Eco-Design: Effects of Thickness and Time in Service for Wood-Based Boards on Formaldehyde Emission

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Abstract

This study investigated the effects of board thicknesses and time in service on formaldehyde emission for different wood-based boards sampled from standard particleboard (PB) and medium-density fiberboard (MDF). The test samples were subjected to formaldehyde emission by multi-RAE multiple gas analyzer at a temperature of 20°C and at 65 percent relative humidity for a period of 3 days (Treatment 1 [T1]) and 6 months (Treatment 2 [T2]) after production in accordance with European Committee for Standardization (CEN) EN 13986 and Turkish Standards Institute (TS) EN 717-1. PB with a thickness of 18 mm yielded the highest value of formaldehyde emission (1.1078 ppm for T1; 0.5089 ppm for T2), while 18-mm MDF gave the lowest emission (0.2311 and 0.1378 ppm). After 6 months of production, the reduction was 54 percent for PB and 40 percent for MDF. A significant increase was detected with respect to time in service for all board types, the highest values of formaldehyde emission (1.2900 and 0.5800 ppm) were found in 18-mm PBs that were treated for 3 hours, while the lowest values (0.2433 and 0.1600 ppm) were obtained in the samples of 18-mm MDF that were treated for 1 hour. Accordingly, after 6 months, the reduction in formaldehyde emission was 55 percent for PB and 34 percent for MDF. All values were found above the limits of E1 (≤0.10 ppm, EN 717-1). In conclusion, thickness, time in service, and type of wood-based boards significantly affect formaldehyde emission.

Globally, consumption of wood materials has greatly increased for the production of wood-based boards, which are commonly used in related sectors driven mostly by demand from building and furniture industries in recent years. In addition, growing environmental concerns during the last decades, coupled with public pressure and stricter regulations, have changed the way people do business. To this end, consumers, investors, shareholders, and regulatory agencies increasingly demand that organizations behave in an environmentally responsible manner. This affects the forest and furniture industries in terms of producing environmentally friendly wood-based boards. Wood-based boards are manufactured from a range of cellulosic materials by bonding small pieces from the residue of woods, sugar canes, corn, or flax stalk with adhesives.

Synthetic resins used in wood-based boards—particleboards (PB), high-density fiberboards, medium-density fiberboards (MDF), and other adhesively bonded composites such as plywood and wet-process fiberboards—come from nonrenewable fossil resources. One of the most commonly used chemical compounds in board manufacturing is urea-formaldehyde (UF) resin because of its good performance and low cost, while phenol-formaldehyde resin is the second most used in the wood-based board industry (Park and Kim 2008, Tang et al. 2009). However, their substantial disadvantage is formaldehyde emission due to the hydrolysis of weak chemical bonds during board production and lifetime use. Formaldehyde is a colorless, distinctive, strong, even pungent smelling, flammable and gaseous substance that can be found in various forms at room temperature. It has been valued in industries as a binder and preservative and is used in hundreds of household products and building materials. Although its presence in each product is small, the cumulative effect of many items together in an enclosed space is hazardous for human health. At concentrations between 0.1 and 0.5 ppm, formaldehyde is detectable by smell, with some sensitive individuals experiencing slight irritation to the eyes, nose, and throat (Salem and Böhm 2013). However, at levels from 0.5 to 1.0 ppm, formaldehyde produces irritation to the skin, eyes, nose, and throat; it is associated with breathing difficulties

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and nosebleeds, and it is also suspected of being carcinogenic (Pearson 1994), while at concentrations above 1.0 ppm exposure to formaldehyde produces extreme discomfort. It can also cause contact dermatitis, associated with an allergic reaction to the chemicals (Isaksson et al. 1999).

There are several factors to consider with formaldehyde: variation in the availability and cost depending on raw materials. It is a naturally occurring chemical in wood because wood contains a diminutive, but still detectable, amount of free formaldehyde. The free formaldehyde in wood-based boards comes from two sources: (a) the wood itself (cellulose, hemicelluloses, and lignin) as well as from its extractives to different extents depending on the boundary conditions (pH value, temperature) and (b) the adhesive. According to Schafer and Roffael (2000), the formaldehyde of wood is a combination of mechanical and chemical degradation of wood during the preparation of flakes and depends on the quality of wood and the intensity of the pretreatment. The concentration of this formaldehyde is generally very low. However, the main release of formaldehyde comes from the adhesives, which are used in wood-based boards during and after manufacturing. From a life-cycle perspective, information sources were identified for the completion of a life-cycle assessment (LCA) of the wood-based boards sector (Todd and Higham 1996) and volatile organic compounds and formaldehyde in nature, wood, and wood-based boards (Raffael 2006).

