

Understanding of Formaldehyde Emissions from Solid Wood: An Overview

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Wood is known to contain and emit volatile organic compounds including formaldehyde. The emission of formaldehyde from wood increases during its processing to lumber and wood-based panels (*i.e.*, particleboard and fiberboard). This increased emission can be attributed to the processing procedure of wood, which includes drying, pressing, and thermo-hydrolysis. Formaldehyde is emitted from wood under very high heat and is not expected to be a significant source of the emissions from composite wood products during normal service. Formaldehyde is also detectable even if wood has never been heated as well as under more or less ambient conditions. The presence of formaldehyde in the emissions from wood that does not contain adhesive resin has been explained by thermal degradation of polysaccharides in the wood. The emission levels of formaldehyde depend on factors such as wood species, moisture content, outside temperature, and time of storage. Additionally, the pyrolysis of milled wood lignin at 450 °C yields benzaldehyde, and the pyrolysis of spruce and pinewood at 450 °C generate formaldehyde, acetaldehyde, 2-propenal, butanal, and butanone, which can be attributed to the breakdown of the polysaccharide fraction of the wood.

Keywords: Formaldehyde emission; Solid wood

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INTRODUCTION

The European Union, the USA, China, and Japan now have legislation regulating the allowed levels of formaldehyde emission (FE) from wood and wood-based products, and without doubt there will be increased focus and controls placed on products that are known to release formaldehyde (Salthammer *et al.* 2010). The main sources of FE from wood-based products such as medium density fiberboard (MDF), particleboard (PB), and plywood are the resins used, such as urea-formaldehyde (UF), melamine-modified urea formaldehyde (MUF), and phenol-formaldehyde (PF) (Salem *et al.* 2011a). Solid wood grown in normal forest conditions releases low levels of formaldehyde, particularly during the manufacturing process (Salem *et al.* 2012a). Furthermore, PF resins are frequently used in the manufacture of cork products. For this reason, formaldehyde and phenol are often measured together (Horn *et al.* 1998).

Formaldehyde has been classified as a known carcinogen by the State of California, Proposition 65 (2008) and the International Agency for Research on Cancer (IARC), a division of the World Health Organization (WHO) (IARC 2004). The National Institute of Health's National Toxicology Program (NTP) states that formaldehyde is

reasonably anticipated to be a human carcinogen (1998). The IARC has recently established that formaldehyde is undetectable by smell at concentrations of less than 0.1 ppm. At concentrations between 0.1 ppm and 0.5 ppm, formaldehyde is detectable by smell, with some sensitive individuals experiencing slight irritation to the eyes, nose, and throat. At levels from 0.5 to 1.0 ppm, formaldehyde produces irritation of the eyes, nose, and throat in most people, while at concentrations above 1.0 ppm, exposure to formaldehyde produces extreme discomfort (IARC 2004). Formaldehyde can cause contact dermatitis, associated with an allergic reaction to the chemical (Isaksson *et al.* 1999).

Formaldehyde is a naturally occurring chemical in wood, as wood contains a diminutive, but still detectable amount of free formaldehyde. Formaldehyde can be formed from the main components of wood (cellulose, hemicelluloses, and lignin) as well as from its extractives (Schäfer and Roffael 2000) to different extents depending on the boundary conditions (pH value, temperature). On the other hand, the inorganic substances in wood do not directly contribute to formaldehyde release.

The FE from solid wood increases at elevated temperatures and prolonged heating times (Schäfer and Roffael 2000), even in the absence of wood resin (Jiang *et al.* 2002). On the other hand, the degree of polymerization of cellulose seems to have no significant influence on the emission of formaldehyde; also, raising the temperature to 100 and 150 °C, the formaldehyde liberation from starch is also very low even at high reaction temperatures (Schäfer and Roffael 2000).

The emission of formaldehyde from wood is produced during hot-pressing of composite panels, and it is generally accepted that FE from the wood itself is an insignificant contributor to the total measurable level of FE in a composite wood product (Birkeland *et al.* 2010). The present article review is focused on the emission of formaldehyde from different wood species as reported in the literature. Additionally, some attention has been given to the test methods used.

Test Methods for Formaldehyde Emission

Some common methods used for the determination of FE from solid wood include the European small chamber method (EN 717-1 2004), gas analysis (EN 717-2 1994), the perforator method (EN 120 1993), the flask method (EN 717-3 1996), a desiccator (JIS A 1460 2001), and the modified National Institute of Occupational Safety and Health (NIOSH) test method 3500 (1994). The test conditions and properties of wood specimens used to measure the FE with various test methods are presented in Table 1.

