundman and Wallin 1999; Blanchet *et al*. 2003; Blanchet 2008; Salem *et al.* 2011a,b; Böhm *et al.* 2012; Salem *et al.* 2012a,b, 2013a,b). Of these resins, polymeric methylene di(phenyl isocyanate) (pMDI) was used in Germany for the first time in the early 1970s to manufacture particleboards. Since then, it has been widely used for the production of fiberboards and OSB in Europe and used by a few medium-density fiberboard mills in North America (Papadopoulos *et al.* 2002). The pMDI resin penetrates deeper into wood cell walls than PF resins used to manufacture OSB (Johnson and Kamke 1994; Frazier and Schmidt 1996; Kamke and Lee 2007), which is related to the low molecular weight of pMDI, as well as the low surface tension. Additionally, Frazier (2003) observed interpenetrating networks of polyurea, as well as biuret linkages, which were found within the cell walls. In wooden buildings, pMDI as a resin for wood-based panels is often used as an alternative to formaldehyde-based resins to reduce the formaldehyde emissions and exposure risks to workers during the production of composite wood-based products (Allport *et al*. 2003; Vangronsveld *et al.* 2010). Compared with UF (62.4% solids) at 7, 10, and 13%, pMDI (100% solids) at 2, 4, and 6% not only results in superior board properties, but the amount required is considerably reduced as well (Papadopoulos 2006). The penetration and performance of pMDI wood binders on selected wood species has also been studied (Zheng *et al.* 2004; Gruver and Brown 2006; Das *et al.* 2007).

The resin pMDI has been used extensively to manufacture OSB panels from aspen strands with a mixed PF and pMDI resin system (Brochmann *et al.* 2004), rubberwood (Malanit and Laemsak 2007), red maple (Paredes *et al.* 2008), a mixture of heartwood cypress (*Cupressus sempervirens*) and pine (*Pinus sylvestris*) (Makowski and Ohlmeyer 2005; Amusant *et al.* 2009; Hrázský and Král 2009; Böhm *et al.* 2011), bamboo strands (Sumardi and Suzuki 2014), and mixtures of strands (Ciobanu *et al.* 2014).

Different factors affect the formaldehyde emissions from OSB and other wood-based panels, such as the raw materials, press temperature, mat moisture content, resin treatment, resin-free formaldehyde, pressing time, and thickness of the panels (Carlson *et al.* 1995; Böhm *et al.* 2012). The perforator method (EN 120 1993) is widely used for production control in measuring the formaldehyde content (FC) in the wood-based panel industry in Europe and China, and has shown significant and positive correlations with the referenced chamber methods (Risholm-Sundman and Wallin 1999; Salem *et al.* 2011a,b, 2012a,b; Liu and Zhu 2014).

In the present work, the physico-mechanical properties of uncoated OSBs made from industrially strands of dried Scots pine (*P. sylvestris* L.), manufactured with different thicknesses, and bonded with pMDI resin were evaluated.

EXPERIMENTAL

Materials

OSB/3 and OSB/4 panels

Two types of typically industrial boards taken from continuous production of OSBs were used, OSB/3 and OSB/4, with thicknesses of 12 mm, 15 mm, 18 mm, 22 mm, and 25 mm (Table 1). The panels were manufactured from industrially manufactured strands of dried Scots pine (*P. sylvestris* L.). The strands were manufactured using a ring splitting machine, and the resulting strands were in the dimensions of 0.4 to 0.6 mm in thickness, 5 to 20 mm in width, and 60 to 150 mm in length. The strands with the long length were used for the surface layers and the small ones were used for the middle layer. The strands were distributed equally (50/50) in the middle and surface layers. The manufactured panels were cooled to ambient temperature after hot pressing and cut to the dimensions of 1250 mm x 2500 mm. The edges of the OSB were wrapped with aluminum-coated tape. The panels were conditioned at 23 °C and 50% relative humidity (RH). The industrial properties of the manufactured panels are presented in Table 2.

Table 1. Number of Samples Cut from Each Thickness for OSB/3 and OSB/4 Testing

OSB Type	Number of Samples				
	12 mm	15 mm	18 mm	22 mm	25 mm
OSB/3 ECO	13	18	11	16	7
OSB/4 ECO	6	6	16	14	3

Table 2. Properties of the OSB/3 and OSB/4 Panels

Condition	OSB/3 ECO		OSB/4 ECO	
	Surface Layer	Middle Layer	Surface Layer	Middle Layer
Raw material	Industrially strands of dried Scots pine (*P. sylvestris* L.)			
Moisture content of the strands before blending (%)	5.1	3.9	5.1	3.9
Pressing pressure (N/mm^2)	< 3		< 4	
Pressing temperature (°C)	180		190	
Adhesive quantity (kg/m^3 board, dry matter)	12 (3.5%)*		27 (3.5%)*	
Paraffin (kg/m^3 board)	2.7		10	
Paraffin emulsion (%)	1.2		-	
H_2O (l/m^3 board)	30		30	
H_2O (dosing converted to the desired moisture of strands)	6.0%	5.5%	6.0%	5.5%
Hardener	-	-	-	-
Wood material (kg/m^3 of the board, ATRO, coniferous)	535		551	
Amount of glue (pMDI percent (%))	3.1	3.5	3.1	3.5
pMDI concentration	100%		100%	
Pressing of the OSB	Dieffenbacher CPS 280-53/OSB continuous press (Dieffenbacher CZ hydraulické lisy, s.r.o., Czech Republic)			

According to EN 300 (2006), the OSB/3 and OSB/4 boards were manufactured as load-bearing boards and heavy-duty load-bearing boards for use in humid conditions, respectively.
* Percentage content of the component on the weight of strands at 0% moisture

Methods

Measurement of the physical and mechanical properties

The bending strength (modulus of rupture, MOR, N/mm^2) and modulus of elasticity (MOE, N/mm^2) in the parallel and perpendicular directions were measured (EN 310 1999) for OSB/3 and OSB/4 using a UTS 100K instrument (measuring range 5 kN to 100 kN; Dongguan ZME Instrument Trading Co., Ltd., Guangdong, China). The density (kg/m^3) and thickness swelling (TS, %) after 24 h were measured according to EN 322 (1993) and EN 317 (1993), respectively.

