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ORIGINAL ARTICLE

Development of an air-injection press for preventing blowout of particleboard V: effects of board density and thickness on property of board manufactured from high-moisture particles

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Abstract Particleboards with thickness of 10 mm and densities of 0.6, 0.7 and 0.8 g/cm^3 were manufactured from high-moisture particles using urea–formaldehyde resin and the effectiveness of air injection was examined. The temperature in the 0.6 and 0.7 g/cm^3 boards was lower with air injection than without during the initial to middle stages of pressing, while the temperature in the 0.8 g/cm^3 board remained lower with air injection than without throughout the entire pressing process. Air injection reduced the pressing time required to manufacture the 0.6 and 0.7 g/cm^3 boards and also increased the internal bond strength of boards of all densities. In the 0.6 and 0.7 g/cm^3 boards, air injection reduced the modulus of rupture (MOR), while in the 0.8 g/cm^3 boards, the MOR was similar between those manufactured by injecting and not injecting air. Air injection was also found to be effective for boards of high densities. The effectiveness of the air injection on thick boards was investigated by manufacturing 20-mm-thick boards of 0.7 g/cm^3. Without air injection, it was not possible to manufacture the 20-mm-thick boards, even by extended hot pressing, but air injection allowed the boards to be manufactured by pressing for 16 min. Air injection was also shown to be effective for manufacturing thick boards.

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

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Introduction

In previous studies [1–3], a hot press that discharges vapor inadvertently trapped inside boards was developed to prevent blowout. The press, which has holes punched in the upper and lower heating plates, injects high-pressure air through the holes of one plate into the particleboard and discharges it through the other plate and the sides of the board during press heating. The injected air discharges vapor trapped inside the boards and prevents blowout. The press is called an air-injection press, and can be used to manufacture boards from particles of high moisture content of 25 % (high-moisture particles) by preventing blowout.

Today, particleboard is mainly produced from wood waste [4], which has a moisture content of about 20 % in Japan. Blowout of board occurs when high-moisture particles are used. However, the air-injection press can be used to manufacture boards from high-moisture particles without drying the particles in advance, which saves energy [1].

The air-injection press has been tested for manufacturing boards from high-moisture particles by using urea–formaldehyde resin as the binder. Initially, boards manufactured using the air-injection press showed low strength properties due to the high-moisture particles [1, 5, 6]. The air-injection press and pressing conditions were subsequently improved by investigating the effects of the diameter of the air-injection holes, pressure of the injected air and press temperature, etc., on the board strength [2, 3].

Based on the working principle of the air-injection press [1–3], the injected air is likely to be unable to pass through highly dense or thick boards [7]. Therefore, the effects of board density and thickness on the air-injection press need to be clarified. In this study, boards of variable density and thickness were manufactured from high-moisture particles, and the effects of the board density and thickness on the air-injection press were analyzed. In previous studies [7, 8], the effects of the air-injection press on preventing blowout were shown when the boards were manufactured from low-moisture particles. However, the conditions for blowout of the boards manufactured from high-moisture particles differed from those from low-moisture particles, and the properties of the former boards also differed from those of latter [9]. Therefore, the condition of blowout occurrence and the properties of boards needed to be investigated according to several moisture contents. In this study, the research target was high-moisture particles.

