Furnish type and mat density effects on temperature and vapor pressure of wood-based panels during hot pressing

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Abstract

The goals of this study were to determine the effects of furnish type and mat density on temperature and vapor pressure inside the mat of wood-based panels during hot pressing and to confirm their effects on panel properties. Two furnish types, hinoki strand (HS) and recycled wood particles (RW), were used for experimental panels using urea-formaldehyde resin at five board densities and 15% mat moisture content. A monitoring device was used to sense the temperature and vapor pressure during hot pressing. The results from this study showed that furnish type and mat density affected temperature and vapor pressure behaviors. The results also showed the effect on panel properties. HS-board had a higher plateau temperature, longer plateau time, and higher vapor pressure than did Mixed- and RW-board. Higher mat density was associated with higher plateau temperature and vapor pressure and longer plateau time and vapor pressure band. Plateau time and temperature were also correlated with vapor pressure. Furthermore, density showed linear relationships with plateau temperature and internal bonding (IB). A linear relationship was also found between plateau temperature and IB, and non-linear relationships were found for vapor pressure with plateau temperature and IB.

Introduction

In panel production, the phenomena of heat and mass transfer during hot pressing are complex. During these processes, a number of factors are involved including not only the raw material itself but also the operating conditions. Hot pressing provides thermal energy and the mechanical force of compression to consolidate the mat [1]. Temperature and gas pressure affect the hot pressing process and the wood-based panel properties [2]. Internal gas pressure develops in the mat during hot pressing due to the compaction of air and vaporization of water and volatile compounds from the wood particles and adhesive. Therefore, the gas is regarded as a vapor [3]. The level of gas pressure affects heat convection into the mat and transient temperature inside the mat [4].

To understand the physical phenomena inside the mat during hot pressing, it is important to understand the interaction between temperature and vapor pressure. The interaction between temperature and vapor pressure can be investigated directly during the wood-based panel hot pressing process. Several studies have used thermocouples connected to a data logger and small stainless steel tubes connected to pressure transducers to measure the transient temperature and gas pressure inside the mat panels [2,5,6,7]. A system called PressMAN was developed by the Alberta Research Council, Canada, to monitor both temperature and gas pressure in laboratory- and industrial-scale panel production [4,8].

This study involved direct measurement of both temperature and vapor pressure change using PressMAN Lite. A previous study reported temperatures inside the mat during hot pressing at various mat moisture levels, resin types and pressing temperatures [9]. Mat permeability, which depends on furnish type, has an important impact on temperature and heat conductivity. Furthermore, as heat is transferred by conduction and convection, the structure of the mat is important. Furnish type is not the only variable affecting the porous structure of the mat; density also plays an important role. Furnish type and density affect mat permeability and, consequently, the rate of heat and mass transfer, i.e., heat transfer from the mat surface to the center and vapor escaping from the center of the mat to the edges. This study was designed to examine the effect of furnish type and density on the relationship of temperature and vapor pressure behaviors inside the mat of wood-based panels during pressing. Mechanical properties of manufactured panels were also investigated to confirm the effects of those behaviors on panel performance.

Materials and methods

Two furnish types, hinoki strand (HS) and recycled wood (RW) particles, were used for experimental panels. The particle-size distribution was determined using a sieve shaker, with particles allocated to six different size classes as shown in Table 1. The dimensions (length, width, and thickness) of 300 randomly selected particles of two furnish were measured for determining its slenderness and aspect ratio. Bulk density of each furnish was also determined. The moisture content (MC) of the particles was about 8% and the target mat MC was 15%. Urea formaldehyde resin, with a solid content of 65.4% (Oshika Co., Ltd.), was used as an adhesive at 9% based on particle weight and a 10% aqueous ammonium chloride solution was used as a hardener at 11% based on the adhesive weight. The target densities of the board were 0.54, 0.61, 0.68, 0.75, and 0.82 g/cm³, and the board size was 340 mm × 320 mm × 10 mm. A distance bar with 10 mm in thickness was used to maintain the thickness of the mats. For each furnish and density, three replicate panels were fabricated, while the Mixed-boards (50% HS and 50% RW, based on weight) were made only for density of 0.75 g/cm³. Pressing was applied at an initial pressure of 3 MPa until the core temperature reached the press temperature of 180°C. A press monitoring system (PressMAN Lite, Alberta Research Council) was used to monitor the temperature and vapor pressure change during hot pressing. A temperature/pressure probe was inserted into the center of the mat.

