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As a part of understanding the influence of wood-based panels on indoor air quality of a building, this study examined the effects of laminate type on the emission of volatile organic compounds (VOCs) such as formaldehyde, toluene, and total VOCs (TVOCs) from particle board (PB) and medium density fiberboard (MDF) panels, using a 20-L small chamber method. Five different types of surface laminates, including three types of surface overlays such as low pressure laminate (LPL), poly(vinyl chloride) (PVC) film, and urethane coated paper (UCP), as well as two types of surfaces coatings, i.e. direct coating (DC) and ultra-violet coating (UVC) were applied to the veneer bonded to a surface of PB and MDF panels that were of different grades with respect to formaldehyde emission (FE) such as E_0, E_1, and E_2 before surface lamination. As expected, the FE grade strongly affected the FE of panels, regardless of types of panel and laminate. All types of surface laminations dramatically reduced the FE compared to the control. However, the surface laminations by overlay significantly decreased the emission of TVOCs and toluene while both types of surface coatings greatly increased the emission of TVOCs and toluene. In particular, styrene was the main component of TVOCs from the DC sample (about 87%), while toluene was the main species of TVOCs from the UVC sample (about 73%). When two different ways of sample preparation (i.e., single- or all-surface exposure) were compared, the FE of the MDF sample was influenced by the surface exposure type. But TVOCs and toluene emissions were independent of the FE grade and the sample preparation. These results suggest that a proper selection of the surface laminate for wood panels has a significant impact on indoor air quality of a building.

Keywords: wood-based panels; formaldehyde; toluene; TVOCs; surface laminates; indoor air quality

1. Introduction

The major sources of formaldehyde and other volatile organic compounds (VOCs) in an indoor environment are building and finishing materials as well as consumer products. Building and finishing materials include paints, wallpaper, plywood, particle board (PB), medium density fiberboard (MDF), adhesives, coatings and coverings on walls, ceilings or floors, and so on. It is well known that contaminating VOCs such as formaldehyde, toluene, benzene, ethyl benzene, or total VOCs (TVOCs) emitted from these materials have a high impact on

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the quality of indoor environment. These contaminants significantly pollute the indoor air of a building. Thus, there is a growing concern for the health and comfort of building occupants. For example, TVOCs concentration in the indoor air was typically 10 times greater than outdoors [1]. It is also reported that the concentration of VOCs from wood-based panels decreases more quickly than that of formaldehyde, with a few exceptions [2].

Typical building products that emit formaldehyde and VOCs include various reconstituted wood panel products such as plywood, PB, MDF, and so on [2]. These wood-based panel products have become increasingly popular and are being used for manufacturing furniture, cabinets, or building products. These reconstituted wood-based panel products emit formaldehyde gas for a relatively long time [3]. So, the formaldehyde emission (FE) has attracted much attention from public as well as wood industry, since formaldehyde has been known as a toxic air contaminant since a German teacher first reported the problem of FE in 1973. In fact, the International Agency for Research on Cancer, a part of the World Health Organization reclassified formaldehyde as 'carcinogenic to human (Group 1)' from 'probable carcinogenic to human (Group 2A)' in June 2004.

The main causes of the FE from these products are due to the fact that these products are mainly bonded with formaldehyde-based resins such as urea-formaldehyde (UF), melamine-UF, and phenol-formaldehyde resins. In particular, UF resins are mainly responsible for the FE from the panels [4]. Many authors have published excellent reviews on this issue [5,6]. The reversibility of the aminomethylene linkage, and hence susceptibility to hydrolysis, explains a lower resistance against the influences of water and moisture, and subsequent FE [7]. Thus, the use of UF resin-bonded wood-based composite panels is limited only to nonstructural applications due to the lack of water resistance. Thus, UF resin-bonded panels are limited to interior applications. Furthermore, the effort to reduce energy losses in houses after the energy crisis in 1970s resulted in an increase of air tightness of indoor environment, which aggravated the FE problem. In the 1980s, the first guideline for FE was adopted in Germany [8]. There are many factors affecting the FE of wood panel products [9].