The tensile strength perpendicular to the surface (internal bond strength) was measured according to EN 319 (1993). After the 50 mm x 50 mm specimens were conditioned at 65% RH and 23 °C for 48 h (EN 319 1993) and boiled (EN 1087-1 1995), the measured internal bond (IB, N/mm^2) was calculated.

Measurement of the formaldehyde content

The manufactured OSB panels were first conditioned for 4 weeks at 20 °C and 65% RH. The FC (mg/100 g o.d board) was then measured with the perforator method (EN 120 1993). Samples of 110 g with the dimensions 25 mm × 25 mm from each type and thickness were used and subsequently extracted with boiling toluene (600 mL) for 2 h in the perforator apparatus (Soxhlet extractor, WENK LabTec GmbH, Germany). The released FC was measured according to the acetylacetone method (Nash 1953). All of the FC values were corrected by normalizing the moisture content to 6.5% (EN 312 2003).

Statistical analysis

The physical and mechanical properties and the corrected FC of the studied OSBs were statistically analyzed using SAS version 8.2 (SAS Institute Inc., Cary, NC, USA). An analysis of variance of completely randomized designs was applied to show the significant differences between the measured values with the Duncan’s multiple-range test at a 0.05-level of probability as affected by two factors (OSB type and thickness) and the interaction between them. The values were presented as the mean plus or minus the standard deviation.

RESULTS AND DISCUSSION

Influence of the OSB Type and Thickness on the Properties of the OSBs

Table 3 shows most of the studied parameters were significantly affected by the OSB type, thickness, and the interaction between them. The pressing factor was an exception and was not significantly affected by the interaction between the OSB type and thickness. The TS was not affected by the OSB type and thickness or the interaction between them. Additionally, the FC was not affected by the OSB type. The significant results measuring the correlation coefficient and coefficient of determination (Table 4) showed that all of the studied parameters were significantly affected, except for the TS and FC.

Table 3. Significant Effects of the OSB Type, Thickness, and Interaction on the Selected Measured Properties

SOV	P-value									
	Pressing Factor	Density	MOR (=)	MOR (II)	MOE (=)	MOE (II)	IB	IB after Boil Test	TS	CFC
OSB Type (A)	***	***	***	***	***	****	***	**	ns	*
Thickness (B)	***	***	***	***	***	**	***	***	ns	ns
A*B	ns	***	***	***	***	**	***	**	ns	ns

SOV: source of variance; IB: internal bond; TS: thickness swelling; CFC: corrected formaldehyde content; =: parallel; II - perpendicular

*: significant, **: highly significant, ***: extremely highly significant, ns: not significant

Table 4. Correlation Coefficient (R) and Coefficient of Determination (R^2) of the Studied OSB Parameters

Parameter	Multiple-R	Multiple-R²	Adjusted-R²	*p*
Pressing factor (s/mm)	0.63	0.40	0.35	***
Density (kg/m³)	0.68	0.46	0.41	***
MOR = (N/mm²)	0.71	0.51	0.46	***
MOR II (N/mm²)	0.72	0.51	0.47	***
MOE = (N/mm²)	0.61	0.37	0.31	***
MOE II (N/mm²)	0.53	0.28	0.22	***
IB (N/mm²)	0.68	0.47	0.42	***
IB after boil (N/mm²)	0.48	0.23	0.16	***
TS	0.28	0.08	-0.01	ns
Corrected FC (mg/100 g)	0.35	0.12	0.05	ns

ns: not significant

Physical and Mechanical Properties of the OSBs

For OSB/3 and OSB/4, the values of the pressing factor ranged from 6.38 s/mm to 7.24 s/mm and from 7.26 s/mm to 9.07 s/mm, respectively (Fig. 1A). The panel densities were between 554.2 kg/m^3 and 580.2 kg/m^3 and between 573.8 kg/m^3 and 610.7 kg/m^3 for OSB/3 and OSB/4, respectively (Fig. 1B). These values fill in the range of the densities (260 kg/m^3 to 650 kg/m^3) of OSBs made from strands of pine wood (*P. sylvestris*) (Mirski and Dziurka 2015), and glued using a 3% loading of pMDI.

Table 5. Minimum Requirements for the Physical and Mechanical Properties of the OSBs

Standard	Density (kg/m³)	MOR = (N/mm²)	MOR II (N/mm²)	MOE = (N/mm²)	MOE II (N/mm²)	IB (N/mm²)	IB after Boil Test (N/mm²)	MC (%)
EN 300 (2006)	±15%	22	11	3500	1400	0.34	0.15	2-12

IB: internal bond

There were differences in the MOE and MOR values along the parallel and perpendicular directions (Table 5). The MOR of OSB/3 ranged from 19.11 N/mm^2 to 22.88 N/mm^2 (parallel, Fig. 2A) and from 10.04 N/mm^2 to 12.03 N/mm^2 (II, Fig. 2B). For OSB/4, the values of the MOR were between 22.27 N/mm^2 and 29.60 N/mm^2 (=, Fig. 2A) and between 12.07 N/mm^2 and 15.48 N/mm^2 (II, Fig. 2B). The lower values of the MOR and MOE were found in the perpendicular direction, which is the minor axis (Ciobanu *et al.* 2014). The average MOE values of OSB/3 ranged from 4515.4 N/mm^2 to 4795.6 N/mm^2 (=, Fig. 3A) and from 1981.9 N/mm^2 to 2124.1 N/mm^2 (II, Fig. 3B). For OSB/4, the values of the MOE ranged between 4694.9 N/mm^2 and 5779.0 N/mm^2 (=, Fig. 3A) and between 2075.0 N/mm^2 and 2487.3 N/mm^2 (II, Fig. 3B). For OSB/3 bonded with pMDI, these results were in agreement with those from Hrázský and Král (2009), who found that the MOR (=) ranged from 21.33 to 25.44 N/mm^2 and from 13.30 to 16.47 N/mm^2 (II), and MOE with 4278 to 5102 N/mm^2 (=), and 2095 to 2399 N/mm^2 (II), and Böhm *et al.* (2011) who found that MOE measured 762 to 4836 N/mm^2 (=) and 2007 to 2076 N/mm^2 (II).