The perforator method measures the total extractable content of formaldehyde present in the wood sample, while the other methods (EN 717-1, EN 717-2, and ASTM D 6007-02) measure the amount of formaldehyde emitted from the surface of the wood specimens (Xiong and Zhang 2010; Salem *et al.* 2012a). The total formaldehyde concentration measured by the perforator method cannot be all emitted at room temperature (Xiong and Zhang 2010) and cannot be taken as a good index for the pollution level of the tested wood materials. Furthermore, the products should be evaluated by intra-laboratory and inter-laboratory comparisons to overcome the problems with the emission levels of different products in different regions or countries, as mentioned by the California Air Resources Board (CARB 2010).

Table 1. The General Conditions used for some Standard Test Methods for the Determination of Formaldehyde Emission^a

Test method	EN 717-1	EN 717-2	EN 120	EN 717-3	ASTM D 6007-2	
Volume	0.225 m ³	4 L	Extractor apparatus	500 mL flask	1 m ³	
Material	Stainless steel	Glass	Glass/perforator	polyethylene bottle with bottle top	Aluminum	
Test sample	1 m ² /m ³	0.4 × 0.05 m	25 × 25 mm, (110 g)	0.025 × 0.025 m, 20 g	0.43 m ² /m ³ (for PB)	
Edge sealing	Yes	Yes	No	No	Yes	
Sample Conditioning	Temp. (°C), RH (%)	No	Varied	Not stated	Not stated	7 days at (24 ±3°C), (50±5%)
Test conditions	Temp. (°C)	23 ± 0.5	60 ± 0.5	Extraction with 600 mL toluene at 110 °C	40 °C	24 ± 3
	RH (%)	45 ± 3	≤ 3 %		100%	50 ± 5
	Air exchange (h ⁻¹)	1.0 ± 0.05	(60 ± 3)		No	2
Air velocity	0.1–0.3 m/s	1L/min	No	No	(2–5 m/s) fan speed	
Test duration	2–4 weeks	4 h	3 h	3 hours	Until steady-state	
Results	E1 ≤ 0.1 ppm or 0.124 mg/m ³	E1 ≤ 3.5 mg/m ² .h	E1 ≤ 8 mg/100 g o.d.	No official limit values published	CARB–Phase 1 and 2 (see Table 3)	

a: From Salem *et al.* (2012a) and Risholm-Sundman *et al.* (2007)

When increasing the temperature from 25.2 to 50.6 °C, the initial emittable formaldehyde from dry building materials was increased significantly, by about 507% (Xiong and Zhang 2010). This means that most of the formaldehyde in building materials cannot be emitted at room temperature; the EN 120 uses temperatures around 110 °C, and the EN 717-2 method uses temperatures of 60 °C (Salem *et al.* 2012a). Wiglusz *et al.* (2002) reported that at 23 and 29 °C, the measurements did not show any emission of formaldehyde; at a temperature of 50 °C, a high initial concentration of FE was found and it decreased with time. The referenced chambers (EN 717-1 and ASTM D 6007-02) use conditions common to an indoor environment (Salem *et al.* 2012b; Salem 2011b; Yu and Crump 1999).

The C-history method for a closed chamber (Xiong *et al.* 2011; Yao *et al.* 2011), multi-emission/flush regression (Xiong *et al.* 2009), and room temperature sorption/emission (Wang and Zhang 2009) methods were developed to rapidly measure the initial emittable formaldehyde concentration and to overcome the overestimation of formaldehyde content (FC) with the perforator method. The developed methods take less than three days, in comparison to the reference methods, which require 7 to 28 days (Salem *et al.* 2012a; Yu and Crump 1999). The new method was validated using the characteristic

parameters determined in a closed chamber experiment to predict the observed emissions in a ventilated, full-scale chamber experiment (Xiong *et al.* 2011).

Regulations and Testing

Most European nations have passed laws that regulate formaldehyde, now known as the E1-emission class. Standards such as EN 312 (2003) and EN 622–5 (2003) all require that the 0.1-mg/m^3 h level be met. Testing for this mainly utilizes the EN 120 and EN 717–1 standard testing methods. In 2004, the EN 13986 (2005) established emission classes E1 and E2 for use in construction (the E1 level is most common). These standards basically require testing to be done on formaldehyde-containing wood products used in construction (Table 2). In 2006, these same methods and the associated limits went into effect for panel production. Because it is very difficult, if not impossible, to eliminate formaldehyde from a building completely, the Japanese standard employs a tiered rating system based on the amount of FE a building material gives off. This system is based on one-star to four-star ratings, with four stars representing the lowest amount of FE (Table 2). The two Japanese desiccator methods JIS A1460 and JAS MAFF 233 both describe determination of formaldehyde release from wood-based materials. Test pieces are placed in a desiccator containing a vessel with water. The formaldehyde released from the test pieces at 20 °C during 24 h is absorbed by the water and determined photometrically. As in the flask method, the RH is very high ((Risholm–Sundman *et al.* 2007).