In practice, a variety of surface finished wood-based composite panels are being used for indoor environment. For fabricating these surface-finished products with a film or coating, various synthetic polymeric materials such as low-pressure laminate (LPL), poly(vinyl chloride) (PVC), or polypropylene are used. However, the influence of these surface-finishing types on the VOCs was not known. Thus, the purpose of the present study was to investigate the influence of surface lamination type of wood-based composite panels on their formaldehyde and VOCs emissions using the 20-L small chamber method.

2. Materials and methods

2.1. Materials

Wood-based composite panels used in this study were general grade PB and MDF with 18 mm thickness from a commercial furniture manufacturing company in Korea. These panels had three different grades of the FE such as E_0 (below 0.3 mg/L), E_1 (below 1.5 mg/L), and E_2 (above 5.0 mg/L) determined by the 24-h desiccator method according to the Korean Standard [10]. Full-size MDF and PB panels (4 f × 8 feet) were used for the surface lamination. Surface laminating materials for overlay, namely LPL, PVC, and urethane coated paper (UCP) were donated by a local furniture manufacturing company. Two different surface coatings, i.e. direct coating (DC) and ultra-violet coating (UVC) were deposited on MDF or PB panels at the same company.

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2.2. Methods

2.2.1. Surface lamination of wood-based panels

Surface laminations with overlays or coatings were done according to standard procedure and process conditions. The LPL was laminated on both surfaces of MDF and PB panels at 165 °C and 23 MPa for 35 s under hot-pressing. And the PVC film was overlaid on the surfaces of MDF and PB panels by spraying 450–500 g of ethylene vinyl acetate adhesive per surface, and then laminated at room temperature and 18–20 MPa for 15–20 min. using a press. The UCP was overlaid on the surfaces of the panels by spraying 150, g of poly(vinyl acetate) adhesive on each surface at a belt speed of 15 mm/min. As coatings for the surface, the DC was carried out by spraying 900 g of unsaturated polyester resin on each surface, and then cold-setting the resins at room temperature. The UVC sample was prepared by surface laminating a fancy wood veneer (0.2 mm thick) with 100 g of UF resin followed by hot pressing at 130 °C for 2 min. And then the surface was sprayed with 90–100 g of UV-coating per surface followed by curing under UV intensity of 700 mJ/cm^2 for 2 s.

2.2.2. Dynamic environmental chamber

The small chamber facility consists of three identical chambers, each 20 L in internal volume and made of stainless steel with a Teflon-encased rubber seal; all chambers are supplied with purified air at closely controlled environmental conditions: 25 ± 1 °C, 50 ± 5% relative humidity, and air change rate of 0.5/h. Background concentrations of formaldehyde, TVOCs, and toluene were determined as 5, 20, and 2 μg/m^3, respectively. These dynamic chambers were circulated for 7 days to reach equilibrium prior to sampling the air for the determination of formaldehyde, TVOCs, and toluene concentrations. A sample loading ratio (sample surface area/chamber volume) of 2.16 m^2/m^3 was used for the chambers.

Two ways of sample preparation were employed to study the effects of surface exposure on the FE, TVOCs, and toluene emission from wood-based panels. All specimens for the study of surface laminate types were prepared with a single-surface exposure (0.043 m^2) by sealing the other surface and the four edges with an aluminum tape to obtain the sample loading ratio as specified. We measured the emission factors of formaldehyde, TVOCs, and toluene from the aluminum tape on glass plates in the chamber to see if the aluminum tape used for both surface and edge sealing influenced the emission of these contaminants. The emission factors of formaldehyde, TVOCs, and toluene were found to be 0.025, 0.031, and 0.003 mg/m^2 h, respectively. For allsurface exposure tests, we selected only two types of surface laminates, i.e. LPL and UVC, for MDF samples. The selected MDF specimens were used as received for allsurface exposure tests, which gave an exposed surface area of 0.13 m^2, and a sample loading ratio of 6.52 m^2/m^3.

2.2.3. Determination of FE from wood-based panels

Air samples for the formaldehyde determination were absorbed in a 2,4-dinitrophenylhydrazine (DNPH) cartridge (Supelco, USA) in a vacuum manifold with a solid phase extraction. Then the cartridge was extracted using acetonitrile solution until the final volume reached 5 mL in the vial. These vials were kept frozen in a refrigerator for no more than 3 days prior to analyzing the air samples using high performance liquid chromatography (HPLC) (Alliance 2695, Separation module, Waters, USA). The concentration of FE was determined from the calibration curve obtained using standard formaldehyde gas diluted to five different levels, and absorbing them in a DNPH cartridge. Table 1 presents parameters for the operation of

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Table 1. Parameters for the HPLC operation.