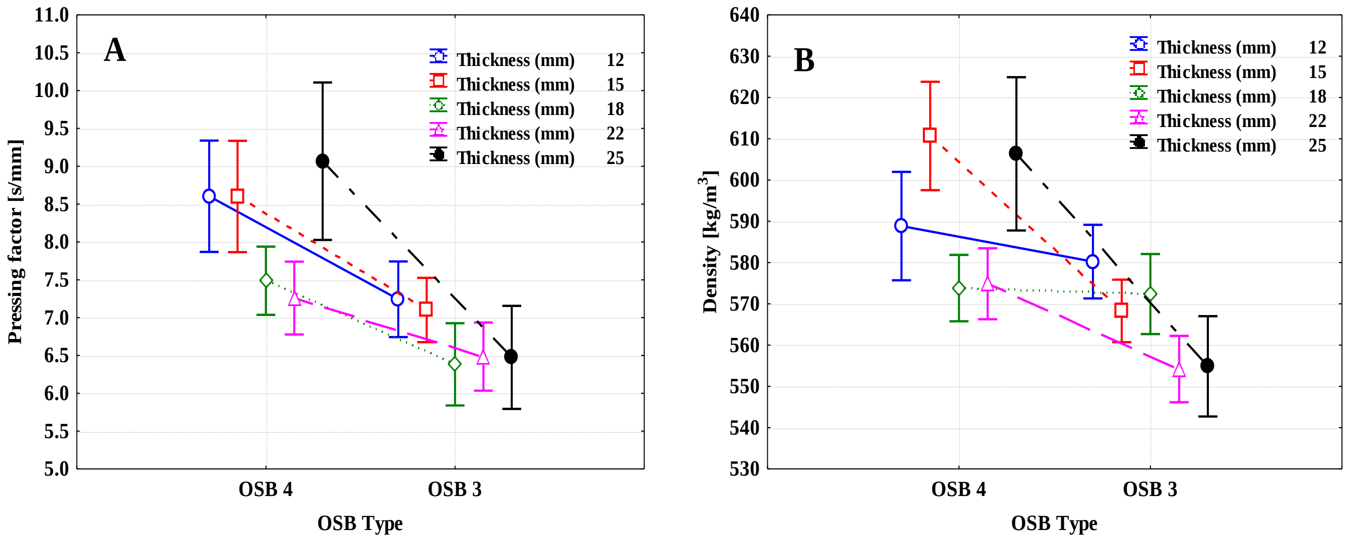

Fig. 1. Effect of the OSB type and thickness on the (A) pressing factor and (B) density of the boards

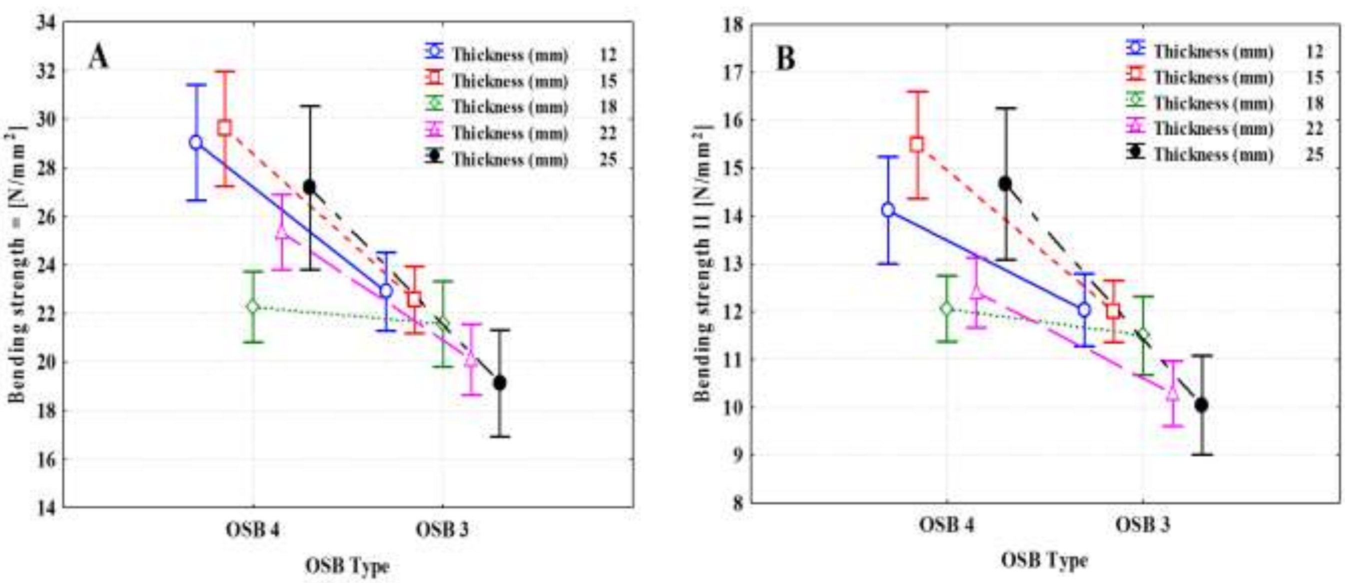

Fig. 2. Effect of the OSB type and thickness on the MOR in parallel (A) and perpendicular (B) directions

Also the present results are consistent with those of Ciobanu *et al.* (2014), who found that the MOR ranged from 22.8 N/mm^2 to 26.8 N/mm^2 and from 12.1 N/mm^2 to 15.4 N/mm^2 parallel and perpendicular to the length axes, respectively, for the OSB/3 board made from a mixture of strands. For the same boards, the MOE ranged from 3934 N/mm^2 to 4769 N/mm^2 and from 1667 N/mm^2 to 2186 N/mm^2 parallel and perpendicular to the length axes, respectively. The MOE and MOR values of the OSB bonded with pMDI resin were found to be 3916.2 N/mm^2 and 25.117 N/mm^2 for the commercial OSB panel, and 7018.9 N/mm^2 and 42.5 N/mm^2 for the OSB from red maple, respectively (Paredes *et al.* 2008). Also, the average values of the MOE and MOR were found to be 2401 N/mm^2 and 22.03 N/mm^2, respectively, for the *P. euroamericana* strands made with PF resin (Cavdar *et al.* 2008).