Table 2. Current Formaldehyde Emission Standards for Wood–Based Panels in Europe, Australia, the U.S.A., and Japan

Country	Standard	Test method	Board class	Limit value
Europe	EN 13986	EN 717–1	E1–PB,	≤ 0.1 ppm
		EN 120	MDF, OSB	≤ 8 mg/100 g o.d. board
		EN 717–1	E1–PLW	≤ 0.1 ppm
		EN 717–2		≤ 3.5 mg/(h.m ²)
		EN 717–1	E2–PB,	> 0.1 ppm
		EN 120		MDF, OSB
EN 717–1	E2–PLW	> 0.1 ppm		
EN 717–2		$> 3.5 \leq 8.0$ mg/(h.m ²)		
Australia & New Zealand	AS/NZS 1859–1 & 2	AS/NZS 4266.16 (Desiccator)	E0–PB, MDF	≤ 0.5 mg/L
			E1–PB	≤ 1.5 mg/L
			E1–MDF	≤ 1.0 mg/L
			E2–PB, MDF	≤ 4.5 mg/L
USA	ANSI A 208.1 & 2	ASTM E1333 (large chamber)	PB	≤ 0.18 or 0.09 ppm
			MDF	≤ 0.21 or 0.11 ppm
Japan	JIS A 5908 & 5905	JIS A 1460 (Desiccator)	F**	≤ 1.5 mg/L
			F***/"E0"	≤ 0.5 mg/L
			F****/"SE0"	≤ 0.3 mg/L

PB: particleboard; MDF: medium density fiberboard; OSB: oriented strand board

F** class in Japan more or less equivalent to European E1-class

F*** and F**** are of much lower emission than the E1

F**** emission is close to the emission of solid untreated wood

In contrast to building material standards in Europe and Japan, the proposed CARB (2010) of Phase 1 and Phase 2 standards for hardwood plywood (HWPW), PB, and MDF, with effective dates between 2009 and 2012, is product-specific. Based on the use of published equations correlating the results of selected FE/FC tests (Risholm–Sundman *et al.* 2007) and results from a study to compare the metrics used in the U.S. and Europe (Groah *et al.* 1991), the relative stringency of the proposed standards has been estimated and is shown in Table 3.

Table 2 lists the equivalent U.S. large chamber test value ASTM E 1333–96 (ASTM 2002) for the European E1, Japanese F^{***} , and F^{****} standards applicable to composite wood products subject to the proposed Airborne Toxic Control Measure (ATCM 2009). Although the CARB regulation is only valid in California, many composite wood product plants around the world have already been certified to satisfy the CARB requirements, and the number of applications for certification is continuously rising. In February 2009, the American National Standards Institute (ANSI) approved revised national voluntary standards for ANSI A208.1–2009 for PB and ANSI A208.2–2009 for MDF for Interior Applications (Table 4).

FORMALDEHYDE EMISSION FROM SOLID WOODS

Wood as a Natural Material

Wood as a natural material contains formaldehyde (Meyer and Boehme 1997; Que and Furuno 2007; Salem *et al.* 2011b), which can be released during thermal treatment (Schäfer and Roffael 2000). Meyer and Boehme (1996) measured the FEs from oak, Douglas fir, beech, spruce, and pine, and the emission of formaldehyde ranged between 2 and 9 ppb. The results are presented in Table 5 as measured using a 1-m³ chamber, gas analysis, a perforator, and the flask method.

Table 3. Proposed Airborne Toxic Control Measure (ATCM) for Composite Wood Products

Standard	Product(s)	Test Method	Numerical Value	≈ ASTM E 1333 (ppm)
CARB–Phase1	HWPW	ASTM E 1333	0.08 ppm	0.08
''''	PB	''''	0.18 ppm	0.18
''''	MDF	''''	0.21 ppm	0.21
CARB–Phase2	HWPW	''''	0.05 ppm	0.05
''''	PB	''''	0.09 ppm	0.09
''''	MDF	''''	0.11 ppm	0.11
E1	HWPW	EN 717–1	0.12 mg/m ³	0.14
''''	PB,MDF	''''	0.12 mg/m ³	0.14
''''	All	EN 717–2	3.5 mg/m ² h	N/A
''''	PB,MDF	EN 120	8 mg/100 g o.d. board	0.10
F^{**}	All	JIS A1460	1.5 mg/L	N/A
F^{***}	All	''''	0.5 mg/L	0.07
F^{****}	All	''''	0.3 mg/L	0.04

The F–star standards apply to all wood products specified in the CARB standards. The “≈ E1333” values were calculated using data in ASTM E 1333–96 (ASTM 2002), Battelle (1996), Risholm–Sundman *et al.* (2007), and CARB (2007 and 2010).