Injection volume	10 μL
Column	Waters Sunfire C18 (150 mm × 4.6 mm, 3.5 μm)
Mobile phase	Isocratic elution, 1.0 mL/min Acetonitrile (A)/Water (B) 0–10 min: A/B = 60/40 (v/v) → 60/40 (v/v)
Detection	UV 360 nm

HPLC. The FE factor was calculated by combining air exchange rate (h^{-1}) and sample loading ratio (m^2/m^3).

2.2.4. *Determination of TVOCs emission from wood-based panels*

For the measurement of TVOCs level, air samples (10 L) were collected with a Tenax TA cartridge at a flow rate of 167 mL/min after 7 days. These cartridges were extracted on a thermal desorption unit (TDU) (TD-20, Shimadzu, Japan) to remove TVOCs from the cartridges, and then analyzed using gas chromatography/flame ionization detector (GC/FID) (GC-2010, Shimadzu, Japan). The parameters for TDU and GC/FID operation are shown in Table 2. The concentration of TVOCs was calculated by the peak integration from hexane (C_6) to hexadecane (C_{16}) from the GC/FID. The emission factors of both TVOCs and toluene were calculated using air exchange rate and loading ratio for the chambers.

3. Results and discussion

Figures 1 and 2, respectively, show the effects of surface laminate type on the FE factors of MDF and PB panels. As expected, the FE of the control MDF and PB panels increased as the emission grade increased from E_0 to E_2. However, the FE factors dramatically decreased for all samples with surface lamination, regardless of panel type. These results indicate that surface lamination on the panel blocks the diffusion of formaldehyde from the inside to the surface, which consequently decreases the FE. In addition, other factors might be responsible for the FE decrease. For example, a high temperature (130 °C) used for hot pressing could reduce the FE of the samples with surface overlay. Also, it should be noted that the surface

Table 2. Parameters used for both TDU and GC/FID operations.

TDU		GC/FID	
Tube desorption temp.	280 °C	Split ratio	1:30
Tube desorption flow and time	60 mL/min, 15 min	Column flow rate	1.5 mL/min
Cryogenic refocusing temp.	−20 °C	GC column	VB-1 (60 m × 0.25 mm × 1.0 μm)
Trap desorption temp.	280 °C	Initial temperature	40 °C (4 min)
Trap desorption time	5 min	1st. Temp. ramp rate	4 °C/min(40–230 °C)
Trap packing material	Tenax TA	2nd Temp. ramp rate	20 °C/min(230–280 °C)
Valve temp.	250 °C	Final temperature	280 °C
Transfer line temp.	250 °C	Detector temp.	280 °C

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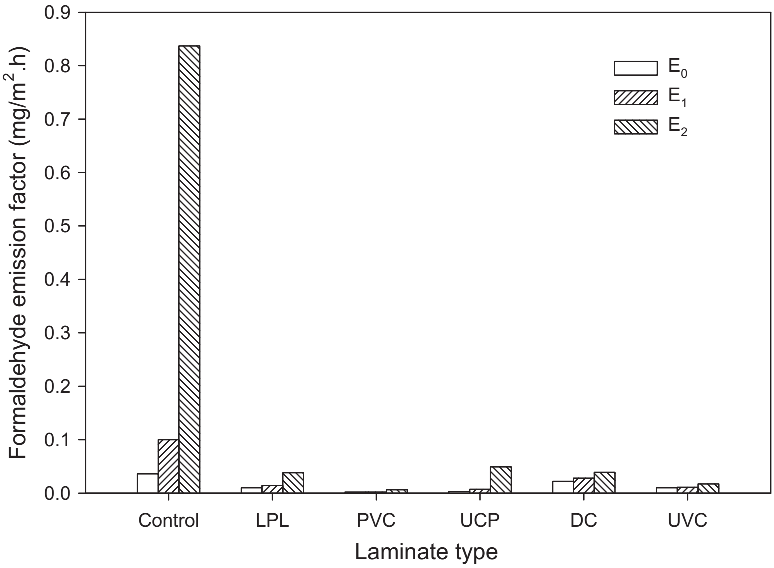

Figure 1. Formaldehyde emission factors of MDF panels with different FE grades and laminate types.