The period at which a constant temperature occurred at the centerline of the mat, called the plateau time, and the constant temperature achieved, called the plateau temperature, were indicators of temperature behavior inside the mat [9]. The plateau temperature was the highest core temperature during the vaporization stage. Maximum vapor pressure (Vp) and vapor pressure band (Vp-band) were used to characterize vapor pressure. Vp is the pressure above atmospheric pressure in kilo-Pascal (kPa) and Vp-band is a period taken from the vapor pressure–time curve at Vk and is measured in seconds; Vk is calculated as follows:

The manufactured panels were conditioned at 20°C and 65% relative humidity for 2 weeks. The internal bonding (IB) strength of the panels was determined according to JIS A 5908 [10].

Results and Discussion

Particle classification

Screen analysis was conducted to characterize the shape of particles, as previously performed by Rofii et al. [11]. Table 1 shows the mean weight percentage of each particle size. For HS-type panels, 87.0% of the fraction was collected on the 5-mesh sieve, which had an opening of 4.0 mm. RW-type particles were mainly distributed in three fractions: 35.5% in the 5(+) sieve, 37.2% in the 10(+) sieve, and 23.4% in the 20(+) sieve. The characteristic of these raw materials was described in a previous study [9]. HS are longer and thinner, while RW are shorter and thicker with slenderness and aspect ratio of 78.6 and 6.1, and 16.9 and 6.5, respectively. The bulk density was 0.06 and 0.10 g/cm³ for HS and RW, respectively. The results indicate that two furnish are different.

Effect of furnish and mat density on core temperature–time and vapor pressure–time curves

The effect of furnish type on temperature during hot pressing was reported in a previous study [9]. Different furnish types resulted in different plateau times and temperatures during the vaporization stage, mainly due to mat permeability. In this study, we observed an obvious effect of vapor pressure on core temperature during the vaporization stage. Figure 1 depicts the vapor pressure of different furnish types during pressing. It shows that the vapor pressure of HS-board started to increase at about 50 s and attained a maximum value of 265 kPa at 245 s. The vapor pressure decreased rapidly up to press time at about 500 s and then gradually up to 1000 s. The same vapor pressure trend occurred for the Mixed- and RW-boards, but the maximum vapor pressure was about 190 kPa at 200 s and 140 kPa at 175 s, respectively. The vapor in low permeable HS-board was more difficult to release to the edge of the mat panels. This resulted in high vapor pressure and required more time to release all water vapor generated during hot pressing.

Figure 2 depicts the temperature behavior of the HS-board at different densities. For a mat density of 0.54 g/cm³, the core temperature started to increase at about 20 s, with a very rapid increase up to 100°C. Thereafter, it stayed at constant temperature at 105°C for about 100 s during the vaporization stage, and then increased again to reach the platen temperature for about 700 s. The same trend of the core temperature curve could be seen for the other mat densities, with different characteristics based on a time index, as previously reported [9]. Densities of 0.54 and 0.61 g/cm³ were associated with typical temperature behavior, whereas at higher densities (greater than 0.68 g/cm³), the core temperature decreased at the end of the vaporization stage and then increased again to reach the platen temperature. These results indicated that different densities have different plateau temperatures. The plateau temperatures were about 105, 115, 130, 145, and 155°C for densities of 0.54, 0.61, 0.68, 0.75, and 0.82 g/cm³, respectively. The lower the density was, the shorter the vaporization stage and the time required to reach the platen temperature were. HS-board had a higher plateau temperature than did Mixed- and RW-boards. The average plateau temperature of 0.75 g/cm³-board was about 145, 135, and 130°C for HS, Mixed, and RW boards, respectively.

