J Wood Sci (2013) 59:195–202
DOI 10.1007/s10086-013-1323-9

ORIGINAL ARTICLE

Performance of particleboard manufactured using air-injection press II: effects of board density and thickness on the performance of board manufactured from low-moisture particles

Hiroshi Saotome · Hideaki Korai

Received: 5 December 2012 / Accepted: 9 January 2013 / Published online: 22 February 2013
© The Japan Wood Research Society 2013

Abstract Particleboards of different densities (0.6, 0.7 and 0.8 g/cm^3) and thicknesses (10 and 20 mm) were manufactured from low-moisture particles using an air-injection press. The effects of the air injection on preventing blowout of the boards of different densities and thicknesses were investigated by artificially creating blowout-prone conditions using metal frames. The effects of the air-injection pressure on the board performance were also investigated. 10-mm-thick boards of 0.8 g/cm^3 pressed at 170 °C blew out when air was not injected, but were successfully manufactured by injecting air. 10-mm-thick boards at 150 °C showed constant internal bond (IB), regardless of density, but at 170 °C, IB was higher in boards of higher densities. This was likely due to accelerated hardening of the urea–formaldehyde resin at 170 than 150 °C. At both pressing temperatures, low air-injection pressure did not cause blowout and a reduction in board performance. Air injection also prevented the blowout of thick boards of 20 mm and enabled successful manufacture, showing its effectiveness. The IB of the 20-mm-thick board manufactured using the air-injection press exceeded that of 20-mm-thick board manufactured using an ordinary hot press.

Keywords Air-injection press · Particleboard · Blowout · Board density · Board thickness

Part of this article was presented at the 62nd annual meeting of Japan Wood Research Society (Sapporo, March 2012).

H. Saotome · H. Korai (✉)
Forestry and Forest Products Research Institute,
Tsukuba 305-8687, Japan
e-mail: korai@ffpri.affrc.go.jp

Introduction

When manufacturing particleboard, vapor is essential for transmitting heat from the heating plates to the core of the board. However, the vapor can increase the pressure inside the board and cause a blowout when the press is opened [1]. To prevent blowout, particles are thoroughly dried in advance to reduce the moisture content and the amount of vapor. However, blowout may still accidentally occur in factories manufacturing large-scale boards. Although the frequency of such accidental blowout is low, the blowout spoils all processes of board production. Generally speaking, blowout dramatically reduces the productivity of the board. Moreover, small localized incipient blowouts, which do not involve bursting, are a more serious problem than burst blowout since these occur inside the board and are difficult to detect. Therefore, it is important to prevent blowout, including small incipient blowout, to improve productivity. This is why the air-injection press that injects air during hot pressing to discharge vapor was developed [1–4].

Previous paper reported the effects of air injection on the performance of boards manufactured from high-moisture (25 %) particles (high-moisture board), which were used to skip the drying process and reduce energy consumption [1–3]. Air injection was successfully used to manufacture high-moisture boards without blowout. On the other hand, it was shown that the air injection also caused the discharge of binder from the boards [2].

The performance of the board manufactured from low-moisture particles was superior to that of high-moisture particles [1, 5]. Conditions for blowout of the boards as well as the performance of the boards manufactured varied according to whether high- or low-moisture particles were used. Another of our previous paper investigated the effects of air injection on boards manufactured from low-moisture (15 %) particles (low-moisture board) [6]. It was necessary to confirm the effects of air injection on preventing blowout of the low-moisture boards since blowout still occurs in factory production as described above. Air injection was also shown to be effective in preventing blowout of low-moisture boards. The air injection inevitably discharges binder from low-moisture boards as well as for high-moisture boards [6]. Although the air injection was expected to impair the board performance due to discharge of the binder, the board performance was unimpaired [6], suggesting that air injection can also prevent accidental blowout in factory production without impairing the performance of the boards and thus improve productivity.

Boards of diverse dimensions and performance are manufactured in factories. In this study, low-moisture boards of different densities (0.6, 0.7 and 0.8 g/cm^3) and thicknesses (10 and 20 mm) were manufactured using the air-injection press. Dense and/or thick boards may reduce the effects of air injection because it is difficult for the injected air to pass through the boards. The effects of density and thickness on blowout and the performance of the boards were investigated.

Experimental

Conditions of particleboard manufacture

The boards were manufactured from particles prepared from wood waste for the core layer of the board (Japan Novopan Industrial Co., Ltd.). The mean length (standard deviation) of 200 measured particles was 15.4 (6.69) mm, and the moisture content was about 10 %. The binder used was a urea–formaldehyde resin (Oshika Co., Ltd.), which had a solid content of 65 % and viscosity of 0.14 Pa s. A hardening agent of 10 % ammonium chloride solution was added to the binder to constitute 10 % (by weight). The binder (based on solid) was sprayed on the particles to constitute 10 % (by weight) while the particles were stirred in a blender. The moisture content of the particles after application of the binder was about 15 %.