Experimental method

Particleboard manufacture

The boards were manufactured from particles produced from wood waste for core layers of particleboard (Japan Novopan Industrial Co., Ltd.). The average length of the particles was 15.4 (6.69) mm. The number in parentheses indicates the standard deviation. The number of particle specimens measured was 200. The binder used was a urea–formaldehyde resin (TB-86, Oshika Co., Ltd.), with resin content of 65 % and viscosity of 0.14 Pa s. 10 % ammonium chloride solution was added to the binder as a curing agent to constitute 10 % of the binder (by weight). The binder (based on solid) of 10 % of the oven-dried particles (by weight) was sprayed on the particles while the particles were stirred in a blender. The moisture content of the particles after spraying the binder was 25 %. Boards were manufactured by pressing at 190 °C for 4–14 min, either by injecting or not injecting air. The air-injection pressure was 0.55 MPa at room temperature. Holes were also punched in the caul (upper) plate, through which the high-pressure air and vapor were discharged. The diameter of the air-injection holes on the lower plate was 1 mm; the spacing between the centers of adjacent holes was 25 mm; and there were 121 holes within an area of 250 × 250 mm. The caul plates also had 121 holes within the same area. Grooves 1.5 mm deep and 1 mm wide were also cut, connecting the holes on one side of the caul plate to discharge the high-pressure air and vapor. The diameter and spacing of the air-injection holes were the same as those of the air-discharge holes. Refer to previous studies [1–3] for the structure of the air-injection press. The injection of high-pressure air was started when the board thickness reached 10 mm and stopped for the final 15 s of pressing time. The board dimensions were 300 × 300 × 10 mm (10-mm board), and the target board densities were 0.6, 0.7 and 0.8 g/cm^3 (0.6, 0.7 and 0.8-g/cm^3 boards, respectively). The pressing time was 4–14 min. Table 1 lists the detailed manufacturing conditions. Thicker boards of 20 mm (20-mm boards) were also manufactured as well as 10-mm boards. The density and dimensions of the 20-mm board were 0.7 g/cm^3 and 300 × 300 mm, respectively. The 20-mm boards were manufactured by pressing at 190 °C for 14–24 min (Table 1). In addition, 10-mm control boards with target board densities of 0.6, 0.7 and 0.8 g/cm^3 were manufactured from low-moisture particles (15 %) after spraying the binder by hot pressing for 4 min (0.6, 0.7 and 0.8-g/cm^3 control boards, respectively; Table 1). Also, 20-mm control boards of 0.7 g/cm^3 were manufactured by pressing for 6–12 min (Table 1). One board was manufactured for each condition. The temperature in the board at the center was measured as described in the previous report [1].

Property tests

The manufactured boards were left in a thermo-hygrostat at 20 °C and 65 % relative humidity until the weight stabilized. For 10-mm boards, the modulus of rupture (MOR), internal bond (IB) and thickness swelling (TS) were determined according to JIS A 5908 [10]. The number of test specimens was 5, 8 and 7, respectively. The 20-mm boards were subjected to IB and TS tests and the number of specimens was 13 and 12, respectively.

Results and discussion

Effects of the air-injection press on pressing time

Table 2 lists the success and failure of the 10-mm boards (0.6, 0.7 and 0.8-g/cm^3 boards) manufactured from high-moisture particles. Failure was defined as a crack or split in the board (see Ref. [3]). The 0.6-g/cm^3 boards required 8 min of pressing without air injection and 6 min with it. The 0.7-g/cm^3 boards required 10 min without air injection and 6 min with it. The 0.6-g/cm^3 boards, which were less dense than the 0.7-g/cm^3 boards, had more spaces in them, making it easy for vapor to escape from the sides. Therefore, the 0.6-g/cm^3 boards could be manufactured in 8 min without air injection, but not the 0.7-g/cm^3 boards. Air injection was effective in both the 0.6 and 0.7-g/cm^3 boards and reduced the pressing time to 6 min. Conversely, the 0.8-g/cm^3 boards required 10 min with and without air injection. Unlike the 0.6 and 0.7-g/cm^3 boards, air injection did not reduce the pressing time of the 0.8-g/cm^3 boards. This was probably because it was difficult for the injected air to pass through the 0.8-g/cm^3 boards, which were dense and had few spaces inside, hence the vapor was insufficiently discharged.