Table 4. The CARB New Standards Phase 1 and Phase 2 Formaldehyde Emission for HWPW, PB, and MDF^a

Effective Date	Phase 1 (P1) and Phase 2 (P2) Emission Standards (ppm)				
	HWPW-VC	HWPW-CC	PB	MDF	Thin MDF
01.01.2009	P1: 0.08	–	P1: 0.18	P1: 0.21	P1: 0.21
01.07.2009	–	P1: 0.08	–	–	–
01.01.2010	P2: 0.05	–	–	–	–
01.01.2011	–	–	P2: 0.09	P2: 0.11	–
01.01.2012	–	–	–	–	P2: 0.13
01.07.2012	–	P2: 0.05	–	–	–

(^a) Based on the primary test method [ASTM E 1333–96 (ASTM 2002)] in ppm. HWPW-VC = veneer core; HWPW-CC= composite core

The formation of formaldehyde took place even when the wood was dried at a low temperature (30 °C), and the low drying temperature was chosen because it has been demonstrated (on wood particles) that drying under industrial conditions causes the formation of formaldehyde (Marutzky and Roffael 1977). Furthermore, the emission levels of formaldehyde depend on numerous factors such as wood species, moisture content (MC), outside temperature, and storing time (Martínez and Belanche 2000; Boehme 2000). It has been shown that an MC change from 0.0% to 4.0% results in a 6-fold increase in FE and that the release is regulated by physical processes (Irle *et al.* 2008).

Table 5. Formaldehyde Parameters from Different Species of Solid Wood^a

Wood	Moisture content	Testing in the 1-m ³ chamber		Gas analysis value	Perforator value	Flask value	
		Testing period	HCHO concentration			3 hr.	24 hr.
		(%)	(hr.)			(ppb)	(µg/m ² h)
Beech	53	360	2	114	359	2	22
	7	336	3	34	155	8	12
Douglas-fir	117	384	4	397	517	4	55
	9	240	5	82	207	6	75
Oak	63	360	9	431	597	17	80
	8	360	4	51	188	6	44
Spruce	42	384	3	133	334	2	9
	7	336	4	71	277	19	132
Pine	134	240	5	195	217	2	18
	8	360	3	86	233	16	80

a: data adopted from Meyer and Boehme (1996).

Relationship between Wood Chemical Composition and Formaldehyde Emissions

Figure 1 shows the formaldehyde release of unextracted and extracted spruce and pine chips at different temperatures using the flask method. The results reveal that extracted chips release significantly lower amounts of formaldehyde compared to unextracted chips. Moreover, pine chips emit more formaldehyde than spruce chips (Schäfer and Roffael 1999 and 2000). Additionally, the fatty acids release only minute quantities of formaldehyde compared to resin acids, and abietic acid emits much higher amounts of formaldehyde compared to saturated fatty acids. Pinewood has a higher

extractive content and an especially higher amount of resin acids (Fengel and Wegener 1984), which are relevant to the release of formaldehyde. Furthermore, Schäfer (1996) found that with increasing storage time, the spruce and pine particles emit less formaldehyde than non-stored wood. Back *et al.* (1987) reported that the composition of extractives changes during storage of wood: the content of extractives decreases and the content of free sugars, lipophilic fats, fatty and resin acids, and sterols decreases enormously.

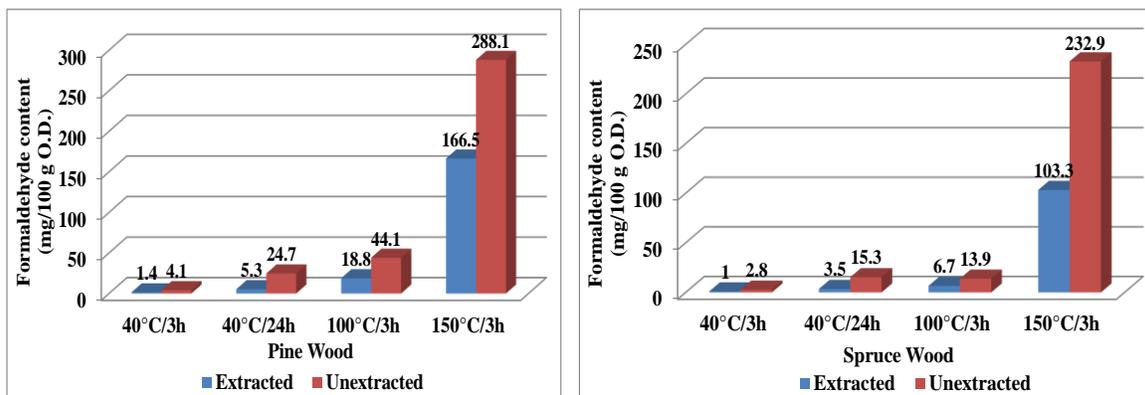


Fig. 1. The released formaldehyde from unextracted and extracted pine and spruce particles measured by the flask method (mg/1000 g O.D. wood) as affected by time and temperature. Data has been replotted from Schäfer and Roffael (1999, 2000).