Blowout hardly occurs in boards manufactured in the laboratory from low-moisture particles (15 %) [6, 7] due to the small size. To induce blowout, a metal frame was used as in the previous study [6]. Particles sprayed with binder were manually spread out in a mat form, and a metal frame was placed on the mat. A mat in a forming box and the metal frame are shown in Fig. 1. The metal frame prevents vapor from escaping from the sides of the board to induce blowout. The frame was used to investigate the blowout prevention effects of air injection for various board densities and thicknesses. The dimensions of the metal frame were thickness and width of 6 mm and inner dimensions of 270 × 270 mm. One frame was used for 10-mm-thick boards, and two frames were used for 20-mm-thick boards (Fig. 2).

As in the previous studies [2–4], the diameter of the air-injection holes was 1 mm, the spacing between the centers of adjacent holes was 25 mm and there were a total of 121 holes within an area of 250 × 250 mm. Air injection was started after the board had been pressed to the final thickness and was stopped for the final 15 s before opening the press.

The abbreviations of the boards and the conditions of manufacture are shown in Table 1. “Air-injection press boards (AIP board)” were manufactured by placing the metal frame in position and then hot pressing with air injection, while “ordinary press boards (OP board)” were manufactured without the metal frame and by hot pressing without air injection. The boards were pressed at 150 or 170 °C for 6 min. The densities of the boards were 0.6, 0.7 and 0.8 g/cm^3, respectively, and their dimensions were 300 × 300 × 10 mm. For the AIP boards, air was injected at 0.55 MPa.

Next, “150 °C boards” and “170 °C boards” were manufactured by placing the metal frame in position and then hot pressing at 150 and 170 °C, respectively, for 6 min with air-injection pressure at 0.20, 0.40 and 0.55 MPa (Table 1) at room temperature. The densities of the boards were 0.6, 0.7 and 0.8 g/cm^3 and their dimensions were 300 × 300 × 10 mm.

To investigate the effects of board thickness, “10-mm boards” and “20-mm boards” were manufactured by placing the metal frame in position and then hot pressing at 170 °C for 4–14 min and injecting air at 0.55 MPa (Table 1). The density of the boards was 0.7 g/cm^3, and the

Fig. 1 A mat and a metal frame in a forming box (300 × 300 mm)

dimensions were 300 × 300 mm. In addition, a "20-mm-control board" was manufactured without the metal frames and by pressing at 170 °C for 10 min. The density was 0.7 g/cm^3.

One board was manufactured for each condition.

Performance tests

The manufactured boards were left in a thermo-hygrostat at 20 °C and 65 % relative humidity until the weight stabilized. For boards that were 10-mm-thick, the modulus of rupture (MOR), internal bond (IB) and thickness swelling (TS) were determined according to JIS A 5908 [8]. The number of test specimens was 5, 8 and 7, respectively.

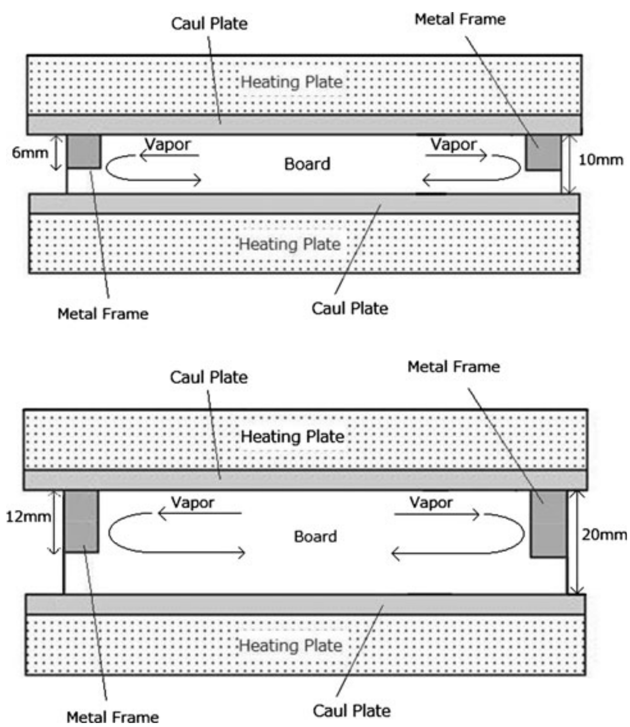

Fig. 2 Schematics of the hot press with the metal frame(s). See Table 1 for the abbreviations. **a** 10-mm-thick board, **b** 20-mm-thick board

The JIS test for determining the MOR requires a span length of 300 mm for 20-mm boards and hence a specimen length of 350 mm. Since the specimen length was not available from the manufactured boards, 20-mm boards were only subjected to IB and TS tests. The number of specimens was 8 in both tests.