Efforts have been focused on the study of environmental properties of wood-based boards and their various finishes: volatile organic compounds (VOCs) in PB with diverse coverings (Brockmann et al. 1998); industrial surface coatings, including wood furniture and fixtures emission inventory development (Anex et al. 1998); emission factors for PB and MDF (US Environmental Protection Agency 1998, 2001); environmental impacts of wood-based boards and surface and edge finishes (Cinar 2005); comparison of standard methods and gas chromatography methods in determination of formaldehyde emission from MDF bonded with formaldehyde-based resins (Kim and Kim 2005); environmental assessment of green hardboard production coupled with a laccase activated system (Gonzalez et al. 2011); formaldehyde and VOC emissions at different manufacturing stages of wood-based boards (Zhongkai et al. 2012); the potential for using the sycamore (*Platus orientalis*) leaves in manufacturing PB (Aghakhani et al. 2014); influence of walnut shell as filler on mechanical and physical properties of MDF improved by nano-SiO_2 (Khanjanzadeh et al. 2014); and effects of temperature and thickness of wood-based boards on formaldehyde emission (Cinar 2018).

Other studies investigated the effects of temperature and humidity on formaldehyde emission from UF-bonded boards: a literature critique (Myers 1985); how mole ratio of UF resin affects formaldehyde emissions and other properties (Myers 1984); formaldehyde concern in wood composite products (Sundin 1986); the effects of log storage time and bark usage ratio on formaldehyde emissions of PB manufactured from black locust (*Robinia pseudoacacia*; Nemli et al. 2002); the influence of moisture content on the formaldehyde release of PB and MDF bonded with formaldehyde-based adhesives (Roffael et al. 2001); the formaldehyde and total VOC emission behaviors according to finishing treatment with surface materials using a 20-liter chamber and field and laboratory emission cell (Kim et al. 2006); long-term impact of formaldehyde and VOC emissions from wood-based products on indoor environments and issues with recycled products (Chuck and Jeong 2012); evaluation of formaldehyde emission from different types of wood-based boards and flooring materials using different standard test methods (Salem et al. 2012); evaluation of formaldehyde emission and combustion behaviors of wood-based composites subjected to different surface finishing methods (Park et al. 2013); the reduction of formaldehyde and VOC emission from wood-based flooring by green adhesive using cashew nut shell liquid (Kim 2010); effect of using walnut and almond shells on the physical and mechanical properties and formaldehyde emission of PB (Pirayesh et al. 2012); effects of adding nano-clay (montmorillonite) on performance of polyvinyl acetate and UF adhesives in *Carapa guianensis*, a tropical species (Moya et al. 2015); and UF resin with low formaldehyde content modified by phenol-formaldehyde intermediates and properties of its bamboo PB (Zhang et al. 2015).

Knowledge of the environmental impact of wood-based boards enables companies to improve their products environmentally and thus expedite their introduction into the growing market for ''green'' products. Environmental factors should be taken into account at the earliest possible stage of product development and design (Cinar 2005). This article analyzes the effects of wood-based board types, board thicknesses, and time in service on formaldehyde emissions for standard PB and fiber density boards that are typically used in the wood-based furniture manufacturing sector in Turkey.

Methods and Materials

Methods

The most popular methods in Europe are the checklist method for qualitative evaluation and LCA for quantitative analysis. LCA is a means of deriving a quantitative evaluation of product design and thereby refining product quality and characteristics. In addition to its use in new product design, it is increasingly regarded as a useful technique for evaluating products already in use. It analyzes the total impact of a product on the environment from extraction of the raw materials that go into the product, through manufacture, usage, and disposal. For this research, Eco-Indicator 99 (Goedkoop and Spriensma 1999) was used to check the quantitative data representing formaldehyde emission, which was measured in accordance with TS EN 717-1 (Turkish Standards Institute 2006) by multi-RAE multiple gas analyzer to analyze the effects of different thicknesses, type of boards, and time in service after 3 days and 6 months of production.