Table 1 Particleboard manufacturing conditions

Abbreviations: Thickness	Abbreviations: Density	Thickness (mm)	Density (g/cm^3)	Moisture content (%)	Air injection (yes/no)	Pressing time (min)
10-mm board	0.6-g/cm^3 board	10	0.6	25	No	6, 8
	0.6-g/cm^3 board	10	0.6	25	Yes	4, 6, 8, 10
	0.7-g/cm^3 board	10	0.7	25	No	8, 10
	0.7-g/cm^3 board	10	0.7	25	Yes	4, 6, 8, 10
	0.8-g/cm^3 board	10	0.8	25	No	8, 10
	0.8-g/cm^3 board	10	0.8	25	Yes	4, 6, 8, 10
10-mm control board	0.6-g/cm^3 control board	10	0.6	15	No	4
	0.7-g/cm^3 control board	10	0.7	15	No	4
	0.8-g/cm^3 control board	10	0.8	15	No	4
20-mm board	–	20	0.7	25	No	16, 20, 24
	–	20	0.7	25	Yes	14, 16, 20
20-mm control board	–	20	0.7	15	No	6, 8, 10, 12

Table 2 Success and failure of 10-mm board manufactured from high-moisture particles

Density (g/cm^3)	0.6		0.7		0.8	
Pressing time (min)	No air injection	Air injection	No air injection	Air injection	No air injection	Air injection
4		Failure		Failure		
6	Failure	Success		Success		
8	Success	Success	Failure	Success	Failure	Failure
10		Success	Success	Success	Success	Success
12						Success
14						Success

Failure was defined as a crack or split in the board, and see Ref. [3]; the 10-mm board is shown in Table 1

Effects of the air-injection press on MOR

Table 3 lists the MOR of the 10-mm control boards manufactured from low-moisture particles. The MOR of the 0.6, 0.7 and 0.8-g/cm^3 control boards was 16.4, 21.7 and 23.9 MPa, respectively. The MOR was apparently higher in the 0.7-g/cm^3 control board than in the 0.6-g/cm^3 control board, but there was no statistically significant difference in MOR between the 0.7 and 0.8-g/cm^3 control boards. Higher densities generally result in higher MOR [11, 12], but the MOR of the 0.8-g/cm^3 control board did not exceed that of the 0.7-g/cm^3 control board.

Figure 1 plots the MOR of the 10-mm boards against pressing time. As shown, the MOR in the 0.6 and 0.7-g/cm^3 boards manufactured without air injection was 13.5 and 19.7 MPa, respectively, and was higher in the denser 0.7-g/cm^3 board than in the 0.6-g/cm^3 board. In contrast, the MOR of the 0.8-g/cm^3 board at 12.6 MPa was lower than that of the 0.7-g/cm^3 board. There was almost no difference in MOR between the 0.7 and 0.8-g/cm^3 control boards (Table 3), which were manufactured from low-moisture particles, but the MOR was lower in the 0.8-g/cm^3 boards, which were manufactured from high-moisture particles without air injection, than in the 0.7-g/cm^3 boards. For all densities, the MOR of the boards manufactured without injection was lower compared to the control boards.

With air injection, the MOR of the 0.6, 0.7 and 0.8-g/cm^3 boards was about 10, 14 and 15 MPa, respectively, regardless of pressing time. Even with air injection, the MOR of the 0.8-g/cm^3 boards did not exceed that of the 0.7-g/cm^3 boards. The air injection reduced the MOR of the 0.7 and 0.6-g/cm^3 boards, which were not dense, but did not affect the MOR of the 0.8-g/cm^3 board. For all densities, the MOR of the boards manufactured by injecting air was lower than that of the control boards.

Effects of the air-injection press on IB

Table 3 lists the IB of the 10-mm control boards. Higher densities generally result in higher IB [11, 12], but the IB of the control boards was similar for all densities (0.607–0.716 MPa).

Figure 2 plots the IB of the 10-mm boards against pressing time. Without air injection, IB was 0.13–0.21 MPa for all densities and was lower compared to the control boards. Conversely, air injection increased the IB to

Table 3 Property of 10-mm control board manufactured from low-moisture particles

Density (g/cm^3)	0.6	0.7	0.8
MOR (MPa)	16.4 (2.59)	21.7 (2.03)	23.9 (1.47)
IB (MPa)	0.607 (0.08)	0.716 (0.24)	0.656 (0.13)
TS (%)	22.4 (0.87)	27.9 (2.98)	28.2 (3.70)