Results and discussion

Effects of density on board performance

Figure 3 shows the relationship between density and MOR for AIP board and OP board. The OP board of 0.8 g/cm^3 did not blow out when pressed at 150 °C but did do so at 170 °C. This was likely due to the high pressing temperature increasing the vapor pressure inside the board, causing blowout [9]. Conversely, the AIP board did not blow out at these temperatures, showing the effect of the air injection in preventing blowout. In the previous reports [1–4], high-moisture boards of 0.7 g/cm^3 could be manufactured by an ordinary hot press. High-moisture (25 %) particles of 0.7 g/cm^3 contained 158 g of water, while low-moisture (15 %) particles of 0.8 g/cm^3 contained 108 g of water. Although the former contained about 1.5 times more water than the latter, boards could be manufactured from the former but not the latter. This was likely attributable to the high density in the latter, which reduced the spaces inside the boards and inhibited the escape of vapor. The blowout of the latter, which generated less vapor than the former, suggested that the major cause of blowout was the trapping of vapor due to the high density rather than the generation of a large amount of vapor. The analysis showed that high-density boards pressed at high temperature (170 °C) were prone to blowout when air is not injected, but that air injection could prevent blowout.

MOR was higher in higher-density boards (Fig. 3) as commonly mentioned [10, 11], while the MOR of the AIP boards was lower compared with OP boards for both

Table 1 Abbreviations for boards and conditions of board manufacture

Abbreviations	Metal frame Yes/No	Pressing method	Pressing temperature (°C)	Pressing time (min)	Board density (g/cm^3)	Board thickness (mm)	Air-injection pressure (MPa)
AIP board	Yes	Air-injection press	150, 170	6	0.6, 0.7, 0.8	10	0.55
OP board	No	Ordinary press	150, 170	6	0.6, 0.7, 0.8	10	0
150 °C board	Yes	Air-injection press	150	6	0.6, 0.7, 0.8	10	0.20, 0.40, 0.55
170 °C board	Yes	Air-injection press	170	6	0.6, 0.7, 0.8	10	0.20, 0.40, 0.55
10-mm board	Yes	Air-injection press	170	4, 6, 8	0.7	10	0.55
20-mm board	Yes	Air-injection press	170	10, 12, 14	0.7	20	0.55
20-mm-control board	No	Ordinary press	170	10	0.7	20	0

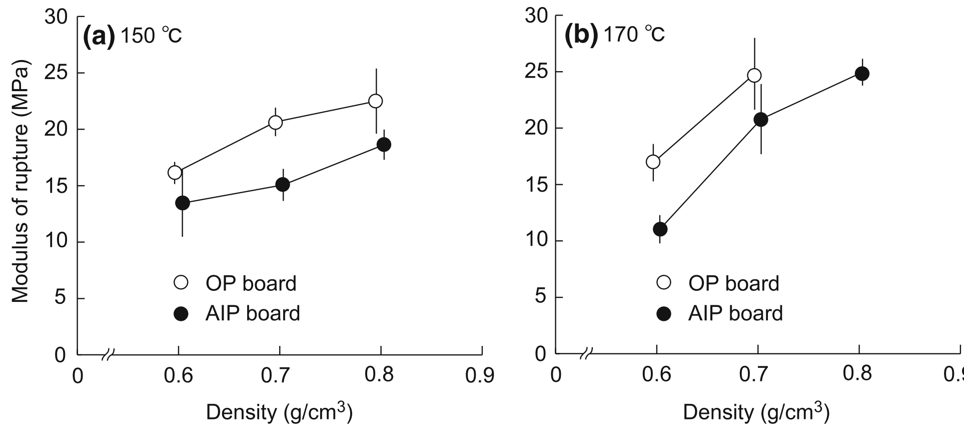

Fig. 3 Relationship between density and modulus of rupture. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** Pressing temperature of 150 °C, **b** pressing temperature of 170 °C

pressing temperatures of 150 and 170 °C. The temperature of the former boards during hot pressing was lower than that of the latter boards because the heat was deprived by the injected air [1]. This, therefore, inhibited the hardening of the urea–formaldehyde resin of the former boards; hence the MOR of the former boards was lower.

Figure 4 shows the relationship between density and IB of the AIP board and OP board. At a pressing temperature of 150 °C, IB was about 0.65 MPa in all boards, showing no difference between the AIP boards and OP boards, regardless of density. IB is affected by the bonding strength of the core [12, 13]. A pressing temperature of 150 °C was low and could not have raised the temperature of the core sufficiently to completely harden the urea–formaldehyde resin. This was likely the reason for the similar IB values between the pressing methods regardless of density. The IB of the AIP boards of 0.7 and 0.8 g/cm^3 was higher at a pressing temperature of 170 than 150 °C. This was likely because the heat was transmitted faster when pressed at 170 than 150 °C, and the urea–formaldehyde resin hardened sufficiently.