Materials

Wood-based boards.—Two types of wood-based boards with three different thicknesses were analyzed: (1) standard PB, produced according to TS EN 312 (Turkish Standards Institute 2005b) and (2) MDF, produced according to TS EN 622-5 (Turkish Standards Institute 2008), which are commonly used in the Turkish furniture industry. Particleboards and fiberboards were supplied from the main factories of Turkey. The samples were obtained from boards 210 by 280 by 0.8 and by 0.12 and by 0.18 cm according to TS EN 326-1 (Turkish Standards

Institute 1999). Some characteristics of the boards are given in Table 1.

Adhesive.—UF adhesive, which is commonly used in the Turkish wood-based board production, was preferred in this study. The characteristics of UF are given in Table 2.

Preparation of samples.—Thirty test samples were prepared from a combination of PB and MDF with thicknesses of 8, 12, and 18 mm. Samples were cut to 500 by 500 mm, weighed with a sensitive scale, Precia Gravimetrics 312-6200C, in compliance with TS EN 326-1 (Turkish Standards Institute 1999), packed with transparent nylon for avoiding emissions, and kept at room temperature of 20°C ± 2°C and 60 ± 5 percent relative humidity in order to obtain a moisture value equal to the internal environmental conditions according to TS 2471 (Turkish Standards Institute 2005a).

Implementation of experiment.—Measurements of formaldehyde emission were carried out twice. The first measurement was taken from the newly manufactured PB and MDF, which were stored less than 3 days in the board factory. The second measurement was done after a 6-month time interval.

The samples were put into the Climatic Test Cabinet TK 600 NUVE (2012) at 20°C and 65 percent relative humidity for the first measurements, which were taken by a multi-RAE multiple gas analyzer at 1, 2, and 3 hours over the test specimens prepared from boards supplied immediately from the factory in accordance with EN 13986 (European Committee for Standardization 2015) and test method 717-1 (Turkish Standards Institute 2006). The second measurement was followed by the repetition of the first measurement method for obtaining parts per million values after a 6-month period. The dimensions of the climatic test cabinet were 75 by 75 by 132 cm, and a multi-RAE multiple gas analyzer was integrated to the climatic test cabinet (Figs. 1 and 2).

Data evaluation.—In order to determine the effects of wood-based board types, thickness and time in service on formaldehyde emission for two types of measurements were carried out for correlation. The results of the first measurement were obtained from the newly produced boards, and the second measurements were obtained from the boards that have been kept waiting for 6 months. In addition, the results were also compared to calculate the distance to limit 0.10 ppm of E1 (EN 717-1). The dependent and independent variables, which constituted the research hypothesis, were tested with suitable statistical methods. To this end, the arithmetic means and standard deviation values of research data were calculated. The analysis of variance test was used to determine whether the differences between the variables at the $P < 0.05$ level were statistically

Table 1.—Some characteristics of boards and samples.

	Dimension (mm)				
Boards[a]	Thickness	Width	Depth	Density (g/cm^3)	Weight (g)
MDF	18	500	500	0.7433	3,620.58
	12	500	500	0.7800	2,348.86
	8	500	500	0.7900	1,715.42
PB	18	500	500	0.6433	2,867.15
	12	500	500	0.6667	2,129.77
	8	500	500	0.7500	1,447.28

[a] MDF = medium-density fiberboard; PB = particleboard.

Table 2.—The characteristics of the urea-formaldehyde adhesive.

Density, 20°C (g/cm^3)	pH, 20°C	Mean ± SD: Viscosity, 20°C (mPas)	Mean ± SD: Amount of solid material (%)	Amount of adhesive application (g·m^3)
1.220	8.0	16.000 ± 3.000	55 ± 1	180–200

Figure 1.—Climatic test cabinet.

Figure 2.—Multi-RAE multiple gas analyzer.

significant or not. SPSS Statistics and Microsoft Office Excel programs were used to evaluate the data.

Reliability test.—Formaldehyde gas, which is contained in the PB (8, 12, and 18 mm) and MDF (8, 12, and 18 mm) included in the study, was measured in two phases. The reliability of the dependent variables of the obtained results was tested with Cronbach's alpha. Accordingly, the reliability coefficient of the scale constructed from two-step measures is 0.79. Previous studies by Bagozzi and Yi (1988), Grewal et al. (1998), and Kim and Jin (2001) have reported that all elements can be considered ''reliable'' when alpha reliability coefficients exceed 0.70. Correspondingly, the Cronbach alpha coefficient obtained in the study is above the specified value. As a result, the scale constructed from two-way measures was found to be reliable.