Additionally, it was reported that polysaccharides and lignin are a source of FE. A pathway for the release of formaldehyde includes the transformation of polysaccharides to hexoses, oxymethylfurfural, and its subsequent disproportionation to furfural and formaldehyde (Schäfer and Roffael 2000). Fengel and Wegener (1984) reported that softwood polyoses contain higher amounts of mannose and galactose than hardwood polyoses, whereas hardwoods are rich in pentoses carrying higher amounts of acetyl groups than softwoods.

At high temperatures, Schäfer and Roffael (2000) found that arabinose and xylose release much more formaldehyde than starch and cellulose, as well as higher amounts than glucose or galactose (Fig. 2). Additionally, the hardwood lignin content lies between 20 and 25%, while softwoods contain up to 32% lignin, and it is well known that treatment of lignin with acid leads to liberation of formaldehyde (Freudenberg and Harder 1927).

Effect of Wood Drying on Formaldehyde Emissions

Wood emits formaldehyde under very high heat but is not expected to be a significant source of formaldehyde in composite wood products during normal service (Salem *et al.* 2012; Böhm *et al.* 2012). On the other hand, oak wood in the green state showed the highest FE, with 9 ppb, and beech wood had the lowest, with 2 ppb. The values for Douglas fir, spruce, and pine were between 3 and 4 ppb. In the dry state, the determined formaldehyde values were 1 to 2 units higher, except for oak. The value of 9 ppb determined in the green state for oak decreased to 4 ppb in the dry state (Meyer and Boehme 1996).

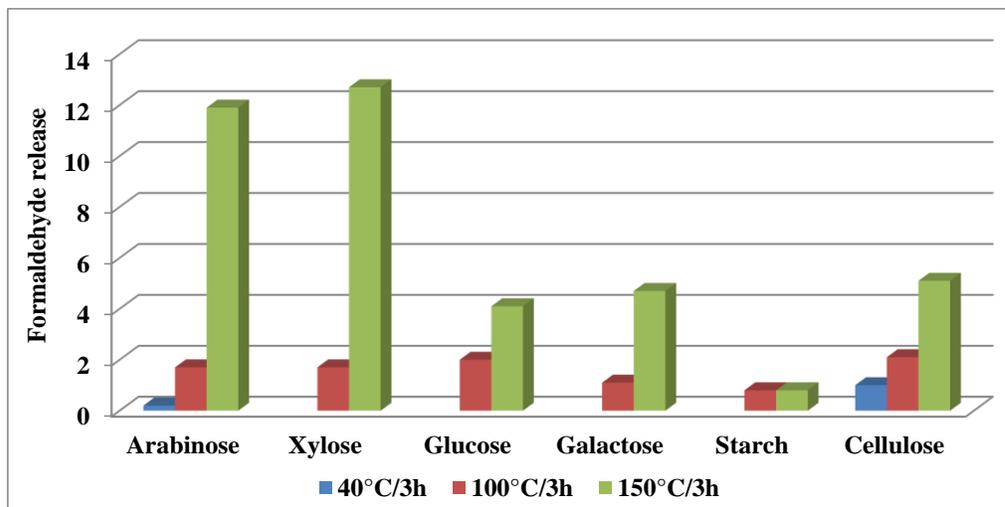


Fig. 2. Formaldehyde release from arabinose, xylose, glucose, galactose, starch, and cellulose measured by the flask method. Data has been replotted from Schäfer and Roffael (2000).

Boehme (2000) measured the formaldehyde release of different wood species in a 1-m³ chamber according to EN 717-1. The highest value was found for oak (9 ppb), and the lowest was found for beech (2 ppb). The emission of formaldehyde from pine and spruce lies in between. Figure 4 shows the formaldehyde release from undried wood in a 1-m³ chamber, as measured by Boehme (2000) at 30 °C. The emission of formaldehyde from wood increases with thermal treatment during the drying and pressing processes (Marutzky and Roffael 1977; McDonald *et al.* 2004).

Significantly, in softwoods (*e.g.*, pine and spruce), extractives affect the formaldehyde release, and the removal of extractives decreases the formaldehyde emitted from the wood by hydrothermal treatments; thermo-mechanical pulping (TMP) also enhances the released formaldehyde in wood (Schäfer and Roffael 2000).