At a pressing temperature of 170 °C, the IBs of AIP boards of 0.6, 0.7 and 0.8 g/cm^3 were 0.56, 1.10 and 1.43 MPa, respectively, showing higher IB in higher-density boards. For the density of 0.6 g/cm^3, IB was lower in the AIP board than in the OP board. For 0.7 g/cm^3, no statistically significant difference in IB emerged between the two boards. Previous studies have revealed a problem of air injection discharging urea–formaldehyde resin together with vapor when the high-moisture boards are manufactured [2–4]. In this study, the air injection while hot pressing at 170 °C probably discharged a large amount of binder from the 0.6-g/cm^3 boards, which had many spaces through which the air could easily pass, and resulted in lowered IB. On the other hand, the air injection did not affect the IB of the 0.7-g/cm^3 boards, which were denser, more difficult for the air to pass through, and discharged less urea–formaldehyde resin than the 0.6-g/cm^3 boards. This was likely the reason why IB was similar in the 0.7-g/cm^3 AIP board and OP board.

Figure 5 shows the relationship between density and TS of the AIP board and OP board. At a pressing temperature of 150 °C, there was no clear difference in TS between the AIP boards and OP boards, and TS was 22.6–31.8 %, regardless of density. At a pressing temperature of 170 °C, TS was higher in the 0.6-g/cm^3 AIP board at 33.2 %, compared with about 23 % in the other boards. TS was lower in boards at 170 rather than 150 °C except for the 0.6-g/cm^3 AIP board, likely because IB was higher in the former than the latter (Fig. 4).

Effects of air-injection pressure on board performance

Figure 6 shows the relationship between the air-injection pressure and MOR of the 150 °C board and 170 °C board. For the density of 0.6 g/cm^3, the MOR was about 13 MPa in all 150 °C boards and 170 °C boards. On the other hand, for 0.7 g/cm^3, the MOR was about 20 MPa in all 170 °C boards and 150 °C boards except for 150 °C board air injected at 0.55 MPa. A similar trend was observed in boards of 0.8 g/cm^3. The MOR was low with 18.6 MPa in the 150 °C board at 0.55 MPa and about 25 MPa in the other boards.

Figure 7 shows the relationship between air-injection pressure and IB of the 150 °C board and 170 °C board. For 0.6 g/cm^3, the IBs of the 150 °C board and 170 °C board were about 0.68 and 0.55 MPa, respectively, regardless of air-injection pressure. For the density of 0.7 g/cm^3, the IBs of the 150 °C board and 170 °C board at 0.2 or 0.4 MPa were 0.85 and 0.95 MPa, respectively. The IBs of the 150 °C board and 170 °C board at 0.55 MPa were 0.63 and 1.10 MPa, respectively. For 0.6 g/cm^3, IB was higher in 150 °C board than 170 °C board. For 0.7 g/cm^3, IB was higher in 170 °C board than 150 °C board. For 0.8 g/cm^3, IB was unchanged between the 150 °C board and 170 °C board at 0.2 or 0.4 MPa and was about 1.1 MPa. At

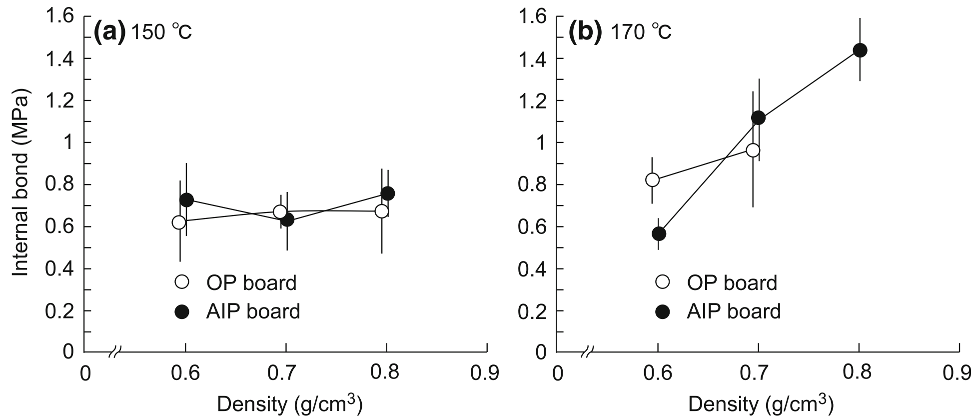

Fig. 4 Relationship between density and internal bond. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** Pressing temperature of 150 °C, **b** pressing temperature of 170 °C

