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ORIGINAL ARTICLE

Effects of air injection on properties of particleboard manufactured using a radio-frequency hot press

Hideaki Korai · Takayoshi Osada · Atsushi Sumida

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Abstract The effectiveness of air injection for preventing the blowout of particleboards manufactured using a radio-frequency hot press was investigated by evaluating the board properties under artificially created conditions that were conducive to blowout. For evaluation, 10-mm-thick boards with densities of 0.7 and 0.8 g/cm^3 and 20-mm-thick boards with a density of 0.7 g/cm^3 were manufactured. Pressing times for the 10-mm-thick boards were 2, 4, 6, and 8 min, and those for the 20-mm-thick boards were 4, 6, 8, and 10 min. Without air injection, blowout occurred in all manufactured boards. With air injection, however, blowout did not occur in the 10-mm-thick boards with a density of 0.7 g/cm^3. Moreover, air injection prevented blowout even when the board density and board thickness were increased to 0.8 g/cm^3 (for 10-mm-thick boards) and 20 mm (the density was kept at 0.7 g/cm^3), respectively. Air-injection radio-frequency pressing reduced the pressing time from 4 to 2 min for 10-mm-thick boards, and from 6 to 4 min for 20-mm-thick boards. Moreover, this reduction in the pressing time was achieved without a large reduction in the internal bond strength of the boards.

Keywords Particleboard · Blowout · Air-injection press · Radio frequency · Hot press

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

T. Osada · A. Sumida
Swood Co. Ltd, Kakamigahara 509-0108, Japan

Introduction

Wood-based board blowout is a burst phenomenon that occurs when a hot press is opened and is caused by vapor inadvertently trapped inside a board during hot pressing [1]. Blowout is a major problem as it causes a significant loss in productivity. Although sufficient drying of particles is an effective method of preventing blowout, it may still occur inadvertently. In previous studies, a hot press was developed to discharge vapor trapped inside a board, thereby preventing blowout [2–6]. This hot press contains holes punched through its upper and lower heating plates; high-pressure air is injected through the lower plate holes into the board and then discharged through the upper plate holes (Fig. 1b, air-injection press). Thus, injecting high-pressure air to discharge vapor trapped inside the board prevents blowout.

As heat does not transfer quickly from the upper and lower heating plates to the center of the board in an ordinary hot press (Fig. 1a, hot press), an additional heating method is needed to reduce the pressing time. Moreover, for manufacturing a thick board, long pressing time is needed owing to low heat conduction at the center of the board. Thus, other heating methods are needed for manufacturing a thick board. A hot press with a radio-frequency heating device installed has been designed to reduce the pressing time and to manufacture thicker boards (Fig. 1c, radio-frequency hot press) [7–10]. This radio-frequency hot press can not only heat board surfaces between the upper and lower heating plates, but can also heat the inside of a board by radio-frequency heating. This results in simultaneous and uniform heating of the entire board and a rapid rise in temperature at the center of the board [10]. Thus, a thick board can be manufactured with reduced pressing time [11]. However, the radio-frequency hot press