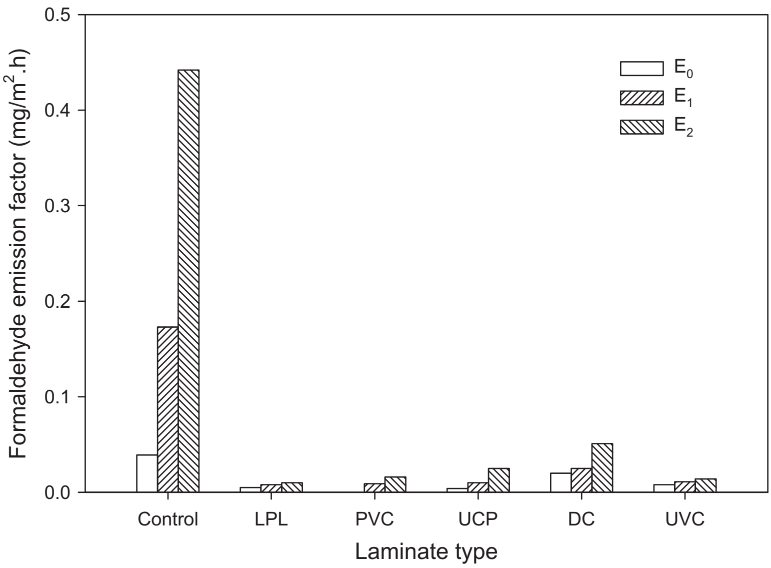

Figure 2. FE factors of PB panels with different FE grades and laminate types.

lamination by overlays such as LPL, PVC, and UCP as well as coatings do not contain any formaldehyde during their processing. The surface laminate type slightly influenced the FEs of both panel types, but they were quite low levels (below 0.1 $mg/m^2 h$). In spite of the surface lamination, the FE grade of base panels also showed a trend similar to the control panels. As shown in Figures 1 and 2, the FE factor increased as the FE grade of panels increased even though the magnitude of FE was significantly reduced after surface lamination.

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The emission factors of TVOCs from both MDF and PB panels are presented in Figures 3 and 4. Compared to the control sample, surface lamination by overlay showed a drastic decrease in the TVOCs emission factors for both MDF and PB panels. In fact, chromatograms of the surface overlaid samples showed a very small amount of TVOCs from C_6 to C_{16} which were found for the control sample. Thus, it was believed that this was mainly responsible for the decreased TVOCs for the surface overlaid lamination. However, surface

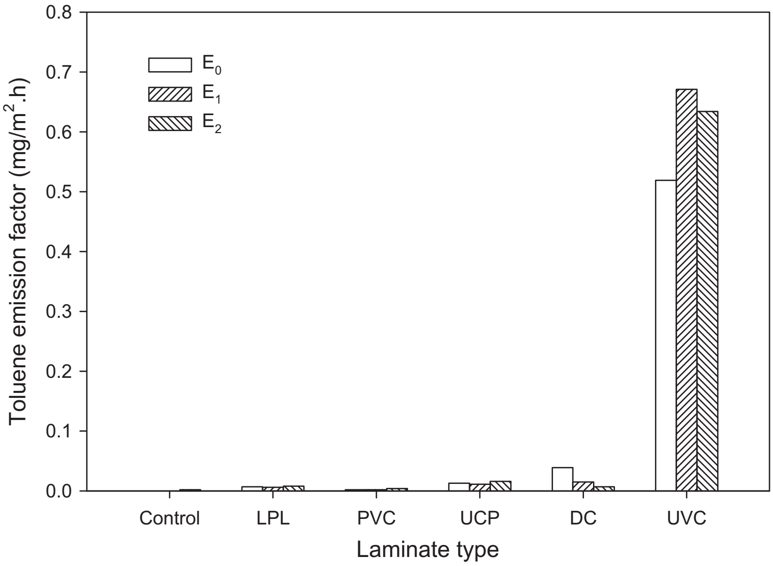

Figure 3. TVOCs emission factors of MDF panels with different FE grades and laminate types.