Numbers in parentheses denote standard deviations; the 10-mm control board is shown in Table 1

MOR modulus of rupture, *IB* internal bond, *TS* thickness swelling

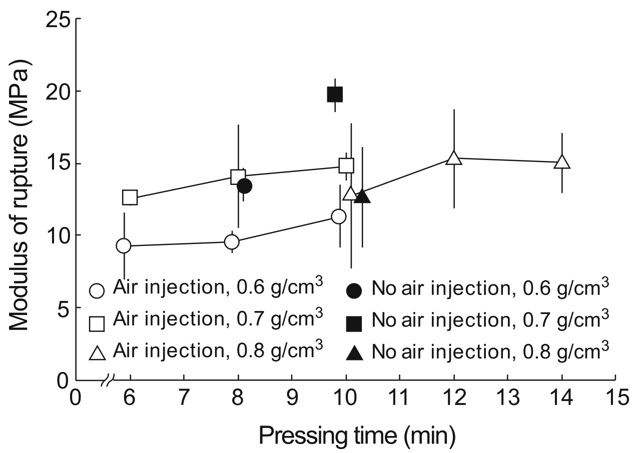

Fig. 1 Modulus of rupture of the 10-mm boards against pressing time. *Vertical bars* denote standard deviations

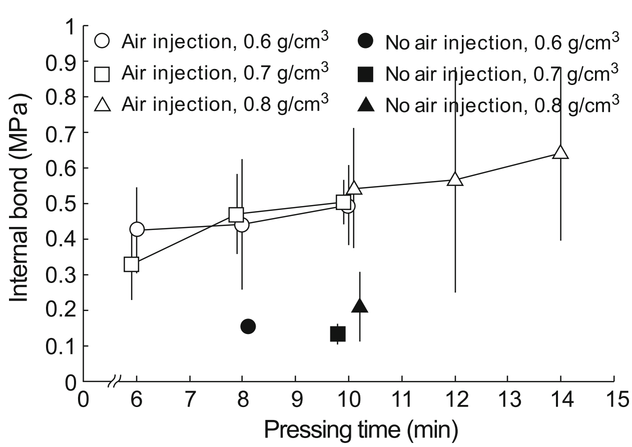

Fig. 2 Internal bond of the 10-mm board against pressing time. Vertical bars denote standard deviations

0.33–0.50 MPa in the 0.6 and 0.7-g/cm^3 boards, regardless of pressing time. The IB of the 0.8-g/cm^3 board was slightly higher compared to the 0.6 and 0.7-g/cm^3 boards. The 0.8-g/cm^3 board also showed a considerable standard deviation because there were sections of high and low IB values in the boards. This was likely because the injected air had difficulty passing through the dense 0.8-g/cm^3 board and could not thoroughly discharge the vapor. Vapor that remained locally inside the board increased the pressure and may have caused very small blowouts, and then inhibited the curing of the urea–formaldehyde resin [5, 6]. Therefore, there were sections in the 0.8-g/cm^3 board where the IB was very low. In contrast, there were sections where the IB was high because the injected air thoroughly discharged the vapor and the binder cured sufficiently. The difference in IB among board sections resulted in considerable standard deviation.

Effects of the air-injection press on the temperature change at the center of the board