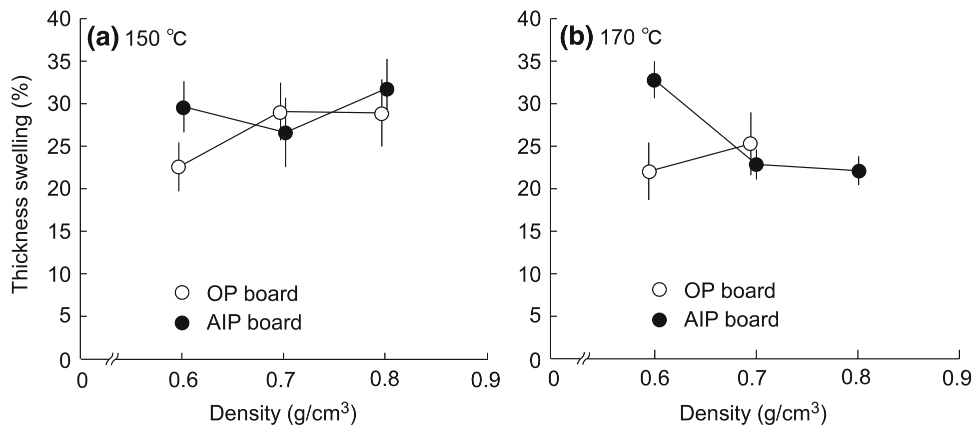

Fig. 5 Relationship between density and thickness swelling. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** Pressing temperature of 150 °C, **b** pressing temperature of 170 °C

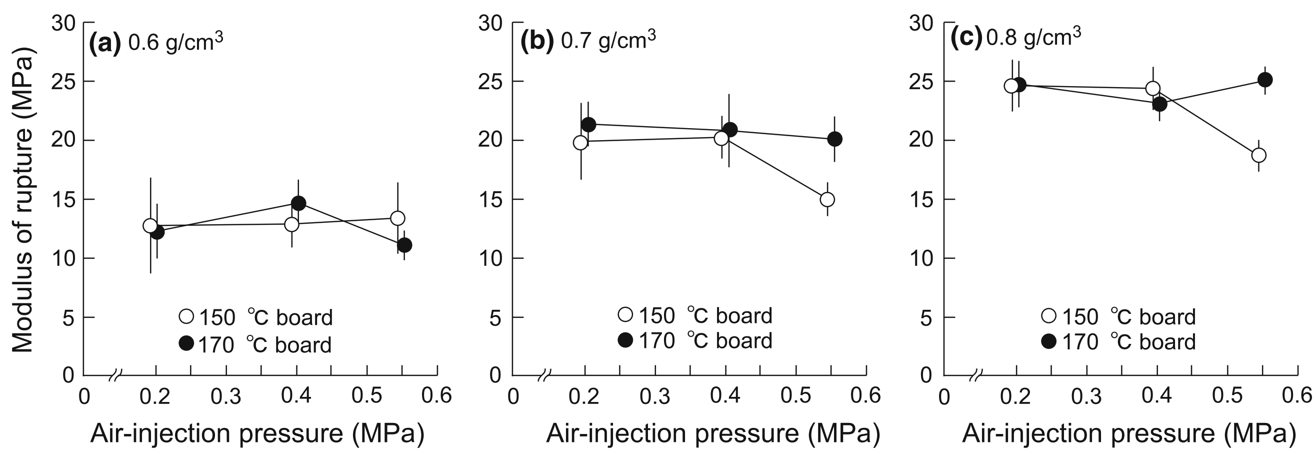

Fig. 6 Relationship between air-injection pressure and modulus of rupture. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** Density of 0.6 g/cm^3, **b** density of 0.7 g/cm^3, **c** density of 0.8 g/cm^3

0.55 MPa, IB was higher in 170 °C board than 150 °C board at 1.43 and 0.76 MPa, respectively. The tendency was similar to the MOR (Fig. 6). Higher-density boards of 0.7 and 0.8 g/cm^3 should have had few spaces and been prone to trapping vapor. A large amount of high-temperature vapor may have deteriorated the hardened urea–formaldehyde resin [14], but the injected air discharged the vapor and prevented the resin from deteriorating. A high air-injection pressure of 0.55 MPa discharged vapor from the 170 °C board, prevented the resin from deteriorating and increased the IB. On the other hand, the high air-injection pressure of 0.55 MPa was likely to have lowered the temperature inside the 150 °C board, inhibited hardening of the resin and lowered the IB. Insufficient hardening of the