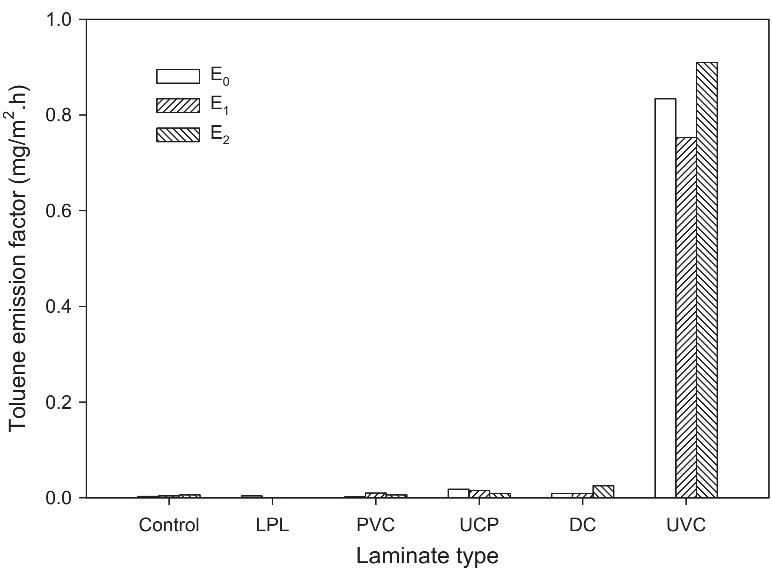

Figure 4. TVOCs emission factors of PB panels with different FE grades and laminate types.

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lamination by coatings (i.e. DC and UVC) significantly increased TVOCs emission, regardless of the panel type. The TOVCs emission factor of the MDF sample with surface coated veneer was much smaller than that of the PB sample while it was much higher than that of PB sample with UVC. Contrary to the FE, TVOCs emission was not directly related to the FE grade of the base panel without surface lamination, regardless of types of panel and surface lamination.

In addition to TVOCs, we also determined the toluene emission factors for MDF and PB panels with different types of surface laminations, and the results are presented in Figure 5. As expected, all the samples except the UVC ones gave a very low level of toluene, regardless of surface laminate type and FE grade. In other words, the UVC lamination is mainly responsible for toluene emission from MDF panel. However, the control and surface laminated samples with overlays showed a very small amount of toluene emission, regardless of panel type and FE grade. A similar result was also found for PB panel samples as shown in Figure 6. These results suggest that the veneer lamination with UV-curable surface coating significantly increases toluene emission from both MDF and PB panels.

In order to better understand the influence of surface coating on TVOCs emission, we tried to identify components of TVOCs emitted from MDF panel with surface coatings. The results are presented in Figure 7. Although many components, such as benzene, ethyl benzene, toluene, etc. were identified, styrene was the main component of the TVOCs from the direct surface coating for MDF panel, which was about 87% of the TVOCs. This result could be due to the fact that styrene monomers were used for polymerization of the unsaturated polyester used for the DC.

We also analyzed the TVOC components from the UVC sample of MDF panel. The results presented in Figure 8 show that toluene was the main component (72.5%) of the TVOCs from the UVC sample. This result could be attributed to the fact that the coating material used for UV-curable coating was mainly composed of toluene as a solvent. In general, commercial UV-curable coatings contain about 40–50% of toluene as well as other solvents.

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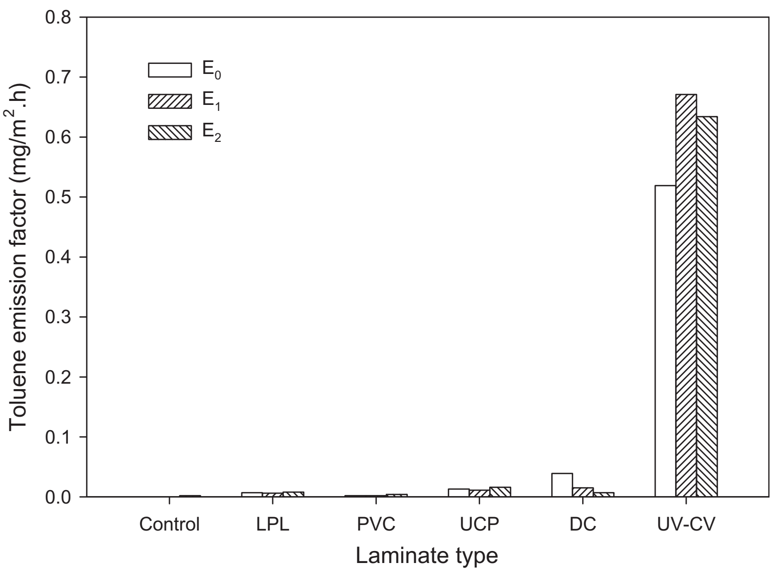

