Physico-Mechanical Properties and the TVOC Emission Factor of Gypsum Particleboards Manufactured with *Pinus Massoniana* and *Eucalyptus Sp*.

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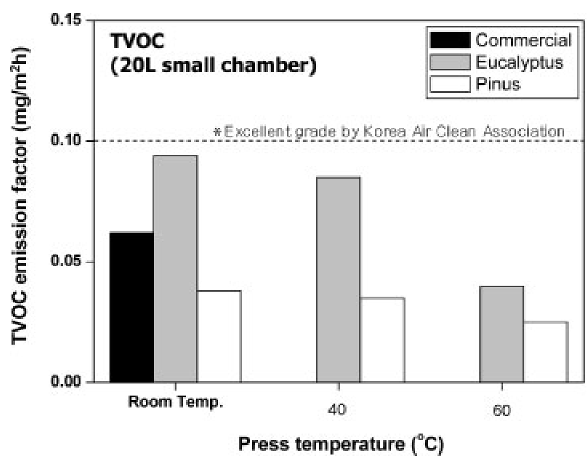
The effect of wood species on the TVOC emission factor and the physico-mechanical properties of GPBs is investigated. Of the two wood species, the water absorption was higher for the GPBs made using *Eucalyptus sp*. than for those using *Pinus massoniana*. The *Eucalyptus sp*. GPBs pressed at room temperature, 40 and 60 °C all demonstrated higher moisture absorption than commercial GPBs. The TVOC emission factor decreased with increasing press temperature, especially for *Eucalyptus sp*. but remained under 'excellent' grade as defined by the KACA. From these results, GPB with higher content of wood particles should be considered for the replacement of wood-based panels such as particleboard and medium density fiberboard (MDF).



Introduction

Many building materials emit volatile organic compounds (VOCs), which have the potential to affect human health and comfort. In recent years, there has been increased concern about the exposure to VOCs from indoor building materials. The health hazards associated with the use of building materials result from inhalation of fumes or vapors and skin absorption. The symptoms include eye, nose and throat irritation, headache, dizziness and tiredness.[1–5]

Gypsum board is extremely light, with a density of approximately 1 $g \cdot cm^{-3}$, and has several useful properties, including fire-resistance, and heat and sound insulation. As a fire retardant, the gypsum-board surface temperature can rapidly exceed 400 °C, causing only 2% shrinkage strain with intense cracking. Therefore, gypsum board can help the structural resistance of walls for considerable periods of time during fire exposure. Gypsum dihydrate can be converted to gypsum hemihydrate by heating at 180 °C for about 30 min. The largest use of gypsum is in the manufacture of gypsum board.[6]

Gypsum particleboard (GPB) has an established market around the world since it can be used for partition wall,

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attachment shuttering, wall and ceiling paneling, suspended ceilings, dry floor covering decorating, and also for vertical columns or beams. GPB has fire- and sound-proofing properties and it is well suited for thermal insulation.[7] This construction material consists of natural gypsum and residual or recycled wood particles. As a building material, GPB possesses a superior linear stability and performs better than other wood composite boards when exposed to fire. The raw materials are mixed with water containing citric acid, and then pressed into stable and odorless panels, dried, and cut to customary sizes. Moreover, the wood particles are not dried, and GPB is pressed under cold conditions, so that the consumption of thermal energy is low.[8] This GPB process is advantageous because it uses industrially-disposed gypsum, which is a by-product of many chemical processes. As a consequence, GPB has low production costs and is easy to manufacture.[9] GPB also has some drawbacks, including a tendency for increased moisture absorption, as both gypsum and wood are hygroscopic.[10] As a residential construction material, GPB is required to have a low thickness swelling (TS) and good mechanical properties to ensure its dimensional stability. GPB is produced in large quantities throughout the world for use as sheathing material in interior applications. These boards are made from foamed β-gypsum hemihydrate and particles.