In the study of Young (2004), the air-dried wood of all the species tested produce low emissions of formaldehyde, as seen in Fig. 3. Radiata pine has similar FE emission to the other species tested.

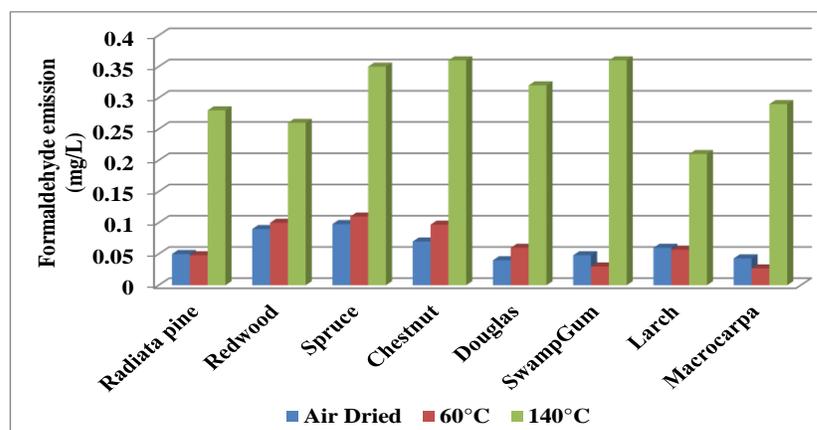


Fig. 3. Formaldehyde emission measured from air-dried wood species as affected by drying periods. On this scale, 0.30 mg/mL JAS units is the Japanese low emission limit. Data has been replotted from Young (2004).

Emission levels from solid radiata wood increase after kiln drying but decrease to low levels quite quickly after drying and stay low. FE from solid radiata pine did not prevent the application of green labeling or sales in low emission markets like Japan. The emission measured from radiata pine after treatment at 140 °C was higher than in previous trials, and the result of 0.29 mg/mL is close to the F****/SE0 level of 0.30 mg/mL, as measured by JIS A 1460 (2001). This difference is due to the shorter period from heat treatment to testing (16 compared to 20 days). FE from radiata pine was found to be similar to the seven other wood types dried under identical conditions.

Recently, Böhm *et al.* (2012) found that the rate at which individual wood species' FE differed was associated with their steady state concentrations or emission rates (Table 2). The values ranged between 0.0068 and 0.0036 ppm, as measured by EN 717-1, after a test period of 15 to 21 days, while they varied between 0.084 and 0.014 mg/m² h when measured using EN 717-2. Beech wood showed the highest FE, at 0.0068 ppm and 0.084 mg/m² h, as measured by EN 717-1 and EN 717-2, respectively, followed by spruce wood (0.0055 ppm) and pine wood (0.0053 ppm). Birch wood had the lowest amount (0.0036 ppm), as measured by EN 717-1, while poplar and oak woods (0.014 mg/m² h) had the lowest values when measured using EN 717-2. Furthermore, when the wood samples from the six species were air-dried (25 to 30 °C), formaldehyde was formed with only relatively slight differences in the values between the wood species (Table 6).

The values of FE could be affected by the anatomy of the respective wood species (Salem *et al.* 2012a, 2013). For example, Böhm *et al.* (2012) found that plywood panels produced from poplar veneer [low specific gravity (SG, 0.33)] with a simple anatomy produce lower FE values. An increase in SG (beech and birch plywood) causes more adhesive to be used to make the boards and consequently releases more formaldehyde. Moreover, Aydin *et al.* (2006) reported that the FE from poplar and spruce plywood decreased with increasing veneer moisture content. On the other hand, Nemli and Öztürk (2006) found that increasing SG, shelling ratio, and pressure increased the FC of PB. For instance, PB made from particles consisting of higher amounts of beech particles had lower FC than that of panels from particles consisting of higher amounts of pine particles.

Table 6. Formaldehyde Emission Values Measured with EN 717-1 (ppm) and EN 717-2 (mg/m² h) from Some Solid Woods^a

Wood species	Formaldehyde emission values	
	ppm [†]	mg/m ² h
Beech	0.0068	0.084
Poplar	0.0042	0.014
Birch	0.0036	0.049
Oak	0.0042	0.014
Pine	0.0053	0.016
Spruce	0.0055	0.069

a: data from Böhm *et al.* (2012)

[†] At 23°C and 1013 hPa, the following relationship exists for formaldehyde measured by EN 717-1: 1 ppm = 1.24 mg/m³ or 1 mg/m³ = 0.81 ppm.