Figures 3 and 4 show the temperature changes at the center of the 10-mm board manufactured by not injecting and injecting air, respectively, against pressing time. All boards manufactured without air injection showed similar temperature changes. The temperature reached 105 °C in 1 min, remained at that level until 4 min, and gradually rose thereafter. On the other hand, the temperature in the boards manufactured by injecting air varied by board density. The temperature in the 0.6 and 0.7-g/cm^3 boards rose continuously until 5 min and then gradually leveled off. The temperature was higher in the 0.6-g/cm^3 board (130 °C in 10 min) than in the 0.7-g/cm^3 board (120 °C in 10 min) and rose faster in the former, whereas the temperature rose sharply in the 0.8-g/cm^3 board, reaching 100 °C in 2 min, remaining at that level until 8 min, and then increasing very gradually. The injected air passed through the 0.6 and 0.7-g/cm^3 boards more smoothly compared to the denser 0.8-g/cm^3 board. Therefore, the 0.6 and 0.7-g/cm^3 boards were cooled by the injected air until 3–4.5 min, delaying the rise in temperature compared to the 0.8-g/cm^3 board. Since the air passed through the 0.6-g/cm^3 board more smoothly compared to the 0.7-g/cm^3 board, vapor was discharged faster from the 0.6-g/cm^3 board, resulting in a faster rise in temperature. Conversely, the effects of air injection were smaller in the 0.8-g/cm^3 board than in 0.6 and 0.7-g/cm^3 boards, through which the air could not easily pass, hence the 0.8-g/cm^3 board was hardly cooled by the air injection. The temperature changes in the 0.8-g/cm^3 board support the hypothesis that air injection does not reduce the pressing time since the air hardly passes through the board (Table 2).

The temperature changes of the 10-mm boards manufactured by not injecting air (Fig. 3) were similar compared to ordinary boards manufactured from low-moisture particles [13, 14], showing that sufficient heat for curing the binder was transmitted to the core even when high-moisture particles were used. This should have resulted in high IB, but the IB of boards manufactured without air injection was low (Fig. 2).

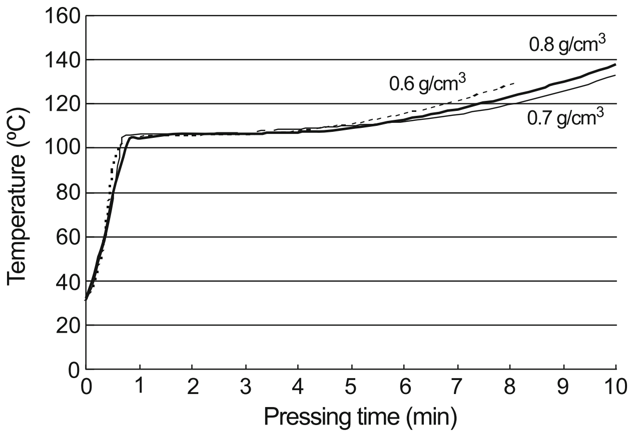

Fig. 3 Temperature changes at the center of the 10-mm board with no air injection against pressing time

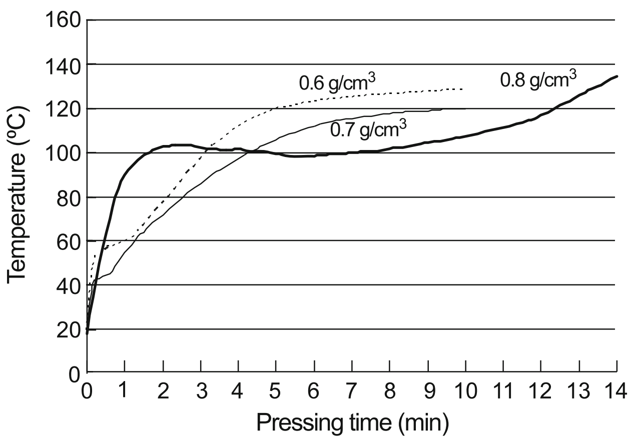

Fig. 4 Temperature changes at the center of the 10-mm board with air injection against pressing time

The temperature of the 0.6-g/cm^3 boards was lower with air injection than without until 3 min. In the 0.7-g/cm^3 boards, the temperature was lower with air injection than without until 6 min. In the 0.8-g/cm^3 boards, the temperature was always lower with air injection than without. Although the temperature was lower with air injection than without, IB was higher in the boards manufactured by injecting air than by not injecting air (Fig. 2). The urea–formaldehyde resin did not act sufficiently as a binder under high moisture conditions, even at high temperatures, possibly because high moisture inhibits curing, and causes excessive penetration of resin into the wood particles [15]. Air injection was found to be effective for accelerating the curing of urea–formaldehyde resin by discharging vapor.