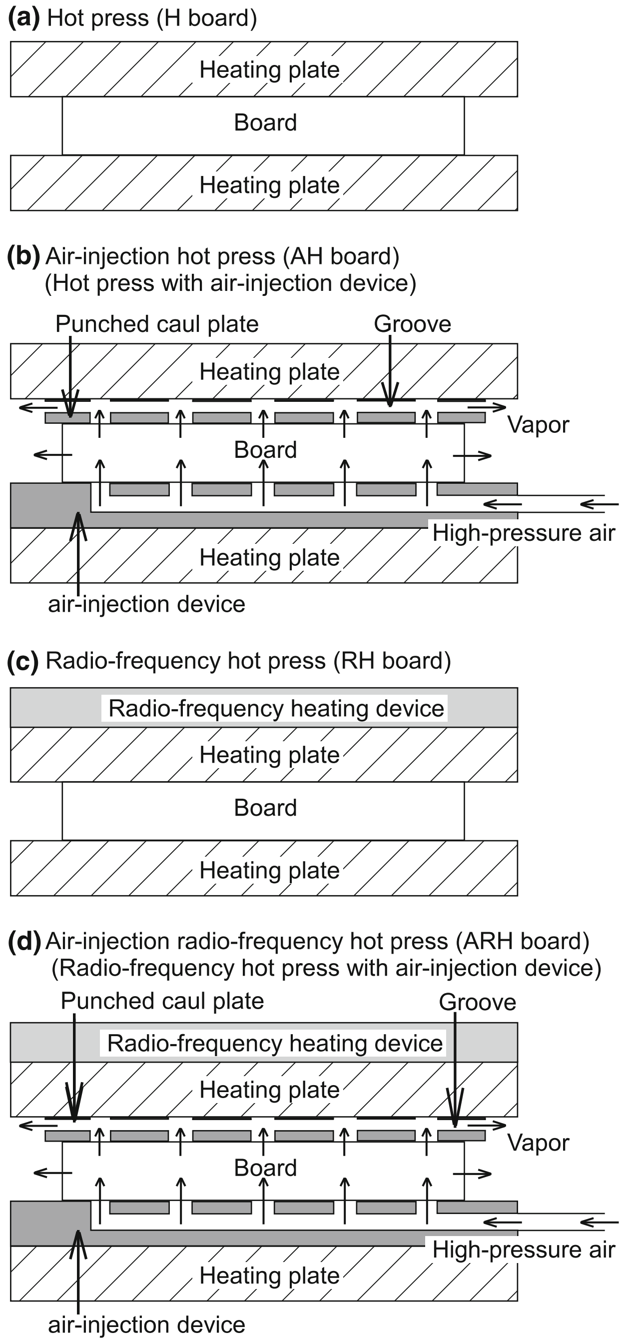

Fig. 1 Hot presses used for manufacturing boards: **a** hot press; **b** air-injection hot press; **c** radio-frequency hot press; **d** air-injection radio-frequency hot press

significantly increases the water vapor pressure inside the board because of the rapid rise in temperature; therefore, this press is likely to be more prone to inadvertent blowout than an ordinary hot press [12].

One objective of this study is to determine the effect of air injection in preventing blowout when a radio-frequency hot press is used. To prevent blowout, an air-injection device was installed on a radio-frequency hot press

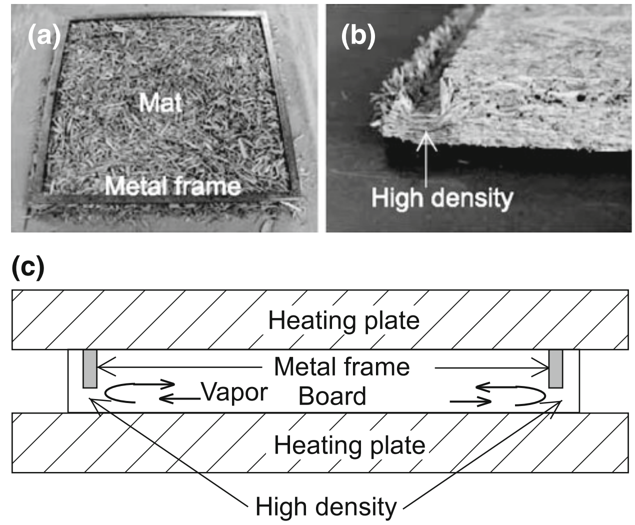

Fig. 2 Board with a metal frame and hot press; **a** board with a metal frame before hot pressing; **b** edge of the board hot pressed with the metal frame; **c** cross section of the hot press installed with a metal frame

(Fig. 1d, air-injection radio-frequency hot press). When a small laboratory-scale board is manufactured from low-moisture particles by using a radio-frequency hot press, vapor can escape through the edges of the board, resulting in no blowout. As reported in previous studies [13, 14], a metal frame was thus placed around the particles to trap vapor inside the board during hot pressing to induce blowout (Fig. 2). Air injection discharged the trapped vapor, and the effect of air injection in preventing blowout by using the radio-frequency hot press was thus confirmed. Moreover, further study was conducted on the manufacture of thick boards with reduced pressing time by using an air-injection radio-frequency hot press.