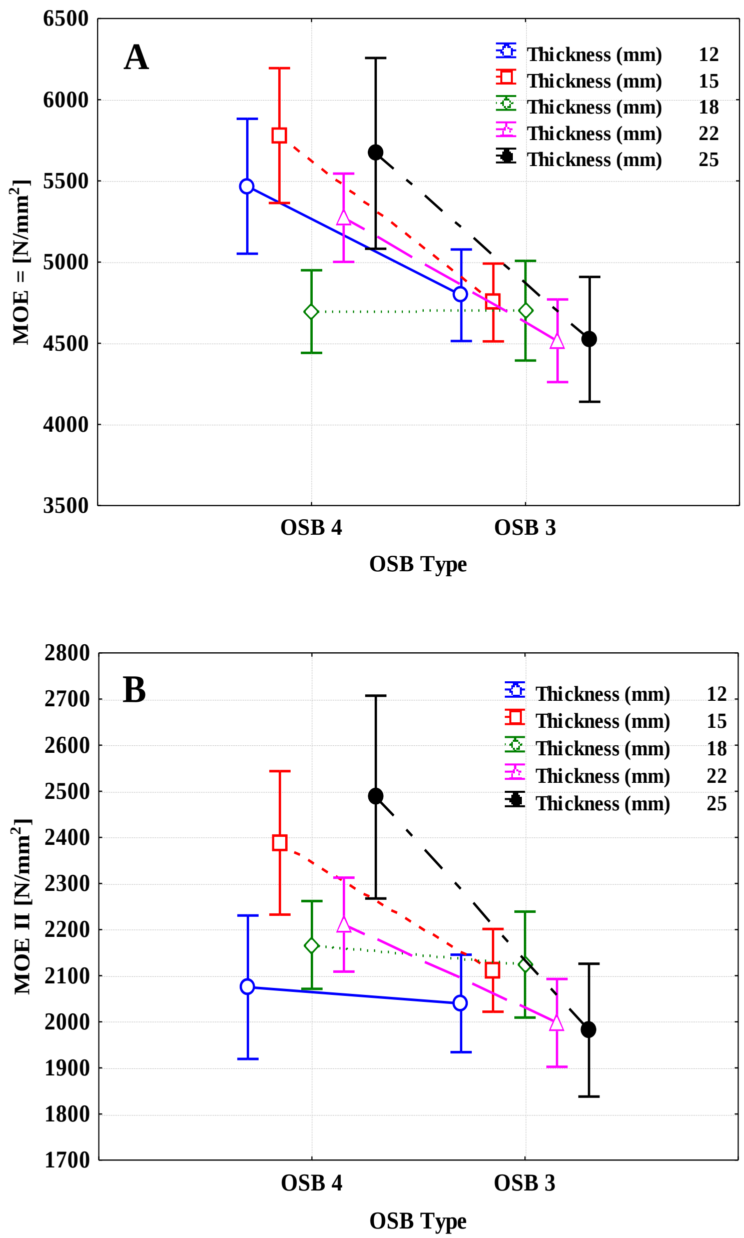

Fig. 3. Effect of the OSB type and thickness on the MOE in parallel (A) and perpendicular (B) directions

After conditioning the panels, the IB strength values of the studied OSB/3 ranged from 0.32 N/mm^2 to 0.37 N/mm^2, which were slightly above the minimum requirements for OSB/3 (0.34 N/mm^2) according to EN 300 (2006). For OSB/4, the IB values ranged from 0.36 N/mm^2 to 0.48 N/mm^2 (Fig. 4A), which were slightly lower than the values stipulated by the standard (0.45 N/mm^2 for boards > 10 mm to 18 mm, and 0.4 N/mm^2 for boards > 18 mm to 25 mm). For OSB 3 it required as follows: (0.34 MPa for boards 6-10 mm, 0.32 for > 10 mm to <18 mm, 0.30 MPa for 18 to 25 mm, and 0.29 MPa for boards > 25 mm to 32 mm).

After the boil test, the values were decreased and ranged from 0.13 N/mm^2 to 0.14 N/mm^2 for OSB/3 and from 0.13 N/mm^2 to 0.16 N/mm^2 for OSB/4 (Fig. 4B), which was within the range of values required by the standard (0.15 N/mm^2 for boards > 10 mm to 18 mm, and 0.13 N/mm^2 for boards > 18 mm to 25 mm).

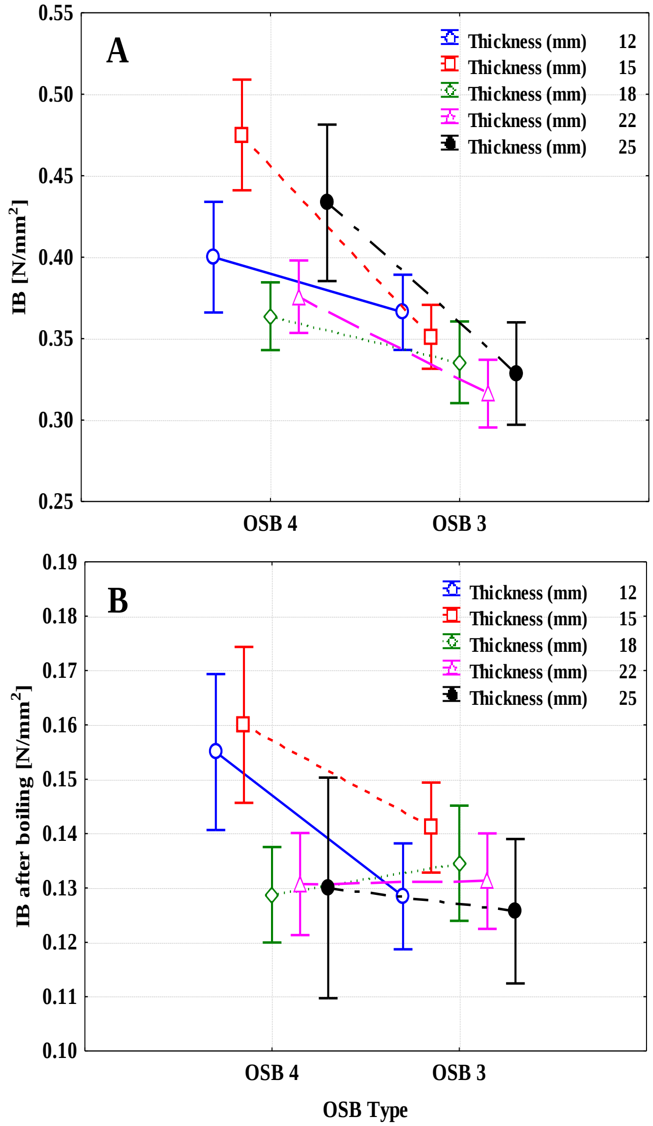

Fig. 4. Effect of the OSB type and thickness on the IB strength (A) after conditioning at 65% RH and 23 °C for 48 h, and (B) after the boil test