Furthermore, the results in Fig. 4 reveal that with decreasing pine particle size, the emanation of formaldehyde increases (Roffael *et al.* 2012); also, extended reaction time (from 3 to 24 h) increased the difference in the formaldehyde release. Additionally, the hot water extractive content of the particles increased in the same direction as the FE

from the particles. These differences can be related to the increase in the surface area of the particles and its effects on decreasing the particle size. Previously, Schäfer (1996) documented that ray cells with a high content of lipophilic extractives are enriched in the fine fraction. Boruszewski *et al.* (2011) reported that FE from pine particles after cutting was higher by 25% than that from the chips prior to cutting (Fig. 5). It was difficult to compare the results with the requirements for PBs, as emission is expressed in mg/h m². However, it is possible to calculate the emission from the particles contained in a PB. When the amount of absolutely dry particles contained in PB of a given density and thickness is known, the obtained results may be recalculated to the surface of PB (EN 717-2 1994). Recalculated release of formaldehyde is shown in Fig. 5. Thus, it was found that FE from pinewood, being an equivalent of PB, was 4.6% of the whole emission permitted by EN 13986 (2005) standard for E1-class products (3.5 mg/h m²).

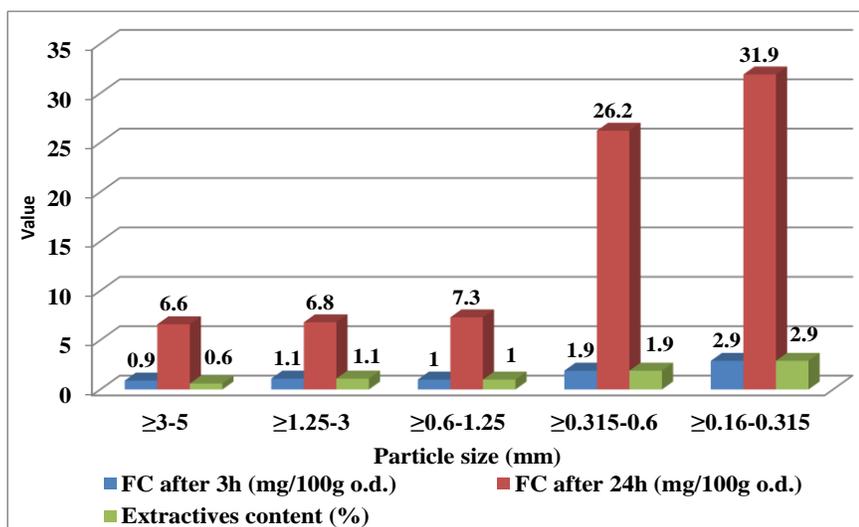


Fig. 4. Formaldehyde content from particles (pine wood) of different particle size, as measured after 3 and 24 h by the flask method and the extractives content (hot water) of pine wood of different particle size. Data has been replotted from Roffael *et al.* (2012).

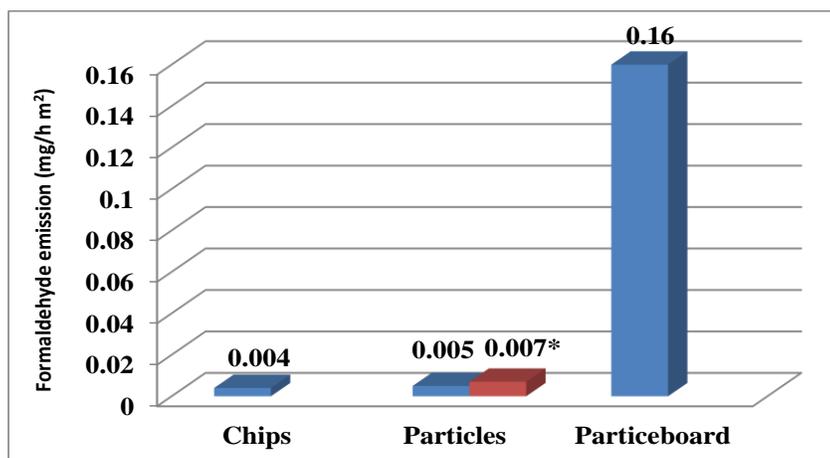


Fig. 5. Formaldehyde emission from wood at the beginning of the processing chain – with respect to 125 g of absolutely dry material (*re-calculated to particleboard of density 650 kg/m³ and thickness 16 mm) and from absolutely dry pine particles contained in particleboard of density 650 kg/m³ and thickness 16 mm. Data has been replotted from Boruszewski *et al.* (2011).