Figure 5. Toluene emission factors of MDF panels with different FE grades and laminate types.

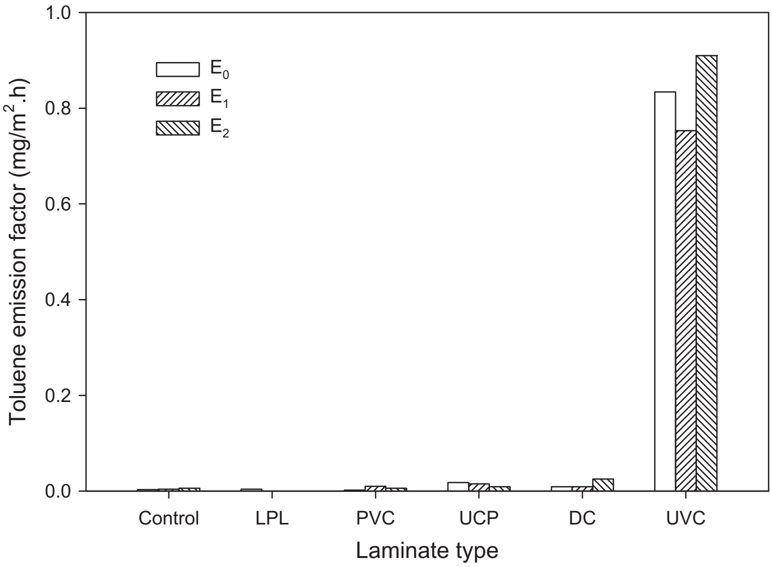

Figure 6. Toluene emission factors of PB panels with different FE grades and laminate types.

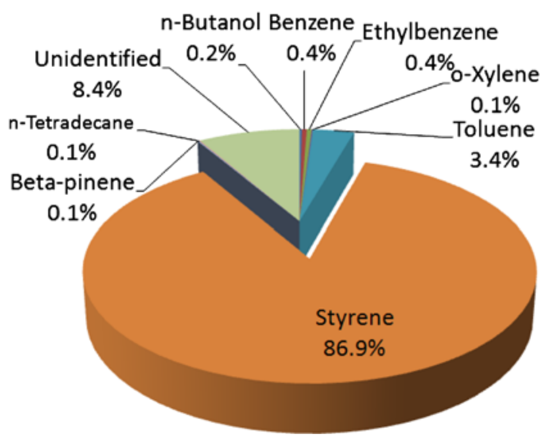

Figure 7. TVOC components of MDF sample with DC on the surface.

When dynamic environmental chamber was used to investigate the influence of surface lamination type on the emissions of formaldehyde and TVOCs from wood-based panels, one of the issues was the sealing of the surface and the four edges of the specimen from wood-based composite panels. In other words, the 20-L small chamber method used in this study is supposed to expose only a single surface of a specimen of wood-based panel by sealing the other surface and four edges. However, formaldehyde or TVOCs could be emitted by their diffusion into the edges or surfaces. Thus, we investigated the effects of exposing a single surface, or all surface of the samples during testing on the emission of formaldehyde, TVOCs, and toluene from MDF samples.