The strength-enhancing advantages of mixing wood with an inorganic binder were foreseen as early as 1980 when a German patent was issued that described a light- weight, gypsum-bonded, wood-wool board. Wood composite boards must be pressed or clamped until the gypsum has hardened sufficiently to withstand the spring-back forces exerted by the wood particles and fibers. GPBs are made commercially in a discontinuous process requiring 2 hours of clamping time. The long press time is needed because of the retarder used to obtain the required open time. Continuous production of gypsum-bonded particleboard on a pilot-plant scale has been reported by Bücking.[11]

In this study, we investigated the effect of wood species on the total VOC (TVOC) emission factor and the physico- mechanical properties of GPBs manufactured under different press temperatures.

Experimental Part

Materials

Gypsum was obtained from a gypsum manufacturer (Shan Xi Province, China). *Eucalyptus sp.* and *Pinus massoniana* wood particles were provided by Cang Song GPB manufacturer (Shan Dong Province, China) and Nanjing New Human Board Industry Co., Ltd (Jiang Su Province, China), respectively. The proportions of screen analysis (S) of particles (opening) were 10.1% in $S < 0.71$ mm, 10.9% in $0.71 < S < 1.00$ mm, 15.2% in $1.00 < S < 1.40$ mm, 35.7% in $1.40 < S < 2.00$ mm, and 28.1% in 2.00 mm $< S$. Citric acid ($C_6H_8O_7$) was added as a retarder at a concentration of 0.05%, based on the gypsum weight.

Test Method

GPB Manufacture Method and Conditions

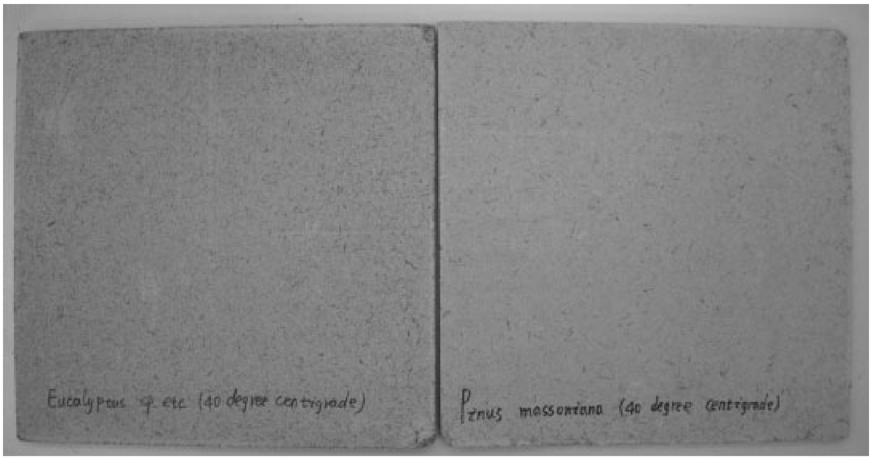
Each material was weighed at a wood/gypsum ratio of 0.3 and a water/gypsum ratio of 0.4. The particles were put in a blender, after which citric acid in water, followed by the weighed gypsum, was added. Boards of $10 \times 300 \times 300$ mm^3 were formed. The sample boards had a target density of 1.20 g $\cdot$ cm^{-3}. The mats were pressed at 3 MPa at room temperature, 40 and 60 °C for 2.0 h. The moisture content of the GPB mats was reduced to about 2–3% in a dryer at 45 °C. After being removed from the dryer, the mats were stored at room temperature for 1 week. GPBs made containing the *Pinus massoniana* and *Eucalyptus sp.* wood particles are shown in Figure 1.

Physical and Mechanical Properties

The physical properties, such as TS and water absorption, and mechanical properties, such as 3-point bending strength and internal bond strength, were determined using a Universal Testing Machine (Zwick) according to the China National Standard (Particleboard Standard 2003),[12] and the China Country Standard (GPB Standard 2002).[13]

Moisture Absorption

As mentioned above, GPB can be used as a partition wall, wall and ceiling paneling and suspended ceilings in indoor interiors. Therefore, the moisture-absorption test is more necessary than the water absorption test, because it is not immersed in water. Depending on the relative humidity, GPB absorbs and emits



1) GPB with *Eucalyptus sp.* 2) GPB with *Pinus massoniana*

Figure 1. GPBs containing *Pinus massoniana* and *Eucalyptus sp.* wood particles.