Çolak *et al.* (2009) reported that values of FE of PB produced from eucalyptus logs stored under water or indoor conditions and pressed at 150 °C were found to be 1.21 and 1.34 mg/100 g O.D. board, respectively, as measured by the EN 120 method. These values are clearly lower than those of the panels produced from steamed log parts (1.88 mg/100 g O.D. board) and the log parts stored in outdoor conditions (1.92 mg/100 g O.D. board). The FE values of the PBs pressed at 190 °C were found to be 0.72 mg/100 g O.D. board for group I (indoor conditions for 2 months), 0.98 mg/100 g O.D. board for group II (outdoor conditions for 4 months), 0.79 mg/100g O.D. board for group III (under water for 3 months), and 0.82 mg/100 g O.D. board for group IV (steaming). There were similar interactions among the FE values of the panels pressed at 190 °C and those of the panels pressed at 150 °C. However, the differences among the emission values of the panels pressed at 190 °C were lower. This may be due to the degradation and splitting of the acetyl groups at this temperature.

MECHANISM OF ALDEHYDE AND KETONE EMISSION FROM WOOD

Mechanisms that may form aldehydes and ketones in extractives and wood products include thermal, enzymatic, and microbial degradation. Research conducted on the oxidative degradation of plant material has yielded some information about how certain types of aldehydes and ketones are formed. However, these mechanisms do not account for the variety of aldehydes and ketones observed in the wood product emissions, and in some cases, the mechanisms occur under conditions that are distinctly different from wood product manufacturing conditions.

The presence of formaldehyde in emissions from wood that does not contain adhesive resin has been explained by thermal degradation of polysaccharides in the wood (Schäfer and Roffael 1996), but this does not explain findings of the presence of FE from wood that has never been heated (Meyer and Boehme 1997). In the work of Faix *et al.* (1990 and 1991), the pyrolysis of milled wood lignin at 450 °C yielded benzaldehyde, and pyrolysis of spruce and pinewood at 450 °C generated formaldehyde, acetaldehyde, 2-propenal, butanal, and butanone, a result that is attributed to the breakdown of the polysaccharide fraction of the wood. Conditions of pyrolysis are extreme and not oxidative, and during the manufacture of wood products, only wood particles for PB are likely to be exposed to such extreme conditions, and then only for a very brief time.

Enzymatic pathways for the oxidation of fatty acids to form hexanal and nonanal have been described for non-woody plants, but no such pathway has been described for other aldehydes (Hamilton-Kemp and Andersen 1986). In short, although pathways exist for some of the aldehydes and ketones that are observed in wood product emissions, there are no mechanisms for other aldehydes (for example, pentanal, heptanal, and octanal). With the exception of hexanal and nonanal, there is no explanation of how the aldehydes and ketones could be formed at room temperature or under the relatively mild conditions that are encountered in wood products manufacturing (Hatanaka *et al.* 1976).

Relationship between Formaldehyde Emission and Wood Pretreatments

Roffael *et al.* (2007) reported that the cold water extracts from pulps produced by the chemo-thermomechanical technique (CTMP process) contain higher amounts of formate and acetate ions compared to cold water extracts from pulps produced by the TMP process. The FE from CTMP is lower than that from TMP due to the Cannizzaro

reaction catalyzed by alkali. Moreover, binderless fiberboards from CTMP are significantly lower in the formaldehyde release compared to binderless boards from TMP. The use of MUF resin increases the FE of the boards from TMP and CTMP. In addition, Roffael (2008) found that FEs from binderless fiberboards using the flask method after 24 h were 58.1 and 10.5 mg/100 g O.D. fibers with TMP and CTMP, respectively.

The effects of waiting time before drying of alder (*Alnus glutinosa*) veneers on various properties of plywood, including FE, were investigated by Çolakoğlu *et al.* (2002). There were no significant differences among the FE values. It has been stated in the literature that FE of plywood is related to the presence of acetyl groups in wood (Çolakoğlu *et al.* 1998). Therefore, IR spectra were obtained to determine the effects of waiting time before the drying process of veneers on acetyl groups. Then, the absorption bands of carboxyl group ($\approx 1740/\text{cm}$) were compared. Similar spectra were obtained for each test group.

SUMMARY

1. Wood itself generates a significant amount of formaldehyde when exposed to certain conditions common to the composite panel manufacturing process that is caused by the thermal degradation of polysaccharides in the wood.
2. Relative to the formaldehyde release from wood, the chemical composition of wood is much more important than its physical or anatomical structure.
3. Formaldehyde emission from solid wood has been shown to be impermanent, and it rapidly decreases to levels below those set by the EN 717-1 and EN 717-2 standards.
4. The pyrolysis of wood generated formaldehyde, which is attributed to the breakdown of the polysaccharide fraction of the wood during the hot pressing.
5. Softwood extractives affect formaldehyde release, and the removal of extractives decreases the formaldehyde emitted from the wood by hydrothermal treatments; thermo-mechanical pulping (TMP) also enhances the release of formaldehyde from wood.

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