Paredes *et al.* (2008) found that in dry conditions, the IB values of the OSB bonded with pMDI resin were 0.627 N/mm^2 for commercial OSB and 0.806 N/mm^2 for OSB made from red maple. However, in wet conditions, the IB values were 0.16 N/mm^2 and 0.24 N/mm^2 for the commercial and red maple OSBs, respectively, for boards with thicknesses of 0.025 inches, 0.035 inches, and 0.045 inches. The IB ranged from 0.39 N/mm^2 to 0.43 N/mm^2 and decreased to the range of 0.13 N/mm^2 to 0.18 N/mm^2 after the boil test for boards with 10 mm thick (Ciobanu *et al.* 2014). Additionally, pretreating the strand with hot water extraction decreased the IB to 0.103 N/mm^2. For the OSB (1.8 cm thick) made from *P. euroamericana* strands and glued with PF, the average IB value was 0.55 N/mm^2 (Cavdar *et al.* 2008).

The OSB boards with *Pinus* sp. and castor oil-based PU resin was found to have average MOE (parallel), MOR (parallel), and IB values of 8126 MPa, 56.5 MPa, and 1.55 MPa, respectively. These values were higher than those obtained for the OSB/4 boards with 10 mm thickness (de Souza *et al.* 2014). Other studies have reported MOR and MOE values of 57.50 MPa and 8061.18 MPa along the parallel direction, and 20.82 MPa and 2022.31 MPa along the perpendicular direction, respectively, with a TS of 23.6% and IB of 0.61 MPa for OSB panels of 15.7 mm thickness made from *P. taeda* and bonded with PF (Mendes *et al.* 2013). Also, the values of the IB, MOR (parallel), and MOE (parallel) were 0.495 MPa to 0.950 MPa, 69 MPa to 72 MPa, and 8135 MPa to 9050 MPa, respectively, for aspen/birch OSB-Ponderosa pine OSB bonded with PVA type I with thickness of 12 mm (Barbuta *et al.* 2012).

The values of the TS were between 11.85% and 13.34% for OSB/3 and between 11.39% and 12.70% for OSB/4 (Fig. 5). These values were below the maximum values required by the standard (15% for OSB/3 and 12% for OSB/4). Other studies have reported that the values of the TS were 14.0% and 11.6% for commercial OSB and OSB made from red maple strands, respectively (Paredes *et al.* 2008), and 12.99% for OSB made from *P. euroamericana* strands (Cavdar *et al.* 2008). The TS ranged from 2.63% to 7.60% for OSB made from bamboo strands and bonded with pMDI (Sumardi and Suzuki 2014). Ciobanu *et al.* (2014) reported that the TS ranged from 20.23% to 22.60% for OSB/3 made from a mixture of strands with a core layer blended with pMDI.

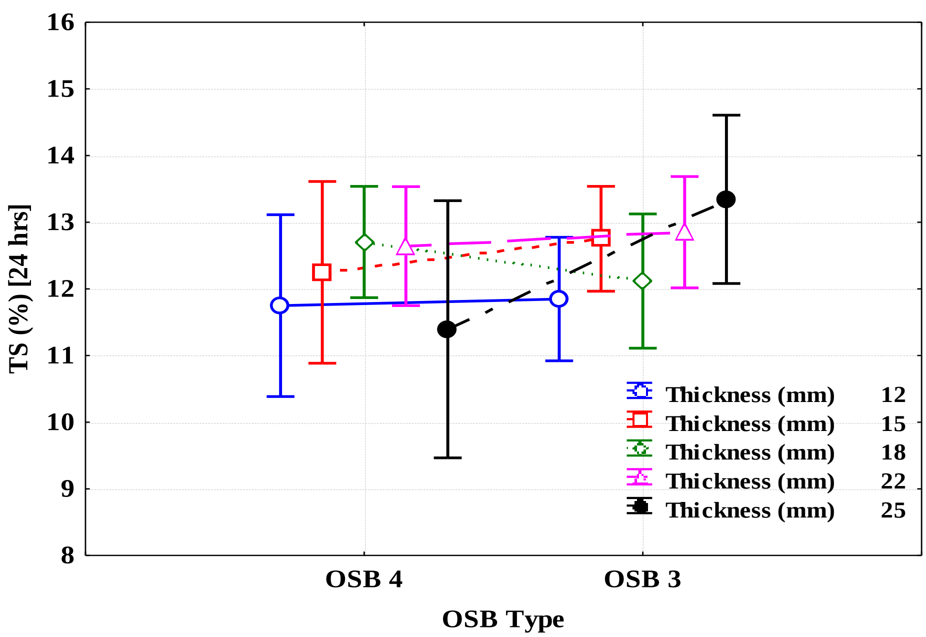

Fig. 5. Effect of the OSB type and thickness on the TS after 24 h

Formaldehyde Content

Very low FC values were measured for the studied OSBs. Figure 6 shows that the FC values of OSB/3 were up to 0.29 mg/100 g, and between 0.18 mg/100 g and 0.47 mg/100 g for OSB/4 (Fig. 6). All of the values were extremely lower than the E1 emission class, as given in EN 120 (1993) (≤ 8 mg/100 g). The authors' previous work (Böhm *et al.*

2012) showed that the formaldehyde emission from wood of *P. sylvestris* were 0.0053±0.0004 ppm and 0.016±0.002 mg/m^2 h as measured by EN 717-1 and EN 717-2, respectively. This amount is generated when the wood exposed to the manufacturing conditions of the panels, where the formaldehyde can by raised with the thermal degradation of wood polysaccharides (Roffael 1999; Schäfer and Roffael 2000; Salem and Böhm 2013).