The results are given in Figures 9–11. Figure, 9 presents the FE factors of MDF specimens for different surface exposures, FE grades, and laminate types. As expected, the FE

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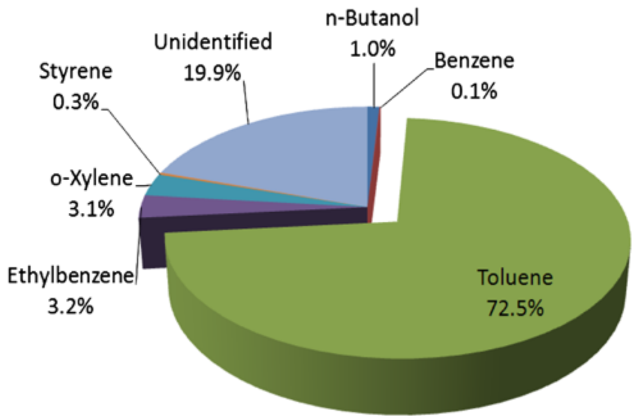

Figure 8. TVOC components of MDF sample with UVC on the surface.

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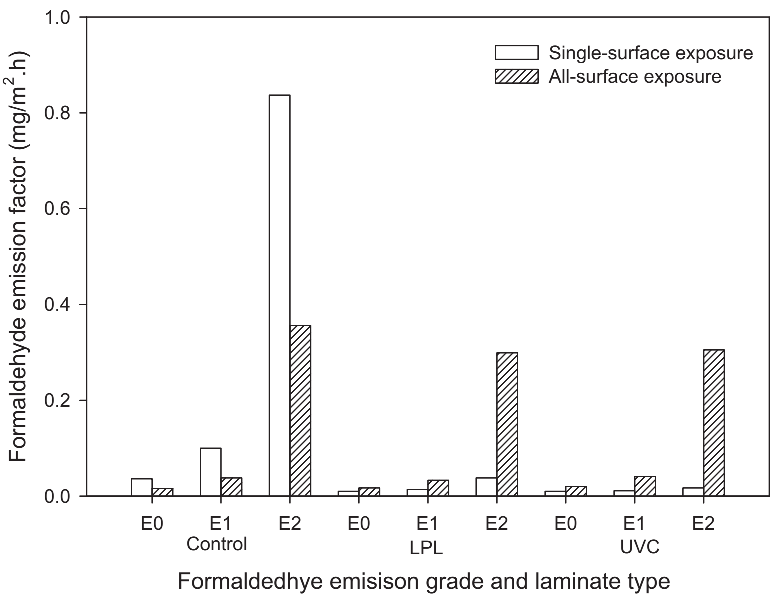

Figure 9. FE factors of MDF panels, depending on FE grade, laminate type, and surface exposure type.

from the control sample showed a clearly increasing trend with increasing FE grade. However, the FE decreased when all surfaces including the four edges of the specimens were exposed to air ventilation during testing. This result suggests that more formaldehyde gas was released by its diffusion through both surfaces as well as the four edges, which consequently reduced the FE of the control sample. In contrast, the surface laminated sample showed an increased FE for all surface exposure tests. This result indicates that the surface lamination prevents the diffusion of formaldehyde gas into the surface, and consequently requires more time for formaldehyde gas to come out of the specimens through its diffusion into the edges.

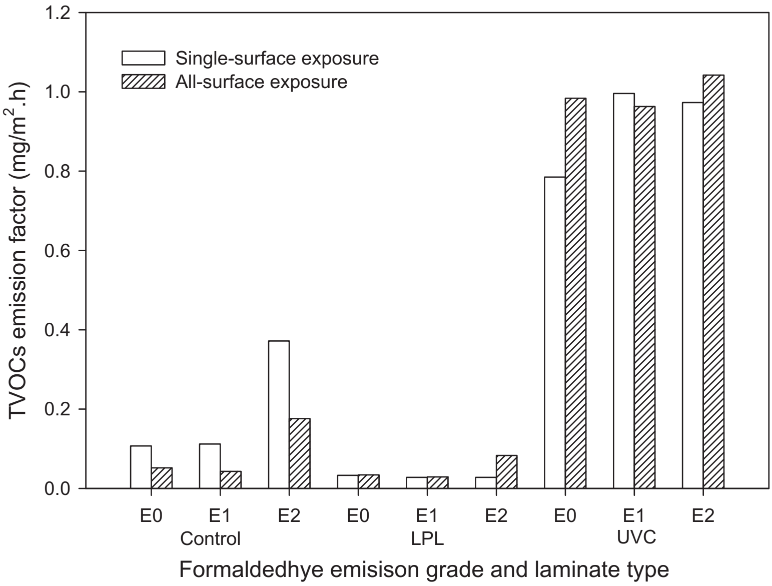

Figure 10. TVOCs emission factors of MDF panels, depending on FE grade, laminate type, and surface exposure type. Single and all surface exposures, respectively, mean that a single surface and all surfaces of the specimen were exposed to the air circulation during the 20-L chamber test.