Results

The results of the formaldehyde emission on wood-based boards related to the board thickness, time in service (3 days and 6 months after production), and the distance to limit values (0.10 ppm) are shown in Table 3.

The effect of board type on the emission values was found to be significant with respect to the means of formaldehyde emission of wood-based boards after 3 days of production. The highest emission value (1.1078 ppm) was found in the samples of PB with a thickness of 18 mm, while the lowest emission (0.2311 ppm) was observed in the samples of MDF with a thickness of 18 mm.

A significant increase in emission related to time in service was detected in all board types. The highest formaldehyde emission (1.2900 ppm) was found in the samples of 18-mm PB that were treated at 20°C for 3 hours, while the lowest value (0.1133) was obtained in the samples of 18-mm MDF that were treated at 20°C for 1 hour. Accordingly, an increase from 10.55 to 40.73 percent for PB and from 4.44 to 20.56 percent for MDF was observed.

For distance to limit values (0.10 ppm), the most distant value was 1,007.78 percent for PB, while the closest value was found to be 131.11 percent for MDF. All values were above the limits of E1 ($\leq$0.10 ppm, EN 717-1).

The effect of board type on the formaldehyde emission values was found to be significant with respect to the means of formaldehyde emission of the wood-based boards after 6 months of production. The highest formaldehyde emission value (0.5089) was found in the samples of 18-mm PB, while the lowest emission (0.2011) was observed in the samples of 8-mm PB. For MDF, the emission was found to be highest in the samples of 8 mm (0.1600) and lowest in the samples of 18 mm (0.1378).

The highest formaldehyde emission (0.5800) was found in the samples of 18-mm PBs that were treated at 20°C for 3 hours, while the lowest value (0.113) was obtained in the samples of MDF that were treated at 20°C for 1 hour, according to the time in service. Accordingly, an increase from 3.61 to 31.82 percent for PB and from 16.67 to 41.18 percent for MDF was observed.

For distance to limit values (0.10 ppm), the most distant value was 408.89 percent for PB, while the closest value was found to be 37.78 percent for MDF.

According to the findings, as the PB thickness increased, formaldehyde emission showed an increasing tendency (Fig. 3), while as the MDF thickness increased, formaldehyde emission showed a decreasing tendency (Fig. 4). Time in service of wood-based boards also affects formaldehyde emission in a slightly positive tendency, as shown in Figures 5 and 6.

The comparison of the results from wood-based boards, 3 days and 6 months after production of wood-based boards for the formaldehyde emission, is given in Table 4.

In Table 4, the lowest reduction of 0.311 to 0.2011 ppm (35%) was found in the 8-mm samples of PB, while the 18-mm PB samples yielded the highest reduction, from 1.1078 to 0.5089 ppm (61%).

The 18-mm samples of MDF gave the lowest reduction, from 0.2311 to 0.1378 ppm (40%), while the highest reduction of 0.6233 to 0.2144 ppm (65%) was yielded in the 12-mm samples of MDF. Accordingly, a significant reduction from 35.35 to 61.10 percent for PB and from 40.37 to 65.60 percent for MDF was observed.

The results of variance analysis for defining effects of time and thickness of wood-based boards on formaldehyde emission are given in Table 5.

In Table 5, the effects of board thickness and time factor on the total formaldehyde emission values were statistically significant at the level of $\alpha = 0.05$. In other words, changing the wood-based board thickness (8, 12, and 18 mm) and

Table 3.—Formaldehyde emission of wood-based boards, 3 days and 6 months after production.

Boards	Density (g/cm^3)	Thickness (mm)	Concentrations (ppm)			Means	Performance (%)		Distance to 0.10 ppm (%)	HG[a]
			Hour 1	Hour 2	Hour 3		Hours 1–2	Hours 1–3		
PB[b]	0.6633	8	0.2733	0.3233	0.3367	0.3111	18.29	23.17	211.11	A
	0.7500	12	0.6633	0.7333	0.8400	0.7456	10.55	26.63	645.56	B
	0.6433	18	0.9167	1.1167	1.2900	1.1078	21.82	40.73	1,007.78	C
PB[c]	0.6633	8	0.1767	0.2067	0.2200	0.2011	16.98	24.53	101.11	A
	0.7500	12	0.2767	0.2867	0.3067	0.2900	3.61	10.84	190.00	A
	0.6433	18	0.4400	0.5067	0.5800	0.5089	15.15	31.82	408.89	B
MDF[b]	0.7900	8	0.6000	0.6267	0.7233	0.6500	4.44	20.56	550.00	B
	0.7800	12	0.5967	0.6233	0.6500	0.6233	4.47	8.94	523.33	B
	0.7433	18	0.2167	0.2333	0.2433	0.2311	7.69	12.31	131.11	A
MDF[c]	0.7900	8	0.2033	0.2500	0.2867	0.2467	22.95	40.98	146.67	B
	0.7800	12	0.1800	0.2100	0.2533	0.2144	16.67	40.74	114.44	AB
	0.7433	18	0.1133	0.1400	0.1600	0.1378	23.53	41.18	37.78	A