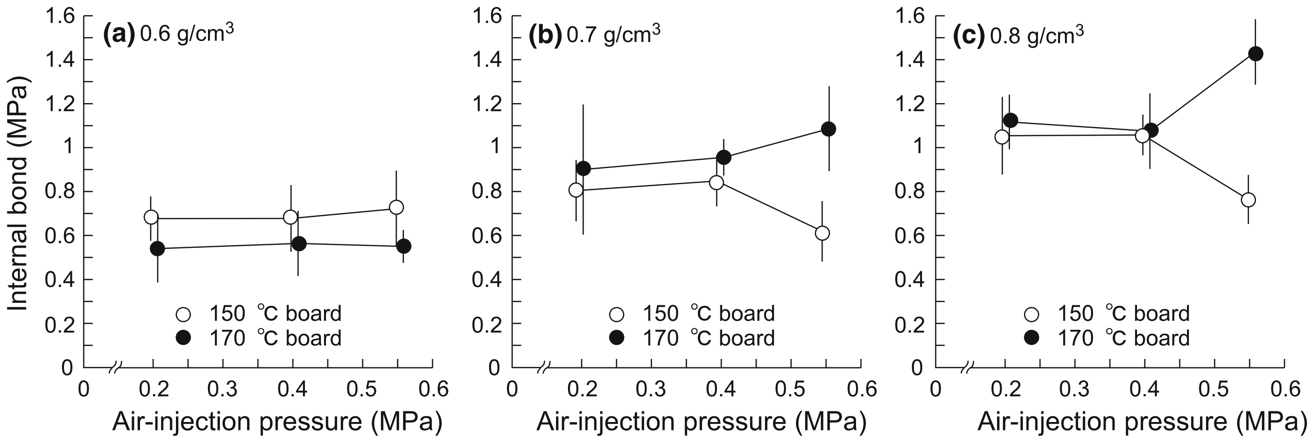

Fig. 7 Relationship between air-injection pressure and internal bond. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** density of 0.6 g/cm^3, **b** density of 0.7 g/cm^3, **c** density of 0.8 g/cm^3

urea–formaldehyde resin was also a cause of the decreased IB in the 150 °C boards of 0.7 and 0.8 g/cm^3, manufactured by air injection at 0.55 MPa.

Figure 8 shows the relationship between the air-injection pressure and TS in the 150 °C board and 170 °C board. TS was 30–35 % in all 150 °C board and 170 °C board of 0.6 g/cm^3, regardless of air-injection pressure. In 150 °C board and 170 °C boards of 0.7 g/cm^3, TS was 25–30 % for all air-injection pressures, except for the 170 °C board at 0.55 MPa (23.2 %). TS was about 30 % in all boards of 0.8 g/cm^3 except for the 170 °C board at 0.55 MPa, which showed a reduction in TS to 22.4 %. The 170 °C boards at 0.55 MPa of 0.7 and 0.8 g/cm^3 had high IB (Fig. 7) and hence showed low TS.

As shown in Figs. 3, 4, 5, the OP board pressed at 170 °C (no air injection) blew out when the density was high (0.8 g/cm^3). However, air injection prevented blowout, even at a low air-injection pressure of 0.20 MPa, as shown in Figs. 6, 7, 8. Low air-injection pressure of 0.20 MPa was found to manufacture boards of favorable performance and prevent blowout.

Effects of the air-injection press on the performance of 20-mm-thick boards

In the previous study [6], the ordinary hot press could not manufacture 10-mm-thick boards with a metal frame placed on particle mats because the boards blew out. Conversely, the air-injection press successfully manufactured 10-mm-thick boards even when the metal frame was used. In this study, 20-mm boards were manufactured by following the methods in the previous study [6]. The 20-mm boards blew out when they were hot pressed using metal frames and no air was injected. In contrast, air injection facilitated the manufacture of 20-mm boards, even when the metal frames were used, showing that air injection was also effective in preventing blowout of 20-mm boards.

Figure 9 shows the relationship between pressing time and IB in 10-mm board, 20-mm board and 20-mm-control board. The IB of the 10-mm boards rose with increased pressing time. In contrast, the IB of the 20-mm boards showed no significant change. IB was higher in 10-mm than 20-mm boards, as the past report showed [13]. This was likely because the thicker 20-mm board required more time for the temperature to rise inside the boards and thus for the urea–formaldehyde resin to harden.

The IB of the 20-mm-control board was 0.29 MPa (pressing time: 10 min). On the other hand, the IB of the 20-mm boards in 10 min was 0.62 MPa. The difference between the 20-mm-control and 20-mm boards was in the pressing method used. The former was manufactured using an ordinary press, while the latter was manufactured using the air-injection press (Table 1), hence the air injection increased the IB. In the previous study [6], the air injection increased the IB of 10-mm-thick boards only slightly, but the IB of the 20-mm boards in this study was increased conspicuously by air injection. This suggests that the effects of air injection are greater on boards that are 20 mm thick than 10 mm thick, but the causes are unknown and must be investigated.

Figure 10 shows the relationship between pressing time and TS of the 10-mm board, 20-mm board and 20-mm-control board. In the 10-mm board and 20-mm board, TS rose as the pressing time was extended. In particular, the TS in the 20-mm boards increased sharply between 12 and 14 min.