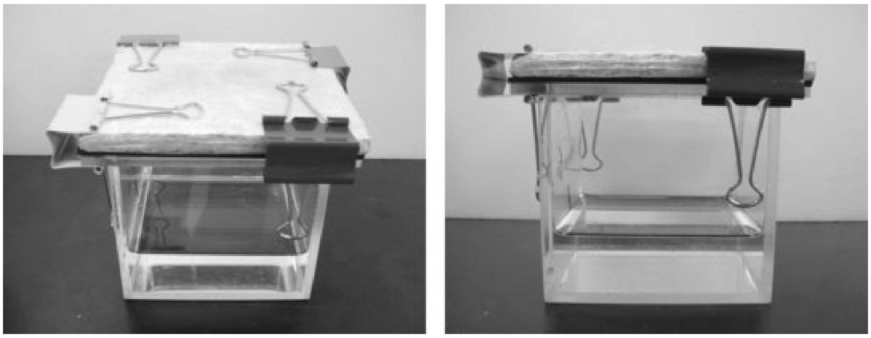


Figure 2. Lab-designed apparatus for moisture absorption.

moisture. The apparatus for the moisture-absorption test is shown in Figure 2. The top of a lab-designed, 10 cm^3 acrylic box was opened, for covering with GPB samples. In a thermo-hygrostat room, 300 mL of distilled water was added to the boxes, which were covered by a clamp-tightened GPB sample. To prevent the passage of water vapor through the GPB, the outer face was sealed with parafilm. Sealing and non-sealing were compared.

Typical Formaldehyde Emission Test: Desiccator

The Japanese standard method with a desiccator (JIS A 1460) was used to determine the formaldehyde emissions from GPB. The formaldehyde-emission test for GPB by the desiccator method was carried out using a glass desiccator. The emitted quantity of formaldehyde was obtained from the concentration of formaldehyde absorbed over a 24 h period in distilled or deionized water, when the test pieces of a specified surface area were placed in the desiccator, filled with the specified amount of distilled or deionized water. The principle for determining the concentration of formaldehyde absorbed in the distilled or deionized water was based on the Hantzsch reaction, in which the formaldehyde reacts with ammonium ions and acetylacetone to yield diacetyldihydrolutidine (DDL) (Japanese Industrial Standard 2001). The 24-hour desiccator method uses a common glass desiccator with a volume of 10×1 L. Eight test specimens, with dimensions of 5×15 cm^2, were positioned in the desiccator. The emission test lasted 24 h in the covered desiccator at a temperature of 20 °C. The emitted formaldehyde was absorbed in a water-filled Petri dish and was analyzed with the chromotropic-acid method.[3]

Formaldehyde and TVOC Emission: 20 L Small-Chamber Method

Before setting up the chamber and sealing the boxes, they were washed with water and baked in an oven at 260 °C to eliminate any pollutants from the chamber itself. The 20 L small chamber was supplied with purified and humidified air at a given ventilation rate. The temperature and relative humidity inside the chamber were kept constant.

The conditions shown in Table 1 were used with the 20 L small chamber.

Test pieces, laminate flooring, engineered flooring, non-veneered medium-density fiberboard (MDF) and particleboard (PB), all sealed with seal boxes, were set in the chamber, and the air inside the chamber was sampled after 12 h. The sampling conditions are shown in Table 2. Throughout the measurements, the air temperature and relative humidity inside the test chamber were kept constant at 25 ± 1 °C and 50 ± 5%, respectively, and ventilated at 0.5 h^{-1}. The aldehydes were analyzed by HPLC, and TDS/GC-MS was used for the VOCs, as shown in Table 3 and 4. In this paper, TVOC was defined as the conversion of all areas of the peaks between C_6 and C_{16} to concentrations using the toluene response factor. A peak area under 10 was defined as the limit of detection. The sample gas was collected using a Tenax-TA and 2,4-DNPH cartridge, 7 d after the sample specimens were installed into the 20 L small chamber, according to the regulations of the Ministry of Environment, Korea.