Figure 3 provides the vapor pressure of HS-board at different densities. The vapor pressure of 0.82 g/cm³-board started to increase at 90 s and reached the maximum value of 320 kPa at 305 s. Vapor pressure then decreased rapidly to 100 kPa at 600 s and then gradually to 1000 s. The maximum vapor pressures were about 11, 45, 125, 270, and 320 kPa for densities of 0.54, 0.61, 0.68, 0.75, and 0.82 g/cm³, respectively. This was because higher density mats had lower permeability, and vapor convection was reduced as a result of mat compaction which limited the release of vapor pressure. The vapor pressure curve of RW-board was almost the same as that of HS-board, but its maximum vapor pressure was less than that of the HS-board at the same density. The maximum vapor pressures of RW-board were about 4, 20, 40, 150, and 220 kPa for densities of 0.54, 0.61, 0.68, 0.75, and 0.82 g/cm³, respectively. The Vp band, based on Eq. 1, also increased with increasing density. HS-board had a longer Vp-band than did RW-board. For HS-board, the Vp-bands were about 181, 191, 263, and 373 s for densities of 0.61, 0.68, 0.75, and 0.82 g/cm³, respectively. For RW-board, the Vp-bands were about 161, 179, 236, and 281 s for densities of 0.61, 0.68, 0.75, and 0.82 g/cm³, respectively. Low-permeable HS-board caused high vapor pressure, which contributed to the higher core temperature. The varying vapor generated inside the mat caused varying plateau times and temperatures. These results were consistent with results reported by Garcia et al. [6], who stated that density has a positive effect on thermal conduction and a negative effect on lateral and transverse permeability and transverse thermal convection.

Relationship between core temperature and vapor pressure

Figure 4 shows a representative relationship between the temperature and vapor pressure curves in the core of the mat during hot pressing. It appears that the vapor pressure started to increase after the core temperature reached approximately 60°C at 65 s and attained the maximum value of 66.5 kPa when the core temperature was 116°C at 255 s. The rapid increase in vapor pressure followed the increasing core temperature as the heat was transferred by convection. The vapor pressure band was also found to corresponded to plateau time. The Vp-band was 350 s at 33.25 kPa, and plateau time was 300 s. The correspondence between the Vp-band and plateau time was apparent if there was no drop in core temperature during the vaporization stage. At the end of the vaporization stage, the vapor pressure decreased rapidly, and the temperature started to increase slowly. These results indicate that the mat panels almost achieved the final thickness because of mat consolidation. Therefore, the heat was transferred only by conduction.

Although some studies have mentioned the relationship between temperature and gas pressure, the present study described their quantitative relationship. The level of vapor pressure also had a strong relationship with plateau temperature (Fig. 5). This relationship implies that the plateau temperature is strongly affected by the vapor pressure. In this study, higher plateau temperature resulted in higher vapor pressure, which was described according to a regression equation, with a correlation coefficient of 0.98 regardless of furnish type. According to theory, vapor pressure is a function of temperature and could be determined using a theoretical correlation such as the Antoine equation [12]. The empirical correlation line between vapor pressure and plateau temperature in this study corresponded to the theoretical correlation line based upon the Antoine equation (Fig. 5). Moreover, this finding is supported by Garcia et al. [6], who reported, based on flake alignment, that lower plateau temperature is related to lower gas pressure, whereas higher gas pressure results in a higher plateau temperature. However, it should be noted that high vapor pressure resulted from higher mat density due to mat permeability, which caused the vapor to be entrapped inside the mat.

The Vp-band increased with increasing plateau time (Fig. 6). The relationship could be expressed by a linear regression line with a correlation coefficient of 0.81, regardless of furnish types. This implies that the Vp-band could be predicted from plateau time. The relationship between plateau time and the Vp-band could also be considered. At 0.6–0.7 g/cm³ density, the period of the Vp-band was similar to that of plateau time. At low density, the core temperature did not produce plateau. Therefore, plateau time could not be determined. In contrast, at high density, plateau time was difficult to determine due to the depression of the core temperature curve, which was attributed to moisture vaporization.