[a] HG = homogeneous group.

[b] For the first measurement, particleboard (PB) and medium density fiberboard (MDF) were stored less than 3 days.

[c] For the second measurement, PB and MDF were stored 6 months.

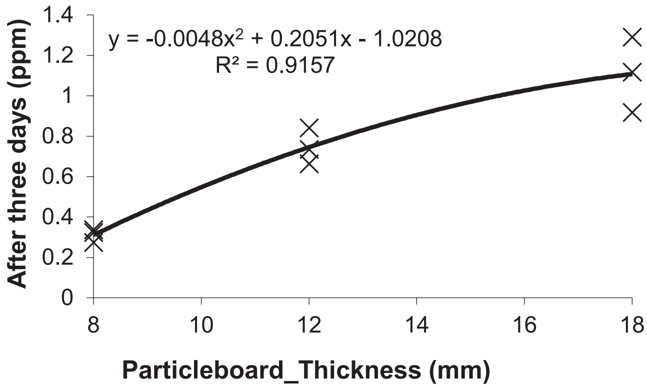

Figure 3.—Particleboard thickness × formaldehyde emission relation.

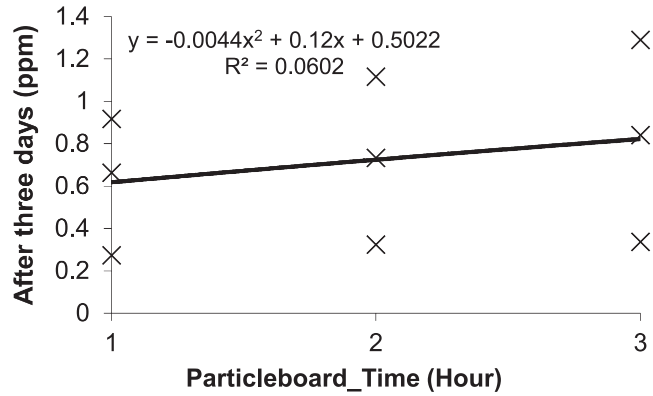

Figure 5.—Particleboard time × formaldehyde emission relation.

time factors (3 days and 6 months) significantly affected the total formaldehyde emission value.

The results of the Tukey honest significant difference (HSD) test, carried out by least significant difference (LSD) critic values, a double comparison for board type, thickness, and time are given in Table 6.

The lowest formaldehyde emission value was obtained from the samples of 18-mm MDF after a 6-month period, while the highest result was found on the samples of 18-mm PB in the first measurement period.

Regression Analysis

Single regression analysis

According to the results obtained from the two stages of formaldehyde emission (3 days and 6 months after production), the relationship between each tried-out factor and formaldehyde emission was investigated. In other words, regression analysis of board thickness–formaldehyde emission and time–formaldehyde emission relations with respect to two different material types (PB and fiberboard) was performed according to the least squares method.

For these relations, four different regression models were created, in which formaldehyde emission was taken as the function of thickness and time factors according to the types of boards, respectively. For the measurements taken 3 days after production, the relationship between the thickness–formaldehyde emissions is given in Figure 3 for PB and Figure 4 for MDF, and time–formaldehyde emission is given in Figure 5 for PB and Figure 6 for MDF.

Figure 1 shows that increasing particleboard from 8- to 12- to 18-mm thicknesses results in a higher emission of formaldehyde. The correlation of formaldehyde emission values in these relationships has a positive R^2 value of 0.9157. However, there was a decrease in tendency for the results of MDF for the same thickness levels with a negative R^2 value of 0.97 as shown in Figure 4.