Results and Discussion

Physical Properties

The size of the wood particles is shown in Table 5. *Pinus massoniana* was bigger than *Eucalyptus sp*. The proportion of *Pinus massoniana* wood particles sized over 20 mesh was 52.9%, but for Eucalyptus sp. was only 9.9%. No significant difference was found between the TS of the *Pinus massoniana* and *Eucalyptus sp*. GPB. The TS values of the GPBs of the *Pinus massoniana* and *Eucalyptus sp*. were in the range of 2.8–3.0 and 2.8–4.0%, respectively. The press temperature had an effect on the WA value of the GPB of the *Pinus massoniana*. The WA was reduced on increasing the press temperature.

The water absorption of the GPBs made containing both *Pinus massoniana* and *Eucalyptus sp*. wood particles is shown in Figure 3. The water absorption of both *Eucalyptus sp*. and *Pinus massoniana* decreased with

Table 1. Conditions in small-chamber method to measure formaldehyde and TVOC emission.

Chamber Volume	Sample Size	Air-flow rate	Ventilation rate	Sample loading factor	Temperature	Humidity
L	m^2	$m^3 \cdot h^{-1}$	h^{-1}	$m^2 \cdot m^{-3}$	°C	%
20	0.0432 (0.147 m × 0.147 m × 2)	0.01	0.5	2.16	25 ± 1	50 ± 5

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Table 2. Sampling conditions of 20 L small chamber method.

	Sampler	Air-flow rate	Total volume
		mL · min^{-1}	L
Formaldehyde	2,4-DNPH Cartridge (Supelco, USA)	167	10
VOCs	Tenax-TA (Supelco, USA)	167	3.2

Table 3. Formaldehyde analysis conditions (Acme HPLC, UV/Vis detector at 360 nm, column Waters Nova-Pak C_{18} (3.9 m × 150 mm), mobile phase acetonitrile:water 60:40).

Analysis time	Injection volume	Column temperature	Mobile-phase flow rate	Purge-gas 99.99% He) flow rate
min	μL	°C	mL · min^{-1}	mL · min^{-1}
10	20	25	1.0	100

increasing press temperature from 29 and 26.1% at room temperature to 26 and 21.9% at 60 °C, respectively. Higher press temperatures hardened the GPB due to the vapor moisture. The space vacated by the vaporized moisture was filled up by fine gypsum particles. The water absorption of the *Eucalyptus sp*. GPBs was higher than that of the *Pinus massoniana* GPBs, because the former contains tracheid as a hardwood, which can absorb more water than the *Pinus massoniana* softwood.

With special apparatus, the moisture absorption was tested for 120 d at 20 °C in a constant temperature/humidity room. To prevent moisture vapor, the upper side of the GPB was sealed. As shown in Figure 4, the moisture absorption of *Pinus massoniana* GPBs was between 7.5 to 10% and that of *Eucalyptus sp*. GPBs was 7 to 9% at 3 000 h. *Pinus massoniana* GPBs showed a slightly higher moisture absorption. The *Eucalyptus sp*. GPBs pressed at room temperature, 40 and 60 °C all demonstrated a higher moisture absorption than commercial GPBs, but there was no difference between the three samples. The *Pinus massoniana* GPBs however, did show an increasing moisture absorption in the order: 40 < 60 °C < room temperature. The moisture absorption of non-sealed GPB is shown in Figure 5. Moisture was vaporized through GPB from the 10 cm^3 acrylic box to the air. The moisture absorption of the *Pinus massoniana* GPBs pressed at 40 and 60 °C was about 45%, while at room temperature it was 90%. Higher press temperatures increased the hardness of the GPBs. Because of the close gap between gypsum and wood particles at a high press temperature, the moisture absorption was much lower than at room temperature.

Mechanical Properties

The bending strengths of the GPBs made containing both *Pinus massoniana* and *Eucalyptus sp*. wood particles, formed at press temperatures of room temperature, 40

Table 4. VOC analysis conditions.

TDS	GC/MS	Column	Carrier gas and flow	Temperature Program	MS condition: Mode	MS condition: Electron energy (eV)	MS condition: Detection mode
Perkin Elmer ATD400	HP6890/ Agilent5973	RTX-1 (105 m × 0.32 mm × 3 μm)	He (99.99%)	40 °C (5 min) → 70 °C (5 min) → 150 °C (5 min) → 200 °C (5 min) → 220 °C (5 min) → 240 °C (5 min)	EI (Electron ion)	70	TIC (scan), m/z: 35/350

Table 5. Screening values of *Pinus massoniana* and *Eucalyptus sp.* particles.

