

FLAKEBOARD THICKNESS SWELLING. PART I. STRESS RELAXATION IN A FLAKEBOARD MAT

Robert L. Geimer

Wood Scientist
USDA Forest Service
Forest Products Laboratory¹
Madison, WI

Jin Heon Kwon

Professor
Department of Wood Science and Technology
College of Forestry
Kangwon National University
Chuncheon 200-701, Korea

and

James Bolton

Director
The BioComposite Centre
Bangor, UK

(Received September 1977)

ABSTRACT

The steam injection schedule best suited for dimensionally stabilizing a flake mat is one in which steam treatment is initiated before the press is closed and is continued at least until the mat attains target thickness. Experiments showed that resinless mats treated with 20 sec of steam at 600 kPa had maximum thickness swelling of 205% compared to 350% for resinless mats pressed in a conventional fashion. Reductions in thickness swelling were proportional to steam duration and pressure. Mats treated with 20 sec of steam at 1,950 kPa had only one-tenth the thickness swelling measured in conventionally pressed mats. We believe that reduction of thickness swelling is dependent on a number of factors, including plasticization of the wood, "lignin" flow, and molecular changes in the wood structure.

Keywords: Flakeboard, Steam injection, thickness swelling, dimensional stability, springback.

INTRODUCTION

A major factor restricting the substitution of flakeboard or oriented strandboard (OSB) for plywood in certain applications is its characteristic greater thickness swelling (TS). Plywood, manufactured at low pressures of 500 to 700 kPa, sustains relatively little wood cell

damage and swells in a manner similar to that of normal wood—from 6% to 12% between oven-dry (OD) and saturated conditions. Flakeboard, on the other hand, is pressed at much higher pressures, from 4,000 to 6,000 kPa, resulting in severe compression and crushing of the wood cells. As the cell walls absorb water during high moisture conditions, the collapsed cells tend to regain their original shape, resulting in TS up to 35% from OD to saturated conditions.

Terms such as compression ratio, flake plas-

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ticity, compression set, springback, and non-recoverable thickness swelling have been conveniently used to describe the behavior of a flakeboard mat during pressing and its response to moisture afterwards. However, the actual mechanisms by which moisture and the time-dependent press variables of temperature and pressure affect springback and ultimately dimensional stability have never been studied in depth. Steam injection pressing provides the potential to study these mechanisms under controlled laboratory conditions. The process that plasticizes and chemically modifies the wood prior to, during, or after compression can relieve internal stress and reduce water adsorption, thus reducing board TS. Knowledge of basic changes that occur within the wood and between wood and resin during pressing can advantageously be used to optimize present commercial installations and develop new systems capable of producing high-quality, dimensionally stable board from low quality wood with a minimum amount of resin.

OBJECTIVE

The purpose of this research was to establish the variables of steam injection pressing most influential in affecting thickness swelling in a flakeboard mat. This information should improve the understanding of those factors that control flakeboard dimensional stability.

This report is the first in a series on thickness swelling in flakeboard. Part II covers the fundamental response of board properties to steam injection pressing (Geimer and Kwon 1998). In the future, we will document the chemical analysis of treated wood and explore the relationship with TS.

BACKGROUND

Work at Bangor, Wales (Razali 1985) suggests that the stresses locked into a mat during consolidation in the press are subsequently released in the presence of water, causing thickness swelling (TS). It is therefore logical to assume that reducing or relaxing those stresses during pressing should reduce TS. Work at the

Forest Products Laboratory (FPL), Madison, WI, has indicated that a noticeable reduction in TS occurs when flakeboards, made from gum and oak, are pressed using an unsealed steam injection process (Price and Geimer 1986). Further exploratory work indicated that lengthened periods of steaming can result in reduced TS for flakeboards of both high density (oak) and low-density (aspen) hardwoods. There is good reason to believe that moisture and temperature interact in their effect on stress relaxation. According to Goring (1963), the glass-transition point of dry lignin and hemicellulose is between 130°C and 190°C, while the same polymers in the wet condition (moisture content > fiber saturation point) show glass transitions in the range of 60°C to 100°C. Kamke and Casey's (1988) work indicates that stress relaxation occurs after press closure in response to differential changes in temperature and vapor pressure throughout the mat.

Shen (1973), working with a sealed steam injection system, was able to improve the stability of boards made from aspen and sugar maple flakes. At moisture levels of between 7% and 13%, good board stability was achieved with saturated steam at pressures between 1,380 and 2,070 kPa (comparable temperatures of 194°C and 221°C, respectively).