Figure 3 shows the correlations have a slightly positive R^2 value of 0.0602 for PB–time, while a slightly negative R^2 value of –0.081 yields for fiberboard–time, as shown in Figure 6.

According to the data in Figures 3, 4, 5, and 6, curvilinear relationships were observed between board thickness × formaldehyde emission and time × formaldehyde emission. The regression coefficients obtained from these relations and the determination coefficients (R^2) indicating the reliability of the regression models are given in Table 7.

In the definition of all three relations, $\mu = ax^2 + bx + c$ has been obtained, where μ is the total formaldehyde emission, x is the material thickness or time point, and *a, b, c* are regression coefficients. According to the determination coefficients, the confidence levels of the obtained regression models are very high for PB and fiberboard thickness, whereas they are not high for PB and fiberboard time points. Accordingly, the relations and mathematical models established from the results of 3 days after production between

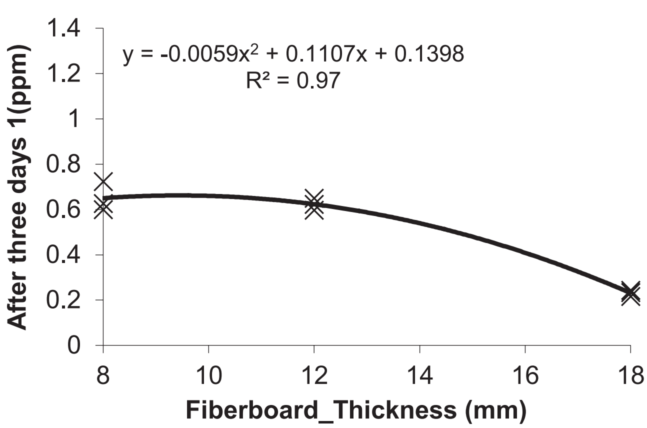

Figure 4.—Fiberboard thickness × formaldehyde emission relation.

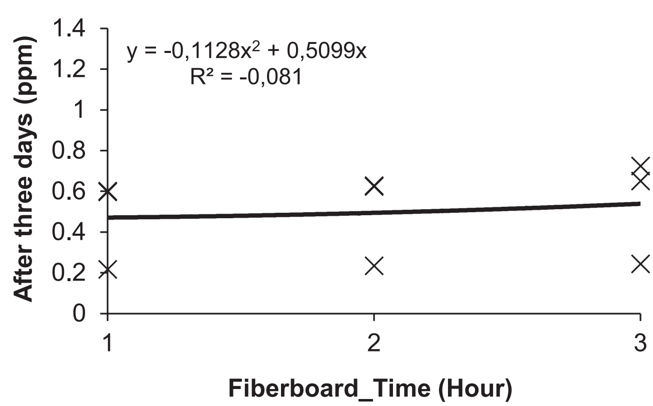

Figure 6.—Fiberboard time × formaldehyde emission relation.

Table 4.—Formaldehyde emission for particleboard (PB) and medium-density fiberboard (MDF) kept for 3 days and 6 months.

Boards	Density (g/cm^3)	Thickness (mm)	3 days after production		6 mo after production		Reduction	
			Mean (ppm)	Distance to limit (%)	Mean (ppm)	Distance to limit (%)	ppm	%
PB	0.6633	8	0.3111	211.11	0.2011	101.11	0.1100	35.35841
	0.7500	12	0.7456	645.56	0.2900	190.00	0.4556	61.10515
	0.6433	18	1.1078	1.007.78	0.5089	408.89	0.5989	54.06211
MDF	0.7900	8	0.6500	550.00	0.2467	146.67	0.4033	62.04615
	0.7800	12	0.6233	523.33	0.2144	114.44	0.4089	65.60244
	0.7433	18	0.2311	131.11	0.1378	37.78	0.0933	40.37213

Table 5.—Variance analysis; effects of variables on formaldehyde emission values.