Internal bonding strength of the panels

In panel production, measuring the IB strength is important because it indicates the strength of the bonds between particles and also the adequacy of the blending and pressing processes [13]. It is already known that density has a significant effect on bonding strength of wood-based panels. Results from this study were consistent with reports that higher density resulted in a higher IB strength [14-17]. The IB strength of RW-board was higher than that of HS-board at the same density level. This might be because the RW particles were shorter and thicker than the HS particles, promoting improved inter-particle bonding, which implies that furnish type had a greater effect than mat density had on IB strength. The core density of the panel can explain this phenomenon. Based on the vertical density profile, at target board density of 0.75 g/cm³, the actual board densities were 0.75, 0.73 and 0.74 g/cm³ with the core densities of 0.69, 0.70 and 0.71 g/cm³ for HS-, RW- and Mixed-boards, respectively. It was found in this study that the IB strength increased linearly with increasing plateau temperature. At the same plateau temperature, RW-board had almost twice the IB strength of HS-board. This indicates that furnish type had a greater effect than plateau temperature on IB strength. As previously mentioned, a higher plateau temperature resulted from higher mat density. This supports the assertion that mat density affects IB strength [18]. If the mat density is higher, the plateau temperature would be higher, and, thus, the IB strength would be greater.

Figure 7 shows the IB strength of manufactured panels as a function vapor pressure, with higher vapor pressure resulting in greater IB strength. This may be due to the effect of mat density, as shown in Fig. 3. However, the relationship between vapor pressure and IB strength was not linear. Very high vapor pressure inside the mat could decrease IB strength. If the vapor pressure is higher than IB strength, it may promote a blow or blister after the press opens during panel manufacturing [3]. This may occur on panels with high mat MC. In the present study, no blow or blister was observed.

It is well known that density affects IB strength. Quantitative evaluation is needed for the next study concerning on how plateau temperature and vapor pressure affect IB, as both are affected by density. Density had a linear relationship with plateau temperature and IB, and plateau temperature had a linear relationship with IB and a non-linear relationship with vapor pressure. A non-linear relationship was also found for vapor pressure with plateau temperature and IB. This implies that vapor pressure influenced inter-particle bonding within the mat. To optimize final board performance, the effect of vapor pressure must be minimized during panel production.

Conclusions

Wood-based panels of different furnish types and densities were produced, and we studied their temperature and vapor pressure behaviors during hot pressing. Their effects on panel properties were also investigated. The results of this study can be summarized as follows:

1. The *Vp*-band had a linear relationship with plateau time regardless of furnish type.

2. The use of HS-board resulted in a higher plateau temperature and vapor pressure compared with the RW-board and with mixtures of these two types.
3. Density strongly affected vapor pressure. The maximum vapor pressure increased from 11 to 320 kPa for density from 0.54 to 0.82 g/cm³ for the HS-board.
4. The maximum plateau temperature was strongly affected by maximum vapor pressure. A higher plateau temperature resulted in higher vapor pressure, which was expressed by a quadratic equation and was in accordance with a theoretical correlation line based upon the Antoine equation.
5. Higher vapor pressure resulted in higher IB strength. A non-linear relationship was found between vapor pressure and IB, whereas the relationship between plateau temperature and IB was linear.

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Figures Legends

Fig. 1. Representative vapor pressure–time curves for different furnish types at a density of 0.75 g/cm³.

Fig. 2. Temperature–time curves of hinoki strand (HS)-board with various densities from 0.54 to 0.82 g/cm³.

Fig. 3. Vapor pressure–time curves of hinoki strand (HS)-board with various densities from 0.54 to 0.82 g/cm³.

Fig. 4. Temperature–time and vapor pressure–time curves in the center of the mat during hot pressing. Mixed-board with 13% mat moisture content (MC) and 0.75 g/cm³ density was used.

Fig. 5. Relationship between maximum vapor pressure and plateau temperature; thin dashed line indicates the empirical line, and thick dashed line indicates the Antoine correlation line.

Fig. 6. Relationship between vapor pressure band and plateau time; the thick line indicates the empirical regression line, and dashed line indicates the diagonal line.

Fig. 7. Effect of vapor pressure on internal bonding (IB) strength.

Table 1. Particle size distribution based on weight percentage (%).

Furnish type	Mesh size[a] and sieve opening (mm)					
	5(+)	10(+)	20(+)	30(+)	40(+)	40(-)
	4.0	2.0	0.85	0.60	0.425	0.425
HS	87.0	8.0	4.1	0.3	0.4	0.2
RW	35.5	37.2	23.4	1.4	1.5	1.0

Each mean represents *n* = 3 sample bags with each bag containing 50 g of furnish type sample.