Effects of the air-injection press on TS

The TS of the 10-mm control boards is shown in Table 3. The TS in the 0.6, 0.7 and 0.8-g/cm^3 control boards was 22.4, 27.9 and 28. 2 %, respectively. The TS was smaller in the 0.6-g/cm^3 control board than in those of 0.7 and 0.8-g/cm^3. In contrast, Fig. 5 plots the TS of 10-mm boards against pressing time. Without air injection, the TS of the 0.6, 0.7 and 0.8-g/cm^3 boards was 26.3, 49.4 and 41.9 %, respectively. The TS of the 10-mm boards exceeded that of the 10-mm control boards for all densities. The difference compared to the control board was more conspicuous in the 0.7 and 0.8-g/cm^3 boards than in the 0.6-g/cm^3 board. With air injection, the TS was 30–40 % for all densities regardless of pressing time. The air injection increased the TS in the 0.6-g/cm^3 board but reduced it in the 0.7 and 0.8-g/cm^3 boards. As shown in Fig. 2, the air injection increased the IB in boards of all densities and thus should have reduced the TS in all boards. The TS decreased in the 0.7 and 0.8-g/cm^3 boards as predicted but increased in the 0.6-g/cm^3 board. The cause of the increase in TS in the 0.6-g/cm^3 board needs to be investigated.

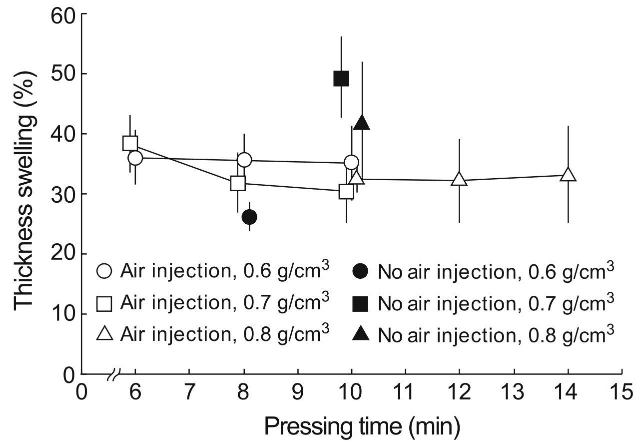

Fig. 5 Thickness swelling of 10-mm board against pressing time. *Vertical bars* denote standard deviations

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

Table 4 lists the success and failure of 20-mm boards manufactured from high-moisture particles. Without air injection, the boards could not be manufactured, even with extended pressing time, due to the high-moisture particles and the center of the board was not cured at all. Conversely, the boards could be manufactured in 16 min by injecting air, showing the effect of air injection in manufacturing 20-mm boards.

Figure 6 shows the temperature changes at the center of the 20-mm board against pressing time. Without air injection, the temperature reached 100 °C in 5 min and remained at that level thereafter. The temperature change of the 20-mm board with air injection in Fig. 6 differed from that of the 10-mm board (0.7 g/cm^3) in Fig. 4 [16]. The temperature of the 10-mm board increased gradually

Table 4 Success and failure of 20-mm board with 0.7 g/cm^3 manufactured from high-moisture particles

Pressing time (min)	No air injection	Air injection
14		Failure
16	Failure	Success
20	Failure	Success
24	Failure	

Failure was defined as a crack or split in the board, and see Ref. [3]; the 20-mm board is shown in Table 1