Hsu *et al.* (1988) reported that steam treatment of wood particles prior to the manufacture of particleboard is one means for imparting dimensional stability to the boards. Thickness swelling decreased with increasing duration of steam treatment (3 to 4.5 min at 1.55 MPa). While lignin and cellulose contents were essentially unchanged with increasing steam treatment time, decreases were noted in the total content of water-insoluble xylan, mannan, and galactan in lodgepole pine and the xylan content of aspen, indicating partial hydrolysis of the hemicellulose. Hemicellulose hydrolysis is said to ease the compressibility of wood, thus inhibiting the buildup of internal stresses during board pressing.

Hsu *et al.* (1989) also reported that contact treatment at 240°C stabilized waferboards that

had been bonded with heat-resistant adhesives. Chemical analysis of these post-treated boards showed negligible chemical changes in wood components, indicating that TS reduction was a result of softening and plastic flow of the lignin and carbohydrate components and the subsequent relief of internal stresses built up during hot pressing.

In a study aimed at establishing process parameters for manufacturing dimensionally stable medium-density fiberboard using a high-pressure steam pressing technique, Okamoto et al. (1994) found that increasing steam pressure and treatment time improved dimensional stability but decreased mechanical properties. Chemical analyses showed that hemicellulose and α -cellulose decreased with increasing treatment time and steam pressure, in the range of 60 to 90 sec at 1,078 kPa and 90 to 180 sec at 588 kPa steam pressure.

PROCEDURE

Equipment development

Press.—Special shielded platens were designed and built to expose mats to high pressure (maximum of 2,000 kPa) steam before, during, or after closure of the press to target thickness (Fig. 1). Circular mats, 152 mm in diameter, are formed on a circular aluminum caul that has perforations matching those in the lower steam injection platen. Screens are usually placed below and on top of the mat. A deep 10-mm-wide circular slot is milled into the top head (surrounding the steam injection ports). This slot contains a piston in the form of a circular sleeve. In practice, the caul, mat, and screens are loaded onto the bottom circular platen with the sleeve in the retracted position (Fig. 2). The sleeve, sometimes referred to as a shield, is then forced to the down position by hydraulic oil pressurized in a nitrogen-loaded accumulator. The mat chamber is sealed when the o-ring gasket in the end of the sleeve contacts the top surface of the caul plate. A hole, drilled in the edge and exiting out the top surface of the caul, provides the means for inserting a thermocouple into the

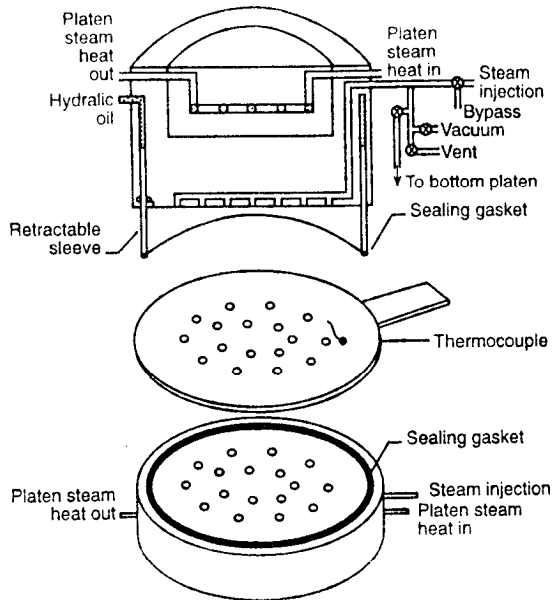


FIG. 1. Schematic of shielded steam injected platens.

mat without interfering with the seal. When the press is closed, the sleeve retracts against the pressure of the oil and compressible nitrogen. Release of pressure in the accumulator system, after the chamber has been vented and while the press is closed, permits the sleeve to remain retracted when the press is opened.

Steam can be injected through the top or simultaneously through the top and bottom platens at any time during the press cycle. Steam pressure can be released instantly by opening the manifold to atmosphere. Air in the mat and the closed chamber formed by the sleeve can be exhausted by either pulling a vacuum on the system prior to steaming, by passing steam through the mat from top to bottom and exhausting to atmosphere, or by passing the steam through the mat to a vacuum. The special platens derive much of their heat from the platens of the hydraulic press to which they are attached (Fig. 3). However, both top and bottom circular steam injection platens are provided with separate steam channels for heating purposes. The pressing operation is completely automated using computer control. This includes press position and pres-



FIG. 2. Flakeboard mats, 152 mm in diameter, are placed on shielded steam injection platens on circular perforated caul.

sure, sleeve operation, steam flow or steam manifold pressure, vacuum application, and steam entry and release.