Experimental

Manufacture of boards

Particles produced from wood waste were used for manufacturing the core layers of the particleboards (Japan novopan industrial Co. Ltd.). The particle sizes have been reported in a previous study [2]. The moisture content of these particles was approximately 10 %. Urea–formaldehyde resin was used as the binder (TB-86 with solid content of 65 % and viscosity of 0.21 Pa s, from Oshika Co. Ltd.); a 10 % aqueous ammonium chloride solution was used as the hardener. The amount of ammonium chloride solution accounted for 10 % of the urea–formaldehyde resin by weight. The amount of urea–formaldehyde resin on the basis of the added solid content accounted for 10 %

of the oven-dried weight of the particles. The moisture content of these particles after spraying the resin was approximately 15 % (mat moisture content).

First, 10-mm-thick boards (10-mm boards) were manufactured. 10-mm distance bars were used to control the board thickness. Each board measured 250 × 250 mm in size with two different densities of 0.7 and 0.8 g/cm^3. The boards were manufactured using a hot press equipped with an air-injection device (Fig. 1b) and a radio-frequency hot press also equipped with an air-injection device (Fig. 1d). A radio-frequency heating device (Model RH-3T from Yamamoto Vinita Co., Ltd.) with a power output of 1 kW was used to generate radio frequency. For manufacturing the boards, the temperature of hot press heating was set at 180 °C with a pressing time of 2–8 min. Air injection was carried out at a pressure of 0.55 MPa, with the temperature of the injected air set at room temperature. Air injection began when board thickness reached 10 mm and was then stopped for the final 15 s of the pressing time. Tables 1 and 2 list the abbreviations and detailed manufacturing conditions. An air-injection device was prepared with holes measuring 1 mm in diameter. The holes were arranged on the lower plate with a spacing of 25 mm between the centers of adjacent holes, resulting in 81 holes in an area measuring 200 × 200 mm through which air was injected. Holes were also punched on the caul plate (upper plate) through which high-pressure air and vapor were discharged (Fig. 1b, d). Because the diameter of and spacing between the holes on the caul plate were equal to those on the lower plate, the caul plate too contained 81 holes in an area of 200 × 200 mm. To discharge high-pressure air, grooves 1.5-mm deep and 3-mm wide were cut to connect the holes on one side of the caul plate. Although holes must actually be punched in the heating plates of the press, it is difficult to do so. Therefore, in this study, an air-injection device was developed and subsequently mounted on the heating plate. The structure of the air-injection press is described in previous studies [2–4]. A metal frame (6 mm in height) was used to trap vapor inside the board for inducing blowout (Fig. 2). If blowout would not occur because of air injection when the metal frame is used, air injection would be effective for preventing blowout. Further, 10-mm boards were manufactured using both the hot press and radio-frequency hot press, but without the metal frame and air-injection device (Fig. 1a, c, respectively). The pressing time was set at 4–6 min. These boards are called the H control board and RH control board (Tables 1 and 2).

Next, 20-mm-thick boards (20-mm boards) were manufactured using both the hot press and radio-frequency hot press under the same conditions as those used for manufacturing the 10-mm board (Table 3). In both cases, a metal frame (12 mm in height) was used for inducing blowout. The boards measured 250 × 250 mm in size with a density of 0.7 g/cm^3. The 20-mm H and RH control boards were also manufactured under the same conditions as those used for manufacturing the 10-mm control board (Table 3).