Wood species	Screening value of particle	
	mesh	%
Pinus massoniana	≈20	52.9
	≈20–40	20.1
	≈40–60	9.2
	≈60–80	6.5
	≈80–100	4.7
	≈100–120	1.4
	≈120	5.2
Eucalyptus sp.	≈20	9.9
	≈20–40	47.9
	≈40–60	21.6
	≈60–80	11.2
	≈80–100	4.6
	≈100–120	1.1
	≈120	3.5

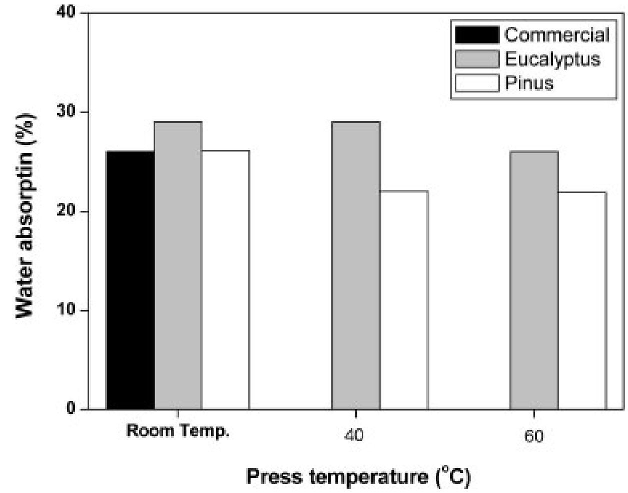

Figure 3. Water absorption of GPBs made using *Pinus massoniana* and *Eucalyptus sp.* wood particles.

and 60 °C, are shown in Figure 6. There was no difference in modulus of rupture (MOR) of the *Pinus massoniana* GPBs between the room temperature and 60 °C press temperatures. The MOR is about 5.4 MPa. The high MOR was produced in 40 °C press temperatures. The MOR of the *Eucalyptus sp.* GPBs was increased at press temperatures of 40 and 60 °C; the value of the MOR reached about 0.8 MPa. The value of the MOR at room temperature is 0.65 MPa. That is to say, under a press temperature of 40 °C, the MOR of the board increased by about 23%. No significant difference was found in the modulus of elasticity (MOE) of the *Pinus massoniana* and *Eucalyptus sp.*

As a reinforced composite material, the MOE values of GPB are related to the bonding strength of the board and the strength of the reinforcing materials themselves.[9] In addition, the MOE values are also related to the compression and tensile deformations under bending conditions. The bending MOE is the slope of the tangent line at the stress point of the proportional limit.[14] The strain (bending MOE) in the *Eucalyptus sp.* GPBs was higher than that of the *Pinus massoniana* GPBs. Greater strain means that the PB is more ductile.

The press temperature has no significant effect on the internal bond strength (IB). The tree species, however, has an effect on IB. The *pinus massoniana* GPBs have the higher values of IB, and the *eucalyptus sp.* GPBs have the lower values, as can be seen in Figure 7.

Formaldehyde and TVOC Emissions

In Figure 8, formaldehyde emission from the GPBs, which were made containing the *Pinus massoniana* and *Eucalyptus sp.* wood particles, formed at press temperatures of room temperature, 40 and 60 °C by the desiccator and 20 L chamber method, is shown. The formaldehyde-