[a] Mesh size opening: (+) particles retained on the sieve; (-) particles passed through the sieve.
HS: hinoki strand, RW: recycled-wood particles

Figure 1

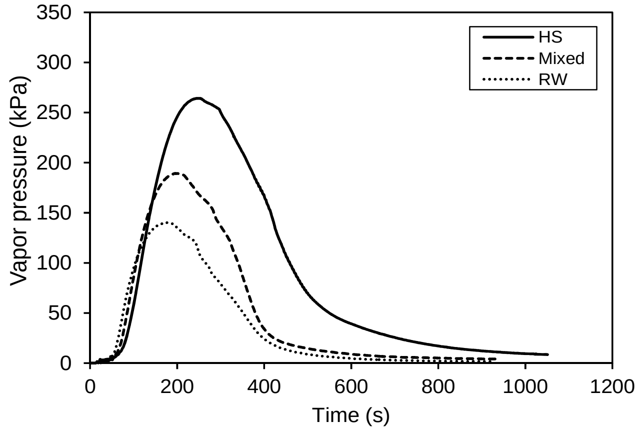


Figure 2

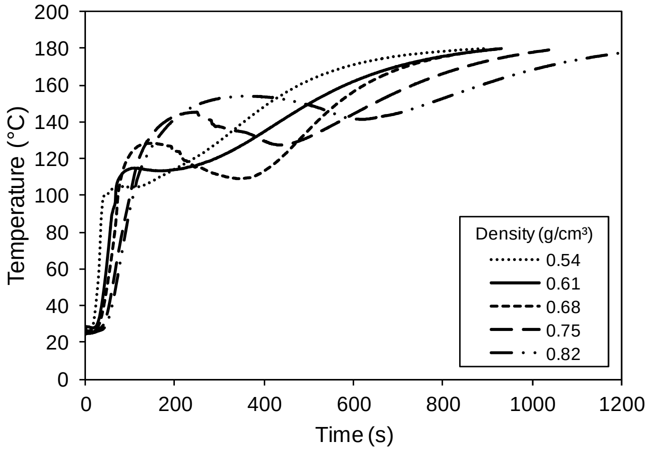


Figure 3

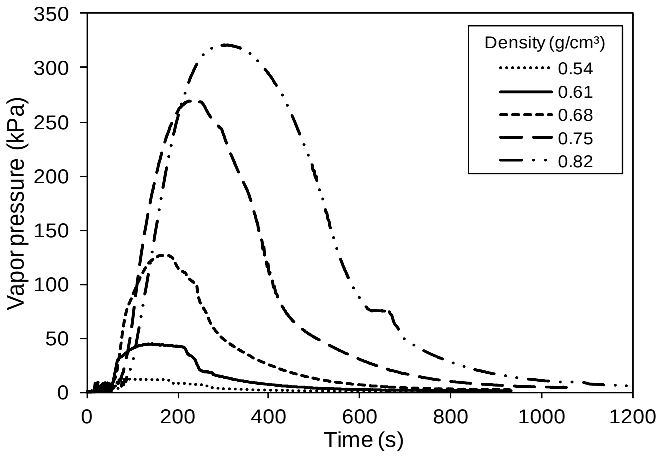


Figure 4

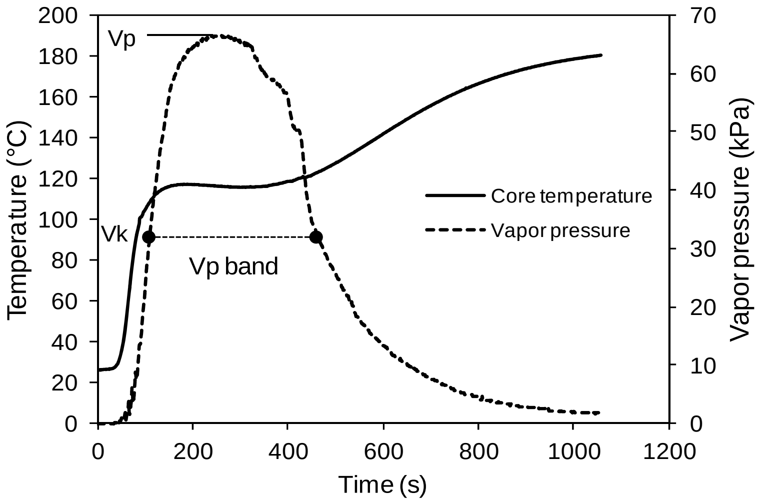


Figure 5

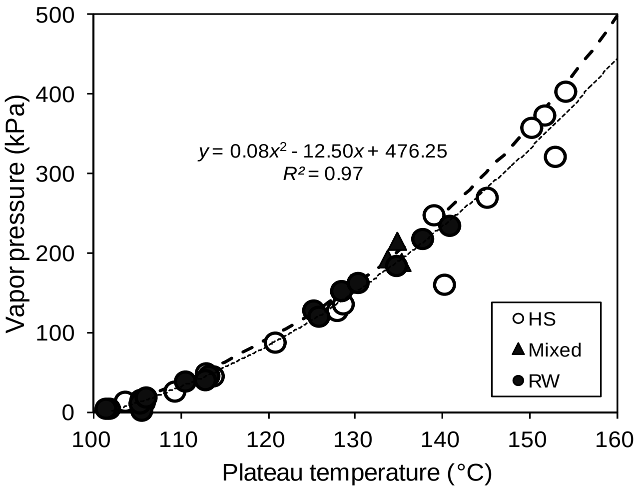

500
400
300
200
100
0
Vapor pressure (kPa)