In this study, boards manufactured using the hot press, air-injection hot press, radio-frequency hot press, and air-

Table 1 Manufacturing conditions for 10-mm-thick particleboard with a density of 0.7 g/cm^3

Abbreviations	Pressing methods	Frame yes/no	Air injection yes/no	Pressing time (min)
H board	H	Yes	No	2, 4, 6, 8
AH board	AH	Yes	Yes	2, 4, 6, 8
RH board	RH	Yes	No	2, 4, 6
ARH board	ARH	Yes	Yes	2, 4, 6
H control board	H	No	No	6
RH control board	RH	No	No	4

H hot press, *AH* air-injection hot press, *RH* radio-frequency hot press, *ARH* air-injection radio-frequency hot press

Table 2 Manufacturing conditions for 10-mm-thick particleboard with a density of 0.8 g/cm^3

Abbreviations	Pressing methods	Frame yes/no	Air injection yes/no	Pressing time (min)
H board	H	Yes	No	2, 4, 6, 8
AH board	AH	Yes	Yes	2, 4, 6, 8
RH board	RH	Yes	No	2, 4, 6
ARH board	ARH	Yes	Yes	2, 4, 6
H control board	H	No	No	6
RH control board	RH	No	No	4

H hot press, *AH* air-injection hot press, *RH* radio-frequency hot press, *ARH* air-injection radio-frequency hot press

Table 3 Manufacturing conditions for 20-mm-thick particleboard with a density of 0.7 g/cm^3

Abbreviations	Pressing methods	Frame yes/no	Air injection yes/no	Pressing time (min)
H board	H	Yes	No	4, 6, 8, 10
AH board	AH	Yes	Yes	4, 6, 8, 10
RH board	RH	Yes	No	4, 6, 8
ARH board	ARH	Yes	Yes	4, 6, 8
H control board	H	No	No	10
RH control board	RH	No	No	6

H hot press, *AH* air-injection hot press, *RH* radio-frequency hot press, *ARH* air-injection radio-frequency hot press injection radio-frequency hot press are called H board (H control board), AH board (AH control board), RH board, and ARH board, respectively (Fig. 1; Tables 1, 2 and 3). Two boards of each type were manufactured for each manufacturing condition.

Evaluation of board properties

The moisture content of the boards was conditioned prior to testing by leaving the boards in a thermo-hygrostat at 20 °C and 65 % relative humidity until their weight stabilized. The internal bond strength and thickness swelling of the boards were determined in compliance with JIS A 5908 [15]. Two sets of eight specimens each were used. For evaluation, specimens measuring 50 × 50 mm were cut out from boards measuring 250 × 250 mm (Fig. 3).

Results and discussion

Effect of air injection in preventing blowout of 10-mm board with a density of 0.7 g/cm^3

Table 4 lists the success, failure, and occurrence of blowout in the manufacture of the 10-mm board with a density of 0.7 g/cm^3. Without air injection, the H and RH boards could not be manufactured at any pressing time because of blowout. With air injection, however, the AH and ARH boards could be manufactured owing to the prevention of blowout. This clearly demonstrates the effect of air injection in preventing blowout by using a hot press and a radio-frequency hot press.

The AH board could not be manufactured at a pressing time of 2 min owing to the lack of curing at the center of the board; however, it could be manufactured in 4 min. In contrast, the ARH board could be manufactured in 2 min because the radio-frequency hot press reduced the pressing time more than the hot press did [11]. Moreover, air injection did not inhibit the reduction of pressing time when the radio-frequency hot press was used.

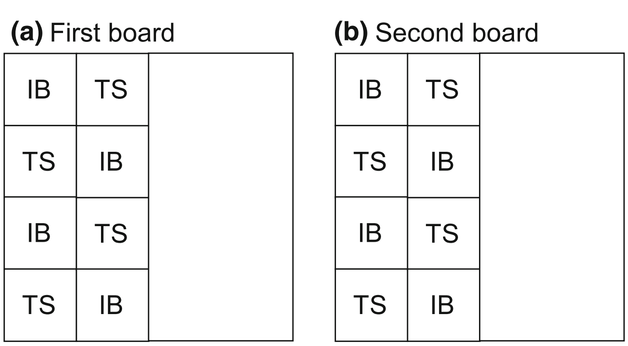

Fig. 3 Trimming of specimens for internal bond strength (IB, 50 × 50 mm) and thickness swelling (TS, 50 × 50 mm)

Table 4 Success, failure, and occurrence of blowout in the manufacture of 10-mm-thick particleboard with a density of 0.7 g/cm^3