Source	Dependent variable	Sum of squares	Degrees of freedom	Mean square	F	Significance ($P = 0.05$)
Corrected model	3 d	1.017	3	0.339	67.411	0.000*
	6 mo	0.158	3	0.053	71.704	0.000*
Intercept	3 d	0.344	1	0.344	68.313	0.000*
	6 mo	0.088	1	0.088	120.310	0.000*
Time	3 d	0.063	1	0.063	12.465	0.017*
	6 mo	0.008	1	0.008	10.317	0.024*
Thickness	3 d	0.955	2	0.477	94.884	0.000*
	6 mo	0.151	2	0.075	102.398	0.000*
Error	3 d	0.025	5	0.005		
	6 mo	0.004	5	0.001		
Total	3 d	5.727	9			
	6 mo	1.162	9			
Corrected total	3 d	1.043	8			
	6 mo	0.162	8			

time point–formaldehyde emission for PB and time point–formaldehyde emission for fiberboards are found to be meaningful. There was a strong correlation between the board thickness and formaldehyde emission (R^2 values ranged between 0.92 and 0.97) and the formaldehyde values.

Multiple regression analysis

A multiple regression analysis was conducted to form a model covering all variables used in the study in relation to the total formaldehyde emission value. In the results of the multiple regression analysis, an equation is obtained in which the total formaldehyde emission values can be predicted using the board thickness and time values.

In accordance with this, the following was formulated:

$$y = -0.473 - (0.078)X_1 + (0.102)X_2$$

where y is the total formaldehyde emission value; X_1 and X_2 are material thickness and time, respectively; 0.078 and 0.102 are regression coefficients; and –0.473 is a regression constant value.

The statistical values of this regression model were obtained; the determinant coefficient (R^2) was 0.951, the corrected coefficient of determination was 0.934, the correlation coefficient was 0.589, and the standard error value was 0.092. To check the significance of the multiple regression analysis, variance analysis was used. The results of regression variance analysis are given in Table 8.

According to Table 8, the F value is calculated as 57.615. The calculated F values are higher than the F values in Table 8 in the case of accepting the regression degree of freedom as 2 and the error degree of freedom as 6 when looking at the result of 2 and 6 degrees of freedom F table values. In this case, the regression analysis (established relation) is found to be important with the significance level of $\alpha = 0.001$.

Table 6.—Board type, thickness, and time; double comparison.[a]

Boards	Time after production	Thickness (mm)	$\bar{x}$	HG	LSD
PB	3 d	8	0.3111	D	
		12	0.7455	B	
		18	1.1078*	A	
	6 mo	8	0.2011	DE	
		12	0.2900	D	
		18	0.5089	C	
MDF	3 d	8	0.6578	B	
		12	0.6233	BC	
		18	0.2311	DE	
	6 mo	8	0.2467	E	
		12	0.2144	DE	
		18	0.1378**	E	

[a] $\bar{x}$ = arithmetic mean; HG = homogeneous group; PB = particleboard; MDF = medium-density fiberboard; * = highest emission; ** = lowest emission; LSD = least significant difference.

Discussion

The results of formaldehyde concentrations were obtained from various specimens. Each specimen was tested twice, and good reliability of results was obtained with a maximum relative standard deviation. It can be seen that PB has a higher formaldehyde concentration than MDF. It is possible to argue that several factors could interfere with the formaldehyde emission. However, assuming the same

Table 7.—Regression and determination coefficients.

Boards[a]	Relation	*a*	*b*	*c*	R^2
PB	Thickness–formaldehyde emission	−0.0048	0.2051	1.0208	0.9157
	Time–formaldehyde emission	−0.0044	0.12	0.5022	0.0602
MDF	Thickness–formaldehyde emission	−0.0059	0.1107	0.1398	0.9700
	Time–formaldehyde emission	−0.1128	0.5099	—	−0.0810

[a] PB = particleboard; MDF = medium-density fiberboard.

parameters were used, pressure, amount of adhesive, pressing time, etc., the only difference is the raw material—chips for PB and fibers for MDF—that plays a significant role for formaldehyde emission. The compaction of the mat of fiberboards to an average density higher than PB may allow better surface contact and a compact structure. This results in better adhesive use because more adhesive-coated fibers might be in intimate contact instead of no contact. This could be the reason PB has higher formaldehyde emission than MDF. Chamber studies have shown that the formaldehyde concentration levels emitted from different wood species ranged from 2 to 9 ppb, which were much lower than the emission limit value of 100 ppb for wood-based boards (Meyer and Boehme 1997). Therefore, as argued by He and Zhang (2010) and Zhongkai et al. (2012), during the drying and hot pressing processes, the formaldehyde content in wood fibers after resin application dramatically decreases. This is probably owing to the formaldehyde being abundantly emitted when drying the wood fibers after the resin application. Moreover, the formaldehyde content in MDF decreases further when the thickness increases.