Previously, Bartekova *et al.* (2006) reported that all of the tested uncoated isocyanate-bonded OSB/3 and OSB/4 made of Scots pine had very low volatile organic compound (VOC) emissions and met the conditions for "very low emitting materials". The resin itself had a very low level of free formaldehyde (0.2%). The main emission of formaldehyde occurred at the press stage and from the wood itself because of condensation reactions (Vangronsveld 2012).

Also, Salem *et al.* (2017) found that OSB bonded with PUR resins and made from mixed wood strands with 80% Norway spruce and 20% Scots pine had extremely low FC values, which was limited to the natural FC in the solid wood. Furthermore, the increase in the FC and VOC emissions was related to the increase in the thickness of the panels (Ohlmeyer *et al.* 2008; Salem *et al.* 2011a,b; Böhm *et al.* 2012; Salem *et al.* 2012a,b, 2013a,b, 2017).

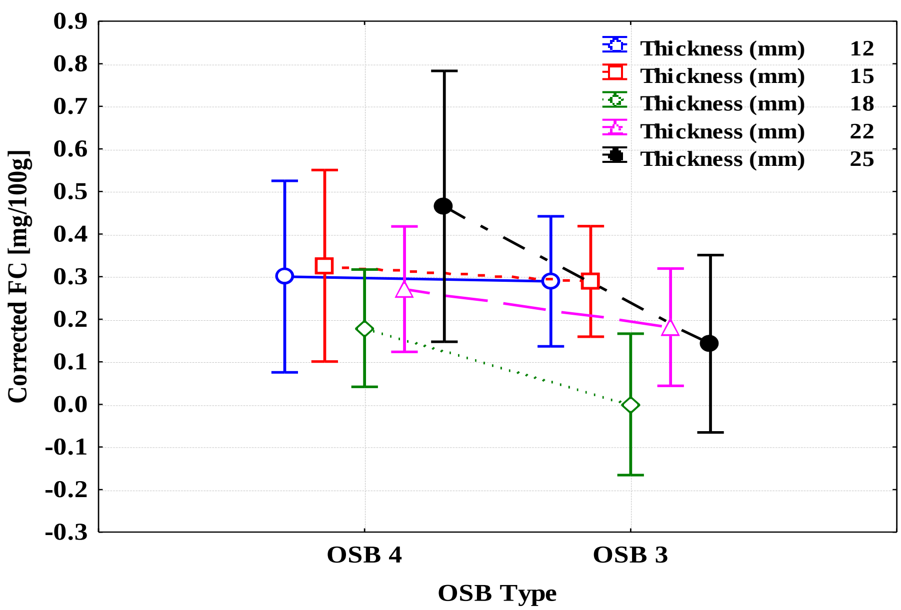

Fig. 6. Effect of the OSB type and thickness on the corrected FC (mg/100 g)

In Europe, the manufactured types of OSB/3 and OSB/4 are widely used for many purposes, *e.g.* heavy-duty load-bearing boards in humid conditions. Overall, the mechanical strength and physical characteristics of the studied panels satisfied the minimum requirements given in the standard (EN 300 2006). Formaldehyde and other VOC emissions were likely to be lower with pMDI compared with the press emissions when using other formaldehyde-based resins (Jian *et al.* 2002).

CONCLUSIONS

1. The MOR values of OSB/3 ranged from 19.11 to 22.88 N/mm^2 (=) and 10.04 to 12.03 N/mm^2 (II), while with OSB/4, it was 22.27 to 29.60 N/mm^2 (=) and 12.07 to 15.48 N/mm^2 (II). The MOE values for OSB/3 were 4515.4 to 4795.6 N/mm^2 (=) and 1981.9 to 2124.1 N/mm^2 (II), while for OSB/4, it was 4694.9 to 5779.0 N/mm^2 (=) and 2075 to 2487.3 N/mm^2 (II). These mechanical properties of the manufactured OSB panels were satisfied the standard requirements.
2. The density ranged between 554.2 kg/m^3 and 580.2 kg/m^3 and between 573.8 kg/m^3 and 610.7 kg/m^3 for OSB/3 and OSB/4, respectively, which met the requirements of EN 300 (2006).
3. The measured mechanical and physical properties of the OSB/4 panels were higher than those of the OSB/3 panels, but there were no differences in the TS after 24 h and FC.
4. Lower values for the MOR and MOE were found in the perpendicular direction.
5. The measured FC of the OSB/3 was up to 0.29 mg/100 g, and between 0.18 mg/100 g and 0.47 mg/100 g for OSB/4. These values were extremely lower than the E1 emission class given in EN 120 (1993) (≤ 8 mg/100 g).

ACKNOWLEDGMENTS

This research was supported by the Czech Ministry of Agriculture – National Agency for Agricultural Research, Project No. Q J1530032.

REFERENCES CITED

Allport, D. C., Gilbert, D. S., and Outterside, S. M. (2003). "The environment" in: *MDI and TDI: Safety, Health and the Environment: A Source Book and Practical Guide*, J. Wiley & Sons, New York City, NY, pp. 229-272.

Amusant, N., Arnould, O., Pizzi, A., Depres, A., Mansouris, R. H., Bardet, S., and Baudassé, C. (2009). "Biological properties of an OSB eco-product manufactured from a mixture of durable and non durable species and natural resins," *Eur. J. Wood Wood Prod.* 67(4), 439-447. DOI: 10.1007/s00107-009-0335-z

Barbuta, C., Blanchet, P., Cloutier, A., Yadama, V., and Lowell, E. (2012). "OSB as substrate for engineered wood flooring," *Eur. J. Wood Wood Prod.* 70(1-3), 37-43. DOI: 10.1007/s00107-010-0494-y

Barbuta, C., Cloutier, A., Blanchet, P., Yadama, C., and Lowell, E. (2011). "Tailor made OSB for special application," *Eur. J. Wood Wood Prod.* 69(4), 511-519. DOI: 10.1007/s00107-010-0477-z

Bartekova, A., Lungu, C., Shmulsky, R., Huelman, P., and Park, J. Y. (2006). "Laboratory evaluation of volatile organic compounds emissions from coated and uncoated oriented strandboard," *Forest Prod. J.* 56(2), 85-90.