Pressing time (min)	Abbreviations			
	H board	AH board	RH board	ARH board
2	Blowout	Failure	Blowout	Success
4	Blowout	Success	Blowout	Success
6	Blowout	Success	Blowout	Success
8	Blowout	Success		

Blowout is a burst phenomenon. Failure denotes that the center of the board was not cured. Abbreviations are explained in Table 1 and in the text. Two boards of each type were manufactured for each manufacturing condition

Internal bond strength of 10-mm board with a density of 0.7 g/cm^3

Figure 4 shows a plot of the internal bond strength versus the pressing time for the 10-mm board with a density of 0.7 g/cm^3. The internal bond strength of AH and ARH boards remained almost constant, regardless of the pressing time. Moreover, the internal bond strength of the ARH board was slightly lower than that of the AH board. This subtle difference in the bond strength of the ARH board does not exactly mean that the radio-frequency hot press is inferior to the hot press. For example, the internal bond strength of the AH board at 4 min was 0.756 MPa, while that of the ARH board at 2 min was 0.678 MPa. Both boards showed no statistically significant difference according to the *t* test; the radio-frequency hot press could be considered superior to the hot press for reducing the pressing time.

Between the AH and H control boards, the internal bond strength of the former was higher because it was manufactured using the metal frame and air injection (Table 1). The effect of the frame is to increase the temperature inside the board [16], while the effect of air injection is to decrease the temperature [2]. In this case, the increase in temperature owing to the frame use presumably exceeded the decrease in temperature owing to air injection, suggesting that temperature inside the AH board was likely higher than that inside the H control board. As a result, the curing of the binder in the AH board was accelerated, and thus the internal bond strength of the AH board was higher than that of the H control board.

Conversely, between the ARH and RH control boards, the internal bond strength of the ARH board decreased; the ARH board was manufactured using the metal frame, air injection and radio frequency (Table 1). The temperature inside the ARH board also increased as in the case of the

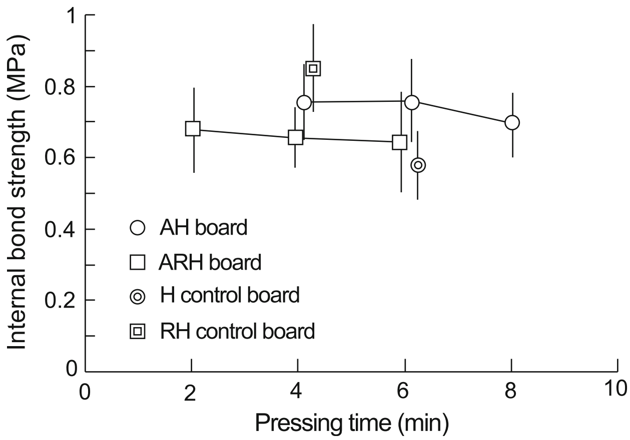

Fig. 4 Internal bond strength versus pressing time for 10-mm board with a density of 0.7 g/cm^3. *Error bars* denote standard deviations. Abbreviations are explained in Table 1 and in the text

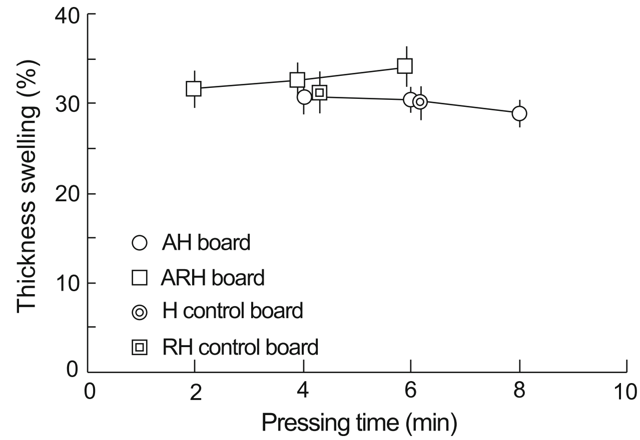

Fig. 5 Thickness swelling versus pressing time for 10-mm board with a density of 0.7 g/cm^3. *Error bars* denote standard deviations. Abbreviations are explained in Table 1 and in the text