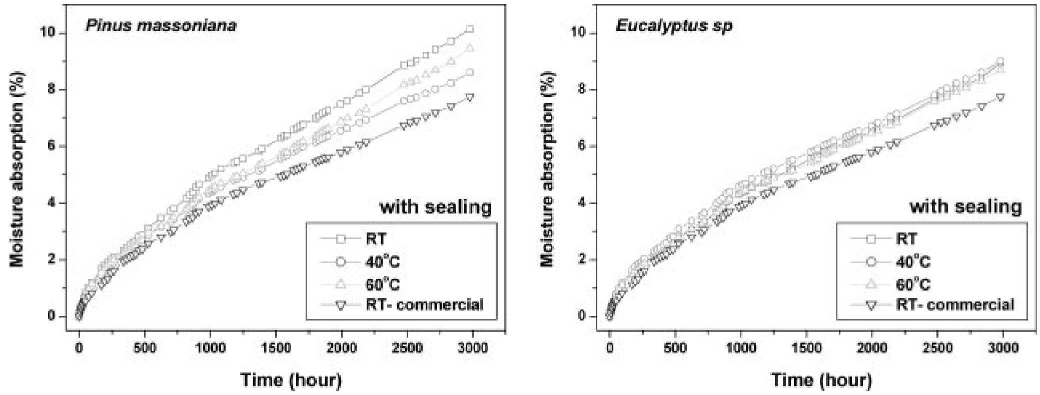

Figure 4. Moisture absorption of GPBs containing *Pinus massoniana* and *Eucalyptus sp.* wood particles; with sealing.

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emission results from all of the GPBs were so low, that there should be no concern about indoor air pollution. In Korea, the Ministry of Environment provides guidelines for formaldehyde and VOC emissions from building materials. Because a gypsum board is used as the interior material for the construction of buildings and houses, the emission of indoor air pollution materials, such as formaldehyde, is important. However, there was a much lower formaldehyde emission according to JIS (Japanese Industrial Standard) and KACA (Korean Air Clean Association), even F ☆☆☆☆ in JIS. Although wood particles were added to the gypsum board for GPB, adhesive was not necessary for bonding between the gypsum and the wood particles. These tendencies were shown in the TVOC emission results. TVOC emission factors of the GPBs made containing the *Pinus massoniana* and *Eucalyptus sp.* wood particles, between C_6 and C_{16}, are shown in Figure 9. From the results, the TOVC levels of the *Eucalyptus sp.* GPBs were twice as high as those of the *Pinus massoniana* GPBs at all press temperatures. On increasing the press temperature, the TVOC emission levels decreased, especially in the *Eucalyptus sp.* GPBs. However, in all cases, the TVOC emission factor was below the 'excellent' grade, as defined by KACA.[15] As interior building materials, GPBs with *Pinus massoniana* and *Eucalyptus sp.* wood particles can be used without indoor air pollution problems because there is no adhesive. From these results, GPB with higher wood-particle added content should be considered for replacement of wood-based panels such as PB and MDF because gypsum can perform the role of a formaldehyde-based resin. Further research will be required to determine the optimum mixing ratio condition of GPB in order for it to replace wood-based panels.

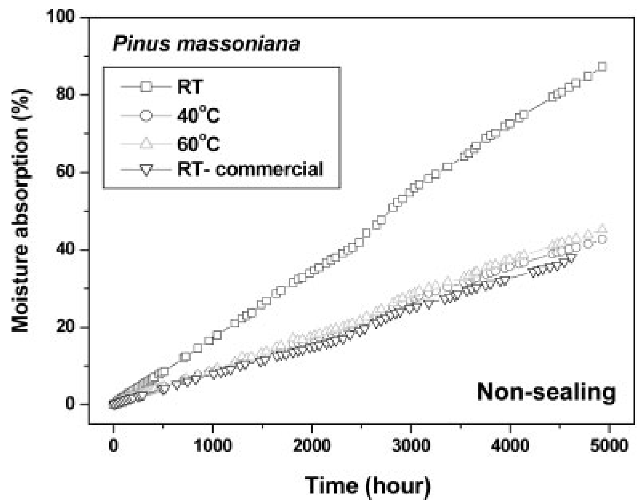

Figure 5. Moisture absorption of GPBs made using *Pinus massoniana* wood particles; non-sealing.