Blanchet, P. (2008). "Contribution of engineered wood flooring components to its hygromechanical behavior," *Forest Prod. J.* 58(7-8), 19-23.

Blanchet, P., Beauregard, R., Erb, A., and Lefebvre, M. (2003). "Comparative study of four adhesives used as binder in engineered wood parquet flooring," *Forest Prod. J.* 53(1), 89-93.

Böhm, M., Salem, M. Z. M., and Srba, J. (2012). "Formaldehyde emission monitoring from a variety of solid wood, plywood, blockboard and flooring products manufactured for building and furnishing materials," *J. Hazard. Mater.* 221-222, 68-79. DOI: 10.1016/j.jhazmat.2012.04.013

Böhm, M., Šedivka, P., Bomba, J., and Reisner, J. (2011). "Strength characteristics of OSB in bending – Difference between upper and lower panel faces," *Drvna Ind.* 62(2), 123-127. DOI: 10.5552/drind.2011.1036

Brochmann, J., Edwardson, C., and Shmulsky, R. (2004). "Influence of resin type and flake thickness on properties of OSB," *Forest Prod. J.* 54(3), 51-55.

Carlson, F. E., Phillips, E. K., Tenhaeff, S. C., and Detlefsen, W. D. (1995). "A study of formaldehyde and other organic emissions from pressing of laboratory oriented strandboard," *Forest Prod. J.* 45(3), 71-77.

Cavdar, A. D., Kalaycioglu, H., and Hiziroglu, S. (2008). "Some of the properties of oriented strandboard manufactured using kraft lignin phenolic resin," *J. Mater. Process. Tech.* 202(1-3), 559-563. DOI: 10.1016/j.jmatprotec.2007.10.039

Ciobanu, V. D., Zeleniuc, O., Dumitrascu, A. E., Lepadatescu, B., and Iancu, B. (2014). "The influence of speed and press factor on oriented strand board performance in continuous press," *BioResources* 9(4), 6805-6816. DOI: 10.15376/biores.9.4.6805-6816

Conrad, M. P. C., Smith, G. D., and Fernlund, G. (2004). "Fracture of wood composites and wood-adhesive joints: A comparative review," *Wood Fiber Sci.* 36(1), 26-39.

Das, S., Malmberg, M. J., and Frazier, C. E. (2007). "Cure chemistry of wood/polymeric isocyanate (PMDI) bonds: Effect of wood species," *Int. J. Adhes. Adhes.* 27(3), 250-257. DOI: 10.1016/j.ijadhadh.2006.05.002

de Souza, A. M., Varanda, L. D., de Macedo, L. B., de Almeida, D. H., da Silva Bertolini, M., Christoforo, A. L., and Lahr, F. A. R. (2014). "Mechanical properties of OSB wood composites with resin derived from a renewable natural resource," *International Journal of Composite Materials* 4(3), 157-161. DOI: 10.5923/j.cmaterials.20140403.01

EN 120 (1993). "Wood-based panels - Determination of formaldehyde content - Extraction method called perforator method," European Committee for Standardization, Brussels, Belgium.

EN 300 (2006). "Oriented strand boards (OSB) - Definitions, classification and specifications," European Committee for Standardization, Brussels, Belgium.

EN 310 (1999). "Wood based panels - Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels, Belgium.

EN 312 (2003). "Particleboard - Specifications," European Committee for Standardization, Brussels, Belgium.

EN 317 (1993). "Particleboards and fibreboards – Determination of swelling in thickness after immersion in water

EN 319 (1993) "Particleboards and fibreboards - Determination of tensile strength perpendicular to the plane of the board," European Committee for Standardization, Brussels, Belgium.

EN 322 (1993). "Wood-based panels - Determination of moisture content," European Committee for Standardization, Brussels, Belgium.
EN 1087-1 (1995). "Particle boards - Determination of moisture resistance - Boil test," European Committee for Standardization, Brussels, Belgium.
Frazier, C. E. (2003). "Isocyanate wood binders," in: *Handbook of Adhesive Technology, 2nd ed.*, A. Pizzi and K. L. Mittal (eds.), Marcel Decker, New York City, NY.
Frazier, C. E. R., and Schmidt, J. N. I. (1996). "Towards a molecular understanding of wood-isocyanate adhesive bondline," in: *Proceedings of the 3rd Pacific Rim Bio-based Composite Symposium*, Kyoto, Japan, pp. 383–391.
Gruver, T. M., and Brown, N. R. (2006). "Penetration and performance of isocyanate wood binders on selected wood species," *BioResources* 1(2), 233-247. DOI: 10.15376/biores.1.2.233-247
Hrázský, J., and Král, P. (2009). "Determination of relationships between density, amount of glue and mechanical properties of OSB," *Drvna Ind.* 60(1), 7-14.
Jian, T., Gardner, D. J., and Baumann, M. G. D. (2002). "Volatile organic compound emissions arising from the hot-pressing of mixed-hardwood particleboard (composites and manufactured products)," *Forest Prod. J.* 52(11-12), 66-77.
Jin, J., Chen, S., and Wellwood, R. (2016). "Oriented strand board: Opportunities and potential products in China," *BioResources* 11(4), 10585-10603. DOI: 10.15376/biores.11.4.10585-10603
Johnson, S. E., and Kamke, F. A. (1994). "Characteristics of phenol-formaldehyde adhesive bonds in steam injection pressed flakeboard," *Wood Fiber Sci.* 26(2), 259-269.
Kamke, F. A., and Lee, J. N. (2007). "Adhesive penetration in wood - A review," *Wood Fiber Sci.* 39(2), 205-220.
Liu, Y., and Zhu, X. (2014). "Measurement of formaldehyde and VOCs emissions from wood-based panels with nanomaterial-added melamine-impregnated paper," *Constr. Build. Mater.* 66, 132-137. DOI: 10.1016/j.conbuildmat.2014.05.088
Makowski, M., and Ohlmeyer, M. (2005). "Influences on VOC emissions of wood-based panels," in: *Proceedings of the 9th European Panel Products Symposium*, Llandudno, Wales.
Malanit, P., and Laemsak, N. (2007). "Effect of strand orientation on physical and mechanical properties of rubberwood oriented strandboard," *Walailak Journal of Science & Technology* 4(2), 215-223.
Mendes, R. F., Júnior, G. B., de Almeida, N. F., Surdi, P. G., and Barbeiro, I. N. (2013). "Effects of thermal pre-treatment and variables of production on properties of OSB panels of *Pinus taeda*," *Maderas-Cienc. Tecnol.* 15(2), 141-152. DOI: 10.4067/S0718-221X2013005000012
Mirski, R., and Dziurka, D. (2015). "Low-density oriented strand boards," *BioResources* 10(4), 6388-6394. DOI: 10.15376/biores.10.4.6388-6394
Nash, T. (1953). "The colorimetric estimation of formaldehyde by means of the Hantzsch reaction," *Biochem. J.* 55(3), 416-421. DOI: 10.1042/bj0550416
Ohlmeyer, M., Makowski, M., Fried, H., Hasch, J., and Scholer, M. (2008). "Influence of panel thickness on the release of volatile organic compounds from OSB made of *Pinus sylvestris* L.," *Forest Prod. J.* 58(1-2), 65-71.
Papadopoulos, A. N. (2006). "Property comparisons and bonding efficiency of UF and PMDI bonded particleboards as affected by key process variables," *BioResources* 1(2), 201-208. DOI: 10.15376/biores.1.2.201-208