AH board. However, the ARH board was heated more extensively than the AH board owing to both hot-press heating and radio-frequency heating, resulting in the temperature inside the ARH board being higher than that inside the AH board. In a previous study [17], the internal bond strength of boards manufactured at core temperatures in the range 130–155 °C and a pressing time of 3 min was found to be approximately 0.7 MPa, which is a high strength value. However, the boards could not be manufactured at 115 °C. Further, Umemura et al. [18] reported that hydrolysis of the urea formaldehyde resin occurs under steam-injection heating at 160 °C. Therefore, the temperature range 130–155 °C was presumably optimum for effectively curing the binder. The temperature inside the ARH board probably exceeded 160 °C, thereby impairing the curing process. In contrast, the temperature inside the RH control board, which was also extensively heated by both hot-press heating and radio-frequency heating, did not presumably increase to an extent that curing of the binder was inhibited. This was because no frame was used in case of the RH control board. In a board without a frame, heat loss occurs from all four sides and the optimum temperature inside the board for curing the binder is thus likely to be maintained. Consequently, the curing of the binder is accelerated, thereby resulting in the internal bond strength of the RH control board being higher than that of the ARH board.

Thickness swelling in 10-mm board with a density of 0.7 g/cm^3

Figure 5 shows a plot of thickness swelling versus the pressing time for the 10-mm board with a density of 0.7 g/cm^3. The thickness swelling in the AH and ARH boards was almost constant irrespective of the pressing time, and its value was approximately 30 %. The thickness swelling in the H and RH control boards was 30.0 and 31.3 %, respectively, showing almost the same values for these two boards. Radio-frequency heating increased the internal bond strength (Fig. 4), but did not reduce thickness swelling.

Internal bond strength and thickness swelling in 10-mm board with a density of 0.8 g/cm^3

Table 5 lists the success, failure, and occurrence of blowout in the manufacture of the 10-mm board with a density of 0.8 g/cm^3. The results obtained were the same as those for the 0.7 g/cm^3 board (Table 4). The increase in density from 0.7 to 0.8 g/cm^3 was presumed to make the smooth flow of high-pressure air more difficult, thereby reducing the effect of air injection in preventing blowout. However, no such negative effect was observed.

Figure 6 shows a plot of the internal bond strength versus the pressing time for the 10-mm board with a density of 0.8 g/cm^3, and Fig. 7 shows a plot of thickness swelling versus the pressing time for the 10-mm board with a density of 0.8 g/cm^3. The internal bond strength and thickness swelling in the 0.8 g/cm^3 board were almost the same as those in the 0.7 g/cm^3 board.

Effect of air injection in preventing blowout for 20-mm board

Table 6 lists the success, failure, and occurrence of blowout in the manufacture of the 20-mm board. Without air injection, the board could not be manufactured at any pressing time owing to blowout. Conversely, with air injection, the board could be manufactured because of no blowout. Increasing the board thickness from 10 to 20 mm was presumed to reduce the effect of air injection and then

Table 5 Success, failure, and occurrence of blowout in the manufacture of 10-mm-thick particleboard with a density of 0.8 g/cm^3

Pressing time (min)	Abbreviations			
	H board	AH board	RH board	ARH board
2	Blowout	Failure	Blowout	Success
4	Blowout	Success	Blowout	Success
6	Blowout	Success	Blowout	Success
8	Blowout	Success		

Blowout is a burst phenomenon. Failure denotes that the center of the board was not cured. Abbreviations are explained in Table 2 and in the text. Two boards of each type were manufactured for each manufacturing condition