Conclusion

From the results of this study, it may be concluded that *Pinus massoniana* and *Eucalyptus sp.* are good reinforcement materials for the manufacture of GPB, with a slight resistance effect on the absorption of water and moisture into the board. In terms of the atmosphere condition, the moisture content in GPB can be controlled through the GPB itself. After 120 d, a moisture content of about 10 wt.-% was added in the upper, sealed GPB. The physical properties of the GPB were slightly influenced by a higher press temperature, at 40 and 60 °C. The effect of *Eucalyptus sp.* on the MOR and MOE of GPB was more significant than that of *Pinus massoniana* wood particles. However, the internal bond strength exhibited the opposite trend with the value for *Pinus massoniana* GPBs being twice as high as that for *Eucalyptus sp.* GPBs. Formaldehyde and TVOC emission factor of *Pinus massoniana* and *Eucalyptus sp.* Wood-particle GPBs were very low, so as not to arouse any concern about the emission of indoor air pollution materials. These results suggest that controlled mixing of gypsum and *Pinus massoniana* and *Eucalyptus sp.* wood particles can generate a suitable GPB-replacement material for wood-based panels, bonded by formaldehyde-based resin.

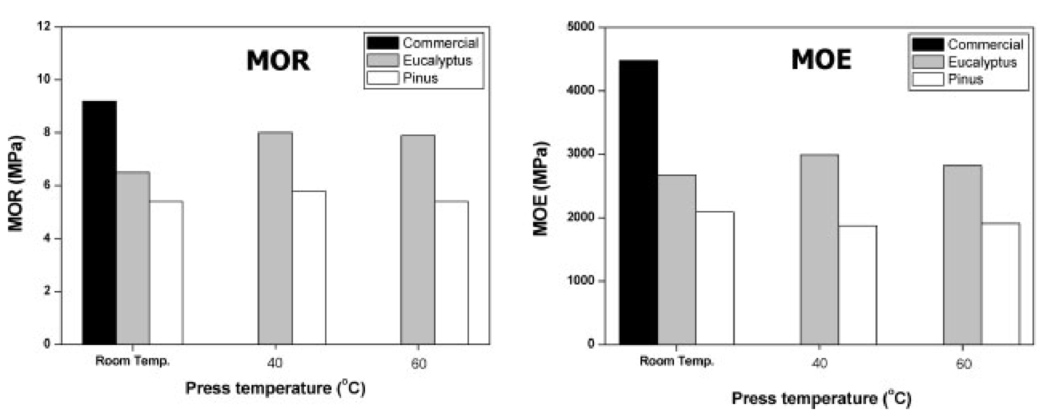

Figure 6. Bending strength of GPBs containing *Pinus massoniana* and *Eucalyptus sp.* wood particles.

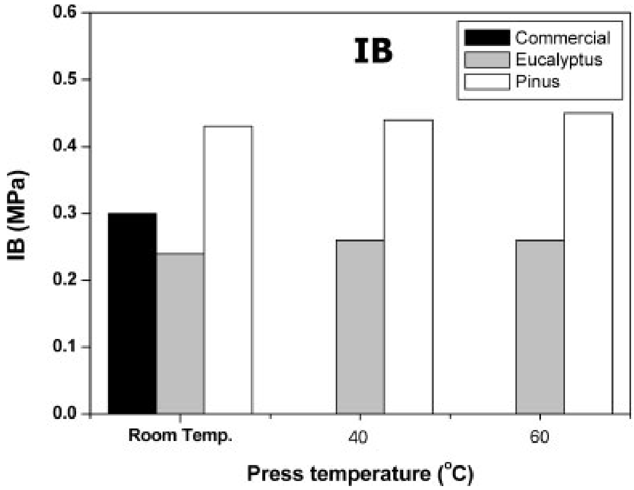

Figure 7. Internal bond strength of GPBs containing *Pinus massoniana* and *Eucalyptus sp*. wood particles.

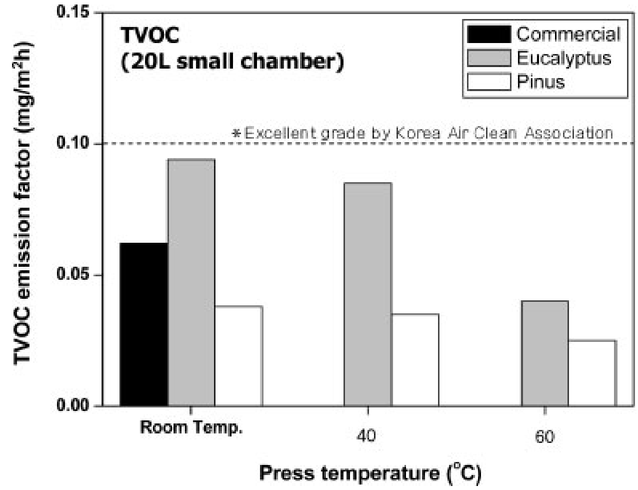

Figure 9. TVOC emission factor of GPBs containing *Pinus massoniana* and *Eucalyptus sp*. wood particles by 20 L small-chamber method.