y = 0.08x² - 12.50x + 476.25
R² = 0.97
○ HS
▲ Mixed
● RW
100
110
120
130
140
150
160
Plateau temperature (°C)

Figure 6

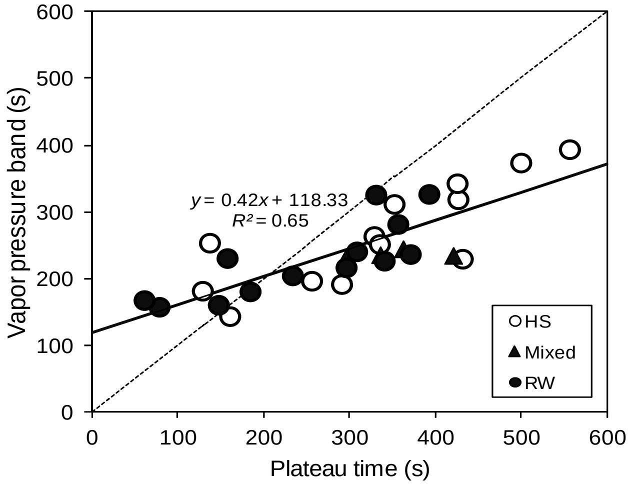
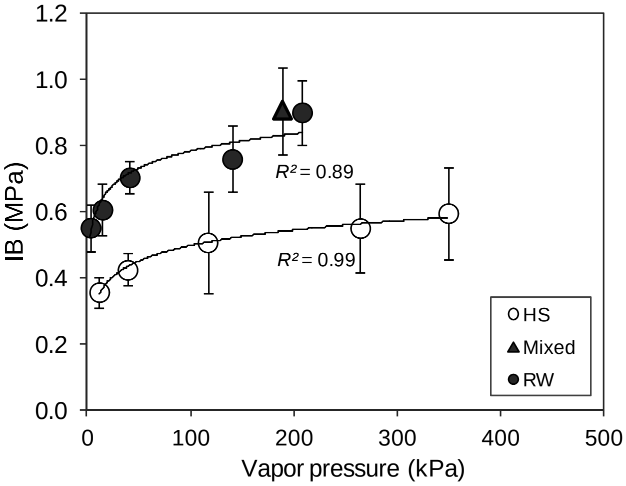

600
500
400
300
200
100
0
Vapor pressure band (s)
y = 0.42x + 118.33
R² = 0.65
○ HS
▲ Mixed
● RW
0
100
200
300
400
500
600
Plateau time (s)

Figure 7


1.2
1.0
0.8
0.6
0.4
0.2
0.0
IB (MPa)
0
100
200
300
400
500
Vapor pressure (kPa)
$R^2 = 0.89$
$R^2 = 0.99$
○ HS
▲ Mixed
● RW