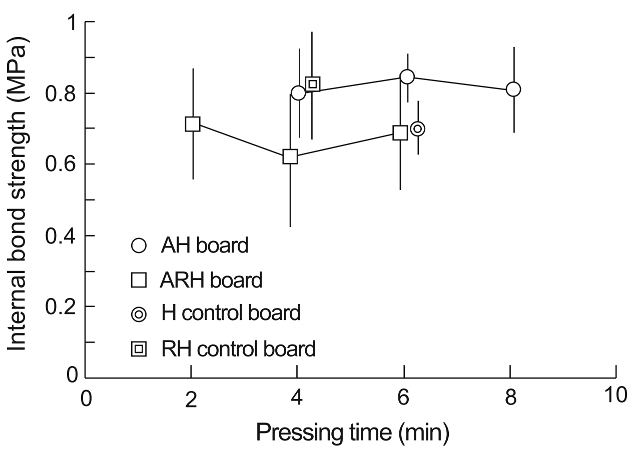

Fig. 6 Internal bond strength versus pressing time for 10-mm board with a density of 0.8 g/cm^3. *Error bars* denote standard deviations. Abbreviations are explained in Table 2 and in the text

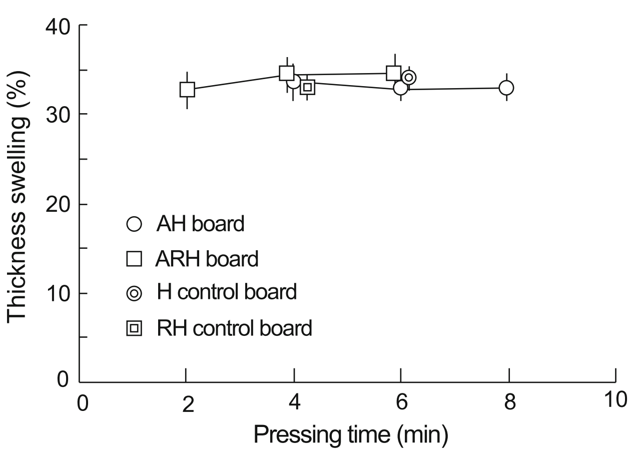

Fig. 7 Thickness swelling versus pressing time for 10-mm board with a density of 0.8 g/cm^3. *Error bars* denote standard deviations. Abbreviations are explained in Table 2 and in the text

induce blowout. However, the effect of air injection in preventing blowout was observed in the manufactured 20-mm board.

Table 6 Success, failure, and occurrence of blowout in the manufacture of 20-mm-thick particleboard with a density of 0.7 g/cm^3

Pressing time (min)	Abbreviations			
	H board	AH board	RH board	ARH board
4	Blowout	Failure	Blowout	Success
6	Blowout	Success	Blowout	Success
8	Blowout	Success	Blowout	Success
10	Blowout	Success		

Blowout is a burst phenomenon. Failure denotes that the center of the board was not cured. Abbreviations are explained in Table 3 and in the text. Two boards of each type were manufactured for each manufacturing condition

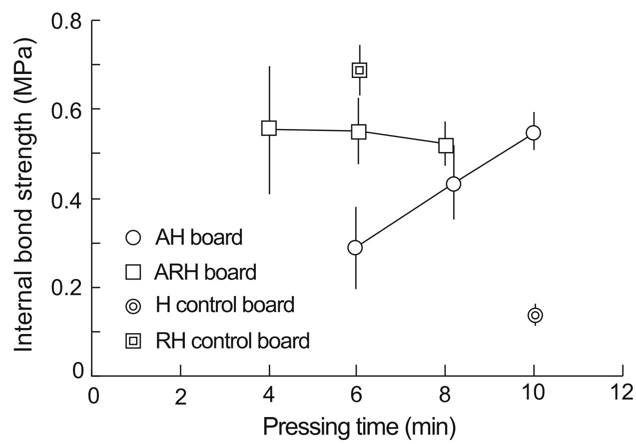

Fig. 8 Internal bond strength versus pressing time for 20-mm board. *Error bars* denote standard deviations. Abbreviations are explained in Table 3 and in the text

The AH board could not be manufactured in 4 min, but the ARH board could be manufactured even in 4 min. The radio-frequency hot press also reduced the pressing time required for manufacturing the 20-mm board.