Papadopoulos, A. N., Hill, C. A. S., Traboulay, E., and Hague, J. R. B. (2002). "Isocyanate resins for particleboard: PMDI *vs.* EMDI," *Holz Roh Werkst.* 60(2), 81-83. DOI: 10.1007/s00107-001-0275-8
Paredes, J. J., Jara, R., Shaler, S. M., and van Heiningen, A. (2008). "Influence of hot water extraction on the physical and mechanical behavior of OSB," *Forest Prod. J.* 58(12), 56-62.
Risholm-Sundman, M., and Wallin, N. (1999). "Comparison of different laboratory methods for determining the formaldehyde emission from three-layer parquet floors," *Holz Roh Werkst.* 57(5), 319-324. DOI: 10.1007/s001070050351
Roffael, E. (1999). "Volatile organic compounds and formaldehyde in nature, wood and wood based panels," *Holz Roh. Werkst.* 64(2), 144-149. DOI: 10.1007/s00107-005-0061-0
Salem, M. Z. M., and Böhm, M. (2013). "Understanding of formaldehyde emissions from solid wood: An Overview," *BioResources* 8(3), 4775-4790.
Salem, M. Z. M., Böhm, M., Barcík, Š., and Beránková, J. (2011a). "Formaldehyde emission from wood-based panels bonded with different formaldehyde-based resins," *Drvna Ind.* 62(3), 177-183. DOI: 10.5552/drind.2011.1102
Salem, M. Z. M., Böhm, M., Barcík, Š., and Srba, J. (2012a). "Inter-laboratory comparison of formaldehyde emission from particleboard using ASTM D 6007-02 method," *Eur. J. Wood Wood Prod.* 70(5), 621-628. DOI: 10.1007/s00107-011-0593-4
Salem, M. Z. M., Böhm, M., Beránková, J., and Srba, J. (2011b). "Effect of some manufacturing variables on formaldehyde release from particleboard: Relationship between different test methods," *Build. Environ.* 46(10), 1946-1953. DOI: 10.1016/j.buildenv.2011.04.004
Salem, M. Z. M., Böhm, M., and Nasser, R. A. (2017). "Measuring the formaldehyde content from different types of oriented strand board manufactured with different thicknesses and glued with different resins," *Drvna Ind.* 68(2), 173-178. DOI: 10.5552/drind.2017.1640
Salem, M. Z. M., Böhm, M., and Srba, J. (2013a). "Evaluation of mechanical properties and formaldehyde emission of plywood manufactured for construction applications," *Drvna Ind.* 64(2), 87-93. DOI: 10.5552/drind.2013.1245
Salem, M. Z. M., Böhm, M., Srba, J., and Beránková, J. (2012b). "Evaluation of formaldehyde emission from different types of wood-based panels and flooring materials using different standard test methods," *Build. Environ.* 49, 86-96. DOI: 10.1016/j.buildenv.2011.09.011
Salem, M. Z. M., Zeidler, A., Böhm, M., and Srba, J. (2013b). "Norway spruce (*Picea abies* [L.] Karst.) as a bioresource: Evaluation of solid wood, particleboard, and MDF technological properties and formaldehyde emission," *BioResources* 8(1), 1199-1221. DOI: 10.15376/biores.8.1.1199-1221
Schäfer, M., and Roffael, E. (2000). "On the formaldehyde release of wood," *Holz Roh. Werkst.* 58(4), 259-264. DOI: 10.1007/s001070050422
Sumardi, I., and Suzuki, S. (2014). "Dimensional stability and mechanical properties of strandboard made from bamboo," *BioResources* 9(1), 1159-1167. DOI: 10.15376/biores.9.1.1159-1167
Vangronsveld, E., Berckmans, S., Verbinnen, K., Van Leeuw, C., and Bormans, C. (2010). "Isocyanate and total inhalable particulate air measurements in the European

wood panel industry," *Int. J. Hyg. Envir. Heal.* 213(6), 475-488. DOI: 10.1016/j.ijheh.2010.08.011

Vangronsveld, E. (2012). "Methylene diphenyl diisocyanate (MDI): EU classification; impact of reach; worker and consumer exposure - Perception *versus* facts," *International Wood Products Journal* 3(1), 58-63. DOI: 10.1179/2042645312Y.0000000013

Zheng, J., Fox, S. C., and Frazier, C. E. (2004). "Rheological, wood penetration, and fracture performance studies of PF/pMDI hybrid resins," *Forest Prod. J.* 54(10), 74-81.

Article submitted: October 29, 2017; Peer review completed: December 30, 2017; Revised version received: January 7, 2017; Accepted: January 13, 2018; Published: January 23, 2018.
DOI: 10.15376/biores.13.1.1814-1828