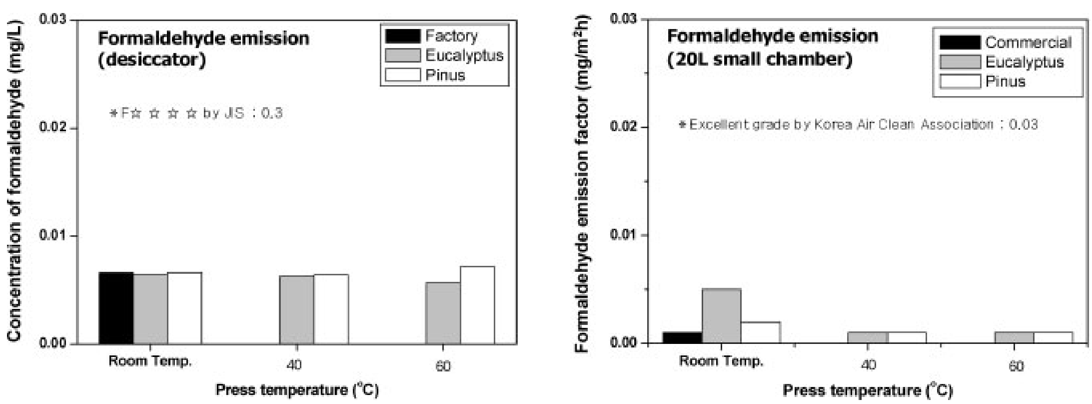

Figure 8. Formaldehyde emission factor of GPBs containing *Pinus massoniana* and *Eucalyptus sp*. wood particles, by desiccator and 20 L small-chamber method.

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[1] S. J. Hansen, H. E. Burroughs, "*Managing Indoor Air Quality*", 2nd Edition, The Fairmont Press Inc., Lilburn 1999, p. 62.
[2] N.-H. Kwok, S.-C. Lee, H. Guo, W.-T. Hung, *Building Environment* **2003**, *38*, 1019.
[3] S. Kim, H.-J. Kim, *Indoor Air: Int. J. Indoor Environment Health* **2005**, *15*, 317.
[4] S. Kim, H.-J. Kim, *Bioresource Technol.* **2005**, *96*, 1457.
[5] T. J. Kelly, D. L. Smith, J. Satola, *Environ. Sci. Technol.* **1999**, *33*, 81.
[6] K. Yoshiyuki, Y. Tamotsu, *J. Eur. Ceram. Soc.* **2006**, *26*, 777.
[7] W. Peterson, "Fields of Application and Production Experience Gained with Gypsum Fiberboards", in: *Proceedings of Inorganic-Bonded Wood and Fiber Composite Materials Conference* 1992, 3, 83.
[8] K. Lempfer, T. Hilbert, H. Günzerodt, *Forest Products J.* **1990**, *40*, 37.
[9] Y. H. Deng, T. Furuno, *Holzforschung* **2002**, *56*, 440.
[10] Y. H. Deng, T. Furuno, *J. Wood Sci.* **1998**, *44*, 99.
[11] G. Bücking, *Holz als Roh-Werkstoff* **1983**, *41*, 427.
[12] China Country Standard GB/T 4987. Particleboard 2003.
[13] China Linye Standard LY/T 1598. Gypsum Particleboard 2003.
[14] S. Kim, Y.-K. Lee, H.-J. Kim, H. H. Lee, *J. Adhes. Sci. Technol.* **2003**, *17*, 1863.
[15] S. Kim, J.-A. Kim, H.-J. Kim, S.-D. Kim, *Polym. Testing* **2006**, *25*, 605.

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