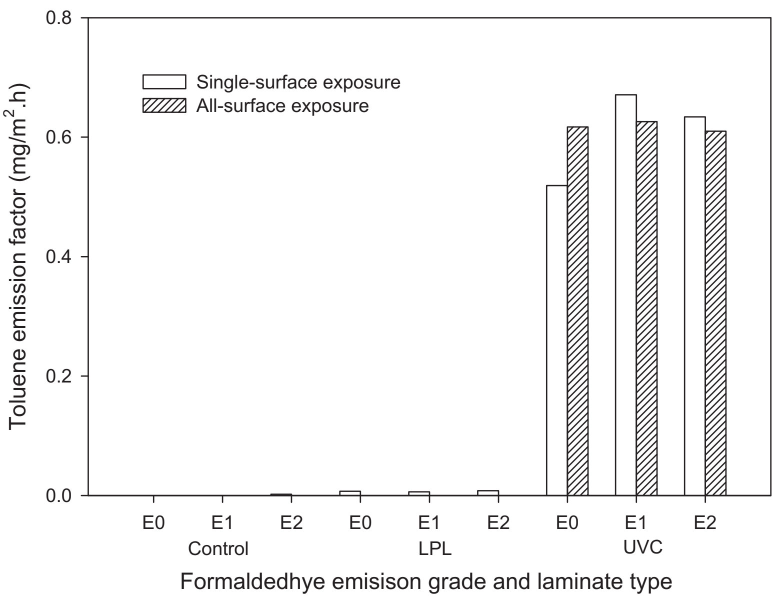

Figure 11. Toluene emission factors of MDF panels, depending on FE grade, laminate type, and surface exposure type. Single and all surface exposures, respectively, mean that a single surface and all surfaces of the specimen were exposed to the air circulation during the 20-L chamber test.

TVOCs emission factors as a function of FE grade, laminate type, and surface exposure are presented in Figure 10. TVOCs emission factors decreased when the surfaces of MDF

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panels were laminated with an overlay, but they dramatically increased for the surface sample laminated by the UVC, regardless of single or allsurface exposure tests. This result is pretty much compatible with the fact that the UVC lamination greatly increases the amount of toluene emission for MDF and PB panels as presented in Figures 5 and 6. This result indicates that the influence of UVC lamination is so large that the FE grade has no impact at all on the TVOCs emission.

Figure 11 also shows the emission factors of toluene from MDF panels with different FE grades, lamination types, and surface exposure types. As expected from Figures 5 and 6, the toluene emission factors greatly increased for the UVC sample of MDF panel. This result is also attributed to the solvent that contains a large quantity of toluene in the coating material.

4. Conclusions

This study investigated the impacts of surface laminate type on the emissions of formaldehyde, TVOCs, and toluene from MDF and PB panels, using the 20-L small chamber method as a part of determining the indoor air quality of a building. Five different types of surface laminates, including three types of surface overlays such as LPL, PVC, and UCP and two types of surface coatings, i.e. DC and UVC were applied to the surfaces of PB and MDF panels with different FE grades. The following conclusions were drawn from this study:

(1) The FE grade strongly affected the FE factors, regardless of panel type, surface laminate type, and surface exposure type. All types of surface laminations reduced the FE level compared to that of the control.
(2) The surface lamination by overlay dramatically reduced TVOCs emission while the surface coatings significantly increased TVOCs emission regardless of the FE grade and panel type. Toluene emission was also greatly increased for the UVC samples. In particular, styrene was found to be the main component of TVOCs from the DC samples (about 87%), while toluene was the main species of TVOCs from the UVC samples (about 73%).
(3) When two different ways of sample preparation (i.e. single- or all-surface exposure) were compared, the FE of the control MDF sample decreased for all surface exposure while it increased for the surface-laminated MDF sample. However, TVOCs and toluene emissions greatly increased for the MDF sample with UVC lamination, which was independent of the FE grade. These results suggest that the surface laminate for wood panels has a significant impact on indoor air quality of a building.

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