According to the results of the study, the formaldehyde concentrations of PB and fiberboards were found to be significantly higher than internationally accepted levels. Finding ways to reduce the formaldehyde emission at accepted levels is a great concern for the Turkish furniture industry. Reduction in F/U molar ratio has been a strategy adopted in the last decades to decrease formaldehyde emissions (Myers 1984). However, this reduction decreases the reactivity of UF resins. Currently, reactivity of industrial UF adhesives is near the minimum limit accepted for industrial board production (Dongbin et al. 2006). A significant reduction of formaldehyde emission could be attained with formaldehyde scavengers: sodium metabisulfite and ammonium bisulfate. The tested scavengers showed distinct performances under the different emission testing conditions, which were interpreted in terms of the stability of the chemical compounds formed upon formaldehyde capture. Sodium metabisulfite proved to be an excellent scavenger for all formaldehyde methods, allowing the production of particleboard boards with zero formaldehyde emission (Costa et al. 2013). Another effective way to reduce formaldehyde emission is the addition of solid scavengers. Pirayesh et al. (2012) suggests that value-added PB containing walnut or almond shell particles is not only environmentally friendly but also an alternative solution for decreasing availability of raw materials in developing countries. According to Pirayesh et al. (2012), walnut and almond shells in PB significantly reduced formaldehyde emission. Similar results were reported by Nemli and Colakoglu (2005) and Buyuksari et al. (2009). They reported that the decrease in formaldehyde emission values in the boards may be because of the high amounts of poly phenolic extractives in bark, especially tannins.

Table 8.—Results of regression variance analysis (Measurement 1).

Model	Sum of squares	df[a]	Mean square	*F*	Significance[b]
Regression	0.991	2	0.495	57.615	0.000*
Residual	0.052	6	0.009		
Total	1.043	8			

[a] df = degrees of freedom.
[b] * = $\alpha = 0.05$ significance level.

Conclusions

The main results of this study indicate that thickness, time in service, and types of wood-based boards significantly affect formaldehyde emission. Standard PB have a higher environmental impact than standard fiberboards.

For newly produced (after 3 days) wood-based boards

- The highest value of formaldehyde emission (1.1078 ppm) was found in the samples of 18-mm-thick PB, while the lowest emission (0.2311) was observed in the 18-mm-thick samples of MDF.
- A significant increase related to time in service was detected in all board types, the highest value of formaldehyde emission (1.2900) was found in the samples of 18-mm PB that were treated for 3 hours, while the lowest value (0.2433) was obtained in the samples of 18-mm MDF that were treated for 3 hours. Accordingly, an increase from 10.55 to 40.73 percent for PB and from 4.44 to 20.56 percent for MDF was observed.
- For distance to limit values (0.10 ppm), the most distant value was 1,007.78 percent for PB, while the closest value was found to be 131.11 percent for MDF.

Six months after the production of wood-based boards

- The highest value (0.5089) was found in the 18-mm-thick samples of PB, while the lowest emission (0.2011) was observed in the 8-mm-thick samples of MDF.
- According to the time in service, the highest formaldehyde emission (0.5800) was found in the samples of 18-mm PB that were treated at 20°C for 3 hours, while the lowest value (0.1600) was obtained in the samples of MDF that were treated at 20°C for 3 hours. Accordingly, an increase from 3.61 to 31.82 percent for PB and from 16.67 to 41.18 percent for MDF was observed.
- For distance to limit values (0.10 ppm), the most distant value was 408.89 percent for PB, while the closest value was found to be 37.78 percent for MDF.

In conclusion, thickness, time in service, and type of wood-based boards significantly affect the formaldehyde emission.

- All values were above the limits of E1 ($\leq$0.10 ppm, EN 717-1 [Turkish Standard Institute 2006]).
- As the particleboard thickness increases, the formaldehyde emission increases, while as the MDF thickness increases, formaldehyde emission decreases.
- Time in service for 3 days and 6 months after production of wood-based boards is significant for formaldehyde emission; the reduction is 35.36 to 61.10 percent for PB, 40.37 to 65.60 percent for MDF, respectively.

Considering the number of wood-based boards and complementary elements that go into the present furniture industry design projects, designers should be aware of the consequence of their work and must begin to consider the impact on the environment. In the not too distant future, ''green'' design might be as expected in project solutions as universal design is today. Further investigation of the influence of design decisions on the product quality and environmental performance of products is encouraged for future studies.

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