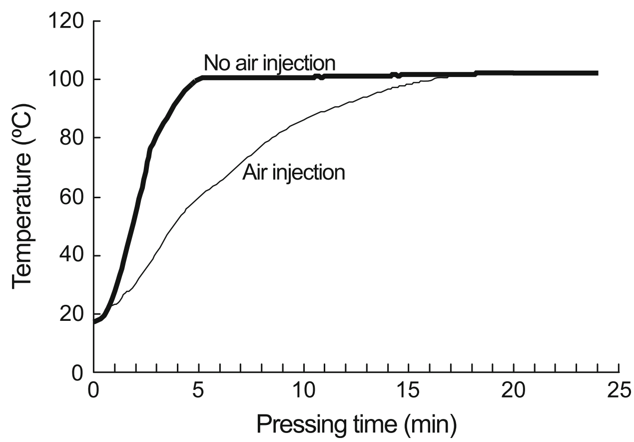

Fig. 6 Temperature change at the center of the 20-mm board against pressing time

over 105 °C in 5 min. However, the temperature of the 20-mm board with air injection did not reach 100 °C until 17 min and was lower compared to the board without air injection. In 17 min, it reached 100 °C and remained constant at that level thereafter. Although the temperature until 17 min was higher without air injection than with it, the boards could not be manufactured without air injection, showing that discharging the moisture from the boards by injecting air was effective for curing the urea–formaldehyde resin.

The 20-mm control board could not be manufactured in 6 min but was successfully manufactured in 8 min (Table 5). The pressing time for 6 min was insufficient for curing the binder. The test for determining the MOR requires a span length of 300 mm for 20-mm boards, meaning a specimen length of 350 mm. Since the specimen length was not available from the manufactured boards, 20-mm boards were not measured for MOR. Table 5 lists the IB of the 20-mm control board, which was 0.228 MPa in 8 min, increasing to 0.497 MPa in 12 min. Table 6 lists the properties of the 20-mm board. The IB was 0.403 and 0.417 MPa in 16 and 20 min, respectively, slightly lower compared to the 20-mm control board in 12 min.

The TS of the 20-mm board is shown in Table 6, 37.2 and 35.0 % in 16 and 20 min, respectively, showing a

Table 5 Property of 20-mm control board with 0.7 g/cm^3 manufactured from low moisture content particles

Pressing time (min)	6	8	10	12
Success/ failure	Failure[a]	Success	Success	Success
IB (MPa)	–	0.228 (0.03)	0.375 (0.08)	0.497 (0.08)
TS (%)	–	16.5 (0.69)	17.3 (1.13)	17.0 (0.69)

Numbers in parentheses denote standard deviations; the 20-mm control board is shown in Table 1

IB internal bond, *TS* thickness swelling

[a] The center in the board was not cured

Table 6 Property of 20-mm particleboard with 0.7 g/cm^3 manufactured from high-moisture particles using air-injection press

Pressing time (min)	16	20
IB (MPa)	0.403 (0.12)	0.417 (0.11)
TS (%)	37.2 (8.11)	35.0 (4.90)

Numbers in parentheses denote standard deviations

IB internal bond, *TS* thickness swelling

twofold increase in TS from the 20-mm control board, which was about 17 % (Table 5). Air injection could not lower the TS to the level of the 20-mm control board.

As in the 10-mm board, the 20-mm board showed reduced IB and increased TS compared to the 20-mm control board. An important future task is to further decrease the TS by air injection. Since 20-mm boards could not be manufactured from high-moisture particles without air injection, the air-injection press is clearly effective.

Conclusions

In this study, 10-mm boards with 0.6, 0.7 and 0.8 g/cm^3 and the 20-mm board with 0.7 g/cm^3 were manufactured using an air-injection press. The following results were obtained:

1. For all densities, the temperature at the core of the boards was lower with air injection than without during the initial to intermediate stages of hot pressing.
2. Urea–formaldehyde resin did not cure sufficiently under high moisture conditions even at high temperatures. Air injection, which lowered the temperature but discharged vapor, helped cure the resin.
3. Air injection reduced the MOR in the 0.6 and 0.7-g/cm^3 boards. The MOR of the 0.8-g/cm^3 boards was not affected by the air injection.
4. Air injection reduced the pressing time of the 0.6 and 0.7-g/cm^3 boards and increased the IB. Air injection

did not reduce the pressing time of the 0.8-g/cm^3 board, but did increase the IB.

5. Air injection lowered the TS of the 0.7 and 0.8-g/cm^3 boards, but slightly increased the TS of the 0.6-g/cm^3 board.
6. A 20-mm board could be not manufactured even by extending the pressing time, but was successfully manufactured in 16 min by injecting air.

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