Internal bond strength of 20-mm board

Figure 8 shows a plot of the internal bond strength versus the pressing time for the 20-mm board. The internal bond strength of the H control board was 0.139 MPa, whereas that of the RH control board was much higher at 0.689 MPa. Moreover, the internal bond strength of the 20-mm H control board was also much lower than that of the 10-mm H control board (0.583 MPa) shown in Fig. 4. Increasing the board thickness was assumed to slow down heat conduction from the hot press to the center of the board [19], thus preventing the binder from curing sufficiently and reducing the internal bond strength. The internal bond strength was very low even at a sufficient pressing time of 10 min, suggesting that it is difficult to increase the temperature in the 20-mm board. However, when the radio-frequency hot press was used, both radio-frequency heating and hot press heating effectively heated the inside of the board. As a result, the binder cured sufficiently to increase the internal bond strength of the RH control board.

The internal bond strength of the 10-mm AH board was high at 0.756 MPa even at 4 min (Fig. 4), whereas that of the 20-mm AH board even at a longer pressing time of 10 min was lower at 0.552 MPa. Sufficient heat transfer to the center of the board was not possible in the thicker 20-mm board when only hot press heating was used, thereby causing insufficient curing of the binder and likely reducing the internal bond strength.

The internal bond strength of the AH board was low at 0.290 MPa at 6 min. In contrast, the internal bond strength of the ARH board even at 4 min was 0.554 MPa, which was much higher than that of the AH board. Thus, it was shown that the radio-frequency hot press increased the internal bond strength of the 20-mm board through air injection.

The radio-frequency hot press increased the internal bond strength of even the 20-mm ARH board at a short pressing time, but the internal bond strength at 0.554 MPa at 4 min was not high. Further, the internal bond strength of the 10-mm ARH board was 0.678 MPa at 2 min (Fig. 4). Thus, the internal bond strength of the 20-mm board was lower than that of the 10-mm board even when the radio-frequency hot press was used. This suggests that the radio-frequency power output must be increased to improve the internal bond strength of thicker boards, given that the power output was set at 1 kW in this study.

Thickness swelling in 20-mm board

Figure 9 shows a plot of thickness swelling versus the pressing time for the 20-mm board. Thickness swelling in the AH and ARH boards was approximately 30–35 %, regardless of the pressing time and showed almost the same values. As shown in Fig. 8, since the internal bond strength of the AH board was low at short pressing times, thickness swelling was assumed to increase. However, in fact the thickness swelling did not increase.

Conclusions

Particleboards were manufactured using an air-injection radio-frequency hot press, and the effect of air injection in preventing blowout was investigated. The effect of air injection in preventing blowout of the 10-mm ARH board with a density of 0.7 g/cm^3 is shown. When the board density increased from 0.7 to 0.8 g/cm^3, the effect was also maintained. The air-injection radio-frequency hot press could be considered superior to the hot press for reducing the pressing time without a large reduction in the internal bond strength. The effect of air injection in preventing blowout was observed even when the board thickness was increased from 10 to 20 mm; however, further study is needed to find ways for increasing the internal bond strength.

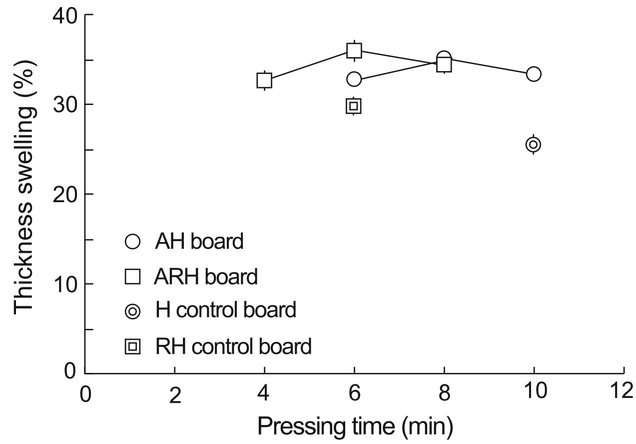

Fig. 9 Thickness swelling versus pressing time for 20-mm board. *Error bars* denote standard deviations. Abbreviations are explained in Table 3 and in the text

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