The TS of the 20-mm-control board was 16.9 % and was lower than the TS of the 20-mm board. As shown in Fig. 9, the IB of the 20-mm-control board was lower than that of the 20-mm board; thus TS was predicted to be higher in the 20-mm-control board than in the 20-mm board, but actually

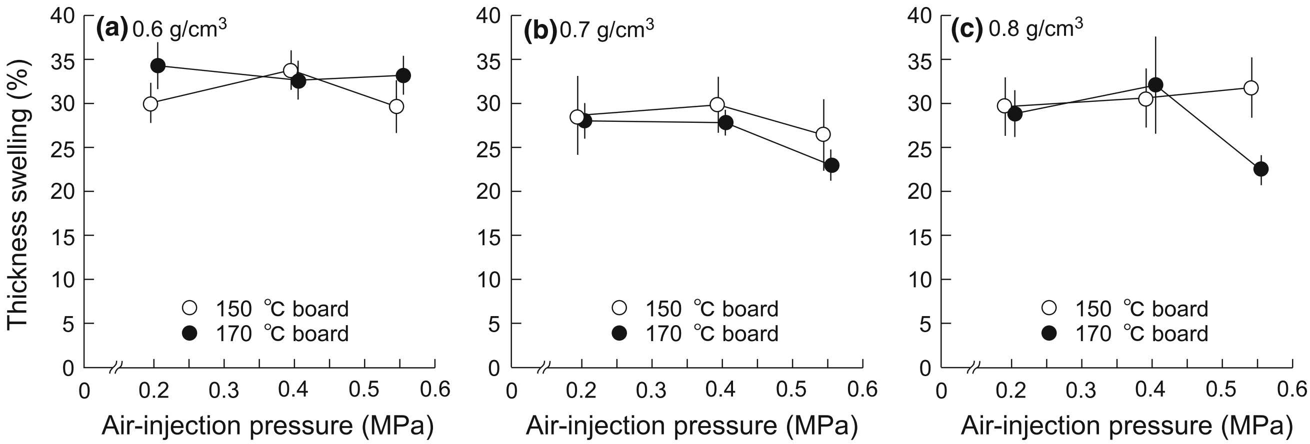

Fig. 8 Relationship between air-injection pressure and thickness swelling. *Error bars* indicate standard deviations. See Table 1 for the abbreviations. **a** density of 0.6 g/cm^3, **b** density of 0.7 g/cm^3, **c** density of 0.8 g/cm^3

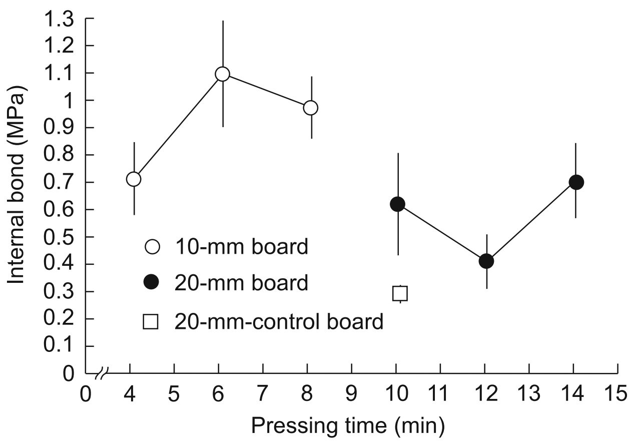

Fig. 9 Relationship between pressing time and internal bond. See Table 1 for the abbreviations. *Error bars* indicate standard deviations

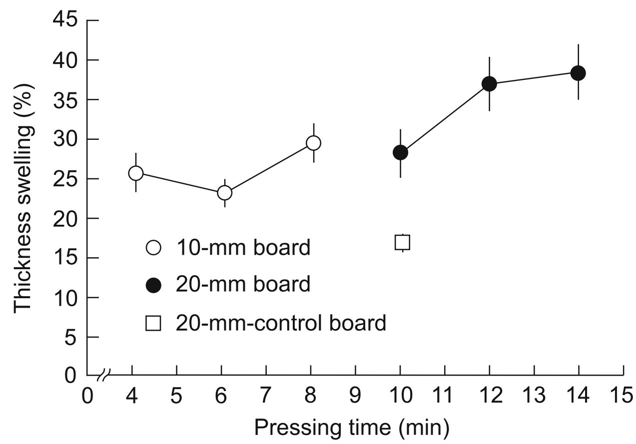

Fig. 10 Relationship between pressing time and thickness swelling. See Table 1 for the abbreviations. *Error bars* indicate standard deviations

was not. This was possibly due to the following reason. The 20-mm board was manufactured using the air-injection press, and the 20-mm-control board was manufactured using the ordinary hot press. Air injection lowers the temperature inside the boards [1]. For thick boards of 20 mm, considerable time would have been required for the heat to reach the core. The 20-mm board is insufficiently heated with pressing time of this study [15] and hence the particles do not plasticize thoroughly, resulting in insufficient contact between particles [16] and increased compressive stress due to hot pressing. The insufficient contact means water is prone to penetrate the board, causing a large springback of particles. Therefore, the TS of 20-mm board increased. On the other hand, the 20-mm-control board, which was hot pressed for a long time without air injection, was sufficiently heated. The particles plasticized and contacted each other tightly, which blocked the entry of water. Plasticized particles reduced the springback and were therefore likely to result in low TS.

Conclusions

10-mm-thick boards and densities of 0.6, 0.7 and 0.8 g/cm^3 were manufactured from low-moisture particles using the air-injection press. Also, 20-mm-thick boards of 0.7 g/cm^3 were manufactured. The effects of air injection on the performance of boards of different thicknesses and densities were investigated.

1. The ordinary hot press could manufacture 0.8-g/cm^3 boards at 150 but not 170 °C. The high pressing temperature increased the vapor pressure inside the boards. Moreover, the high board density reduced spaces in the boards, which resulted in increased trapped vapor and resultant blowout. The air injection enabled the manufacturing of the boards.
2. At pressing temperatures of 150 and 170 °C, MOR was higher in the OP boards than in the AIP boards for all densities.

3. The IB of the AIP boards pressed at 150 °C was constant regardless of density. However, the IB of the AIP boards pressed at 170 °C rose with increasing density. This was likely because the urea–formaldehyde resin hardened more thoroughly when pressed at 170 than 150 °C.
4. Even with a low air-injection pressure of 0.20 MPa, air injection prevented blowout of all boards, regardless of density, while pressing temperature did not adversely affect the performance of the board.
5. The air-injection press prevented blowout of thick boards of 20 mm and manifested its effects. The IB of the 20-mm boards was lower compared with the 10-mm boards, possibly because the thick boards were not sufficiently heated.

Acknowledgments This study was supported by grants from the Research and development projects for application in promoting new policies of agriculture, forestry and fisheries from the Ministry of Agriculture, Forestry and Fisheries. The authors express their gratitude to Mr. Hiroshi Tanaka of Oshika Corporation for providing the binders and Mr. Kazuo Hattori of Japan Novopan Industrial Co., Ltd. for providing wood particles for particleboards, which were helpful in conducting the experiment in this study.

References

1. Korai H, Ling N, Osada T, Yasuda O, Sumida A (2011) Development of an air-injection press for preventing blowout of particleboard I: effects of an air-injection press on board properties. J Wood Sci 57:401–407
2. Korai H, Ling N (2011) Development of an air-injection press for preventing blowout of particleboard II: improvement of board properties using small-diameter holes for air injection. J Wood Sci 57:507–511
3. Korai H, Ling N, Saotome H, Iida T, Hamano T, Kawarada K (2012) Development of an air-injection press for preventing blowout of particleboard III: effects of pressing temperature on board performance. J Wood Sci 58:216–221
4. Korai H, Ling N, Saotome H, Iida T, Hamano T, Kawarada K (2012) Development of an air-injection press for preventing blowout of particleboard IV: effects of air-injection conditions on board performance and formaldehyde emission. J Wood Sci 58:417–422
5. Iwashita M, Matsuda T, Ishihara S (1960) Studies on particle board (III): on the curing condition, especially moisture content of wooden particles. Bulletin of the Government Forest Experiment Station No.126, pp 63–89
6. Saotome H, Korai H, Iida T, Hamano T, Kawarada K (2012) Performance of particleboard manufactured using air-injection press I: effects of air-injection press on preventing blowout of board manufactured form low moisture-content particles. J Wood Sci 58:423–428
7. Fukino M, Horie H, Shimokune N, Ogawa N (2007) Production Technology for Strand-Particle Board (SPB) III. Effect of isocyanate adhesives (EMDI) on physical properties and blisters (in Japanese). Mokuzai Gakkaishi 53:187–193
8. Japanese Industrial Standard (2003) JIS standard specification for particleboard, JIS A 5908. Japanese Standards Association, Tokyo
9. Malony TM (1986) Modern particleboard & dry-process fiberboard manufacturing. Miller Freeman Publications Inc., San Francisco, pp 519–520
10. Han G, Zhang C, Zhang D, Umemura K, Kawai S (1998) Upgrading of urea formaldehyde-bonded reed and wheat straw particleboards using silane coupling agents. J Wood Sci 44:282–286
11. Xu J, Han G, Wong ED, Kawai S (2003) Development of binderless particleboard from kenaf core using steam-injection pressing. J Wood Sci 49:327–332
12. Wong ED, Zhang M, Wang Q, Kawai S (1998) Effects of mat moisture content and press closing speed on the formation of density profile and properties of particleboard. J Wood Sci 44:287–295
13. Schulte M, Frühwald A (1996) Some investigations concerning density profile, internal bond and relating failure position of particleboard. Eur J Wood Wood Prod 54:289–294
14. Umemura K, Kawai S, Ueno R, Mizuno Y, Sasaki H (1996) Curing behavior of wood adhesives under high-pressure steam II. Mokuzai Gakkaishi 42:65–73
15. Uchida H, Ogane K, Shimizu T (1958) On the relation between preparing conditions of particle board and inner temperature during pressing cycle (in Japanese). Wood Ind 13:511–515
16. Kawai S, Suda H, Nakaji M, Sasaki H (1986) Production technology for low-density particleboard II. Effects of particle moisture content and resin content on board properties. Mokuzai Gakkaishi 32:876–882