Measurement of thickness swelling.—To measure the relative effectiveness of various pressing conditions, a system was devised to measure the TS of a mat (pressed without resin) by submerging it in water at ambient temperature (Fig. 4). The mat, caul, thermocouple, and screen assembly were weighed before and immediately after removal from the press. Thickness of the entire assembly was also measured immediately after removal from the press. The assembly was then placed into a tub

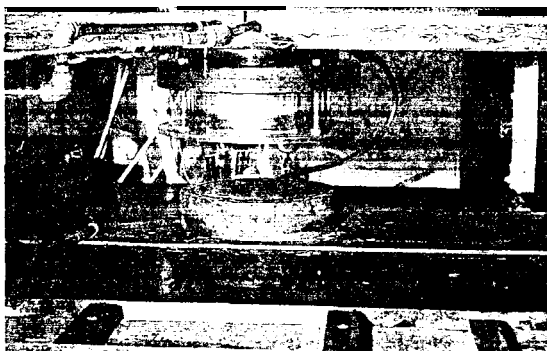


FIG. 3. Shielded platens (shown with shield in closed position) obtain a portion of their heat from the heated press platens.

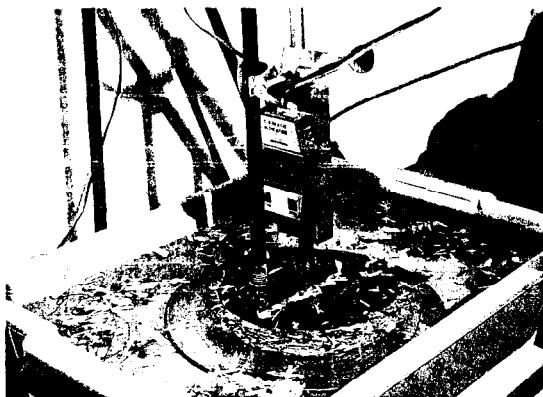


FIG. 4. Resinless mats are monitored for thickness swelling after submergence in water.

and a brass weight placed on the top screen. The 76.2-mm-diameter brass weight was approximately 10.0 mm thick and weighed 435 g. This weight was sufficient to counteract the buoyancy of the brass weight itself plus that of the wood and air in an uncompressed mat. A micrometer capable of reading to the nearest 0.0025 mm was then calibrated to zero on the top surface of the brass weight, and the tub was filled with water. Mat springback was negligible during this procedure, which took less than 3 min. Out-of-press density was such that very little, if any, mat compression occurred when the brass weight was placed on top of the mat. Micrometer TS data were monitored and collected by computer.

Methods

Flake production.—Flakes were made from air-dried, 5-cm-thick rough aspen (*Populus grandidenta* and/or *P. tremuloides*) lumber. The lumber was ripped to approximately 23 cm wide and saturated with water in a vacuum pressure tank. The wet lumber was then converted to 1.9-cm chips and further reduced to flakes in a ring flaker. The flakes, which averaged 0.762 mm in thickness, were dried to a moisture content of approximately 4% in a steam-heated drum dryer and screened an 0.16-cm and 0.08-cm mesh vibrating screens: 23% of the total material passed through the 0.08-cm mesh and was eliminated. The two

Table 1. *Press and steam injection schedules and variables.*

Press schedule	Press and steam injection schedules ^a		Steam schedule
	Cumulative time ^b (sec)		
Hold at 137 mm for 2 sec	2		
Linear closure rate of 5 mm/sec to 50 mm	19		
Parabolic closure rate of 2 mm/sec to 13 mm	(26)		
	(29)		Steam flow of 350 kg/h; on at 28 mm for 3 sec ^c
	37		Steam at pressure (a) for (b) seconds
Hold at 13 mm for (c) seconds	(29 + b)		
	37 + c		Vent
Decompress at 2mm/sec to 30 mm	45 + c		
Open at 6 mm/sec to 137 mm	63 + c		
<i>steam injection variables</i>			
<i>Steam manifold Pressure (a) (kPa)</i>	<i>Steam time (b, c) (sec)</i>	<i>Steam temperature (°C)</i>	<i>Platen temperature (°C)</i>
600	20	165	175
	40		
	80		
	160		
1,050	10	186	190
	20		
	40		
	80		
1,500	5	201	205
	10		
	20		
	40		
1,950	5	213	220
	10		
	20		
	40		

^aLetters (a), (b), and (c) refer to steam injection variables (steam pressure, steam time, and press hold time, respectively) at target position. See Fig. 8.

^bCumulative times (in parentheses) apply to changes in steam injection schedule only.

^cSteam purges manifold for 1 sec and mat (top to bottom) for 2 sec.

screen fractions were recombined and stored in polyethylene bags.

Board fabrication and exposure.—Mats, 152 mm in diameter, were pressed in the steam chamber using the pressing schedule shown in Table 1. One mat, fabricated without resin,

was pressed at each combination of steam manifold pressure, steam time, steam temperature, and platen temperature (Table 1). The mats were then submerged in water and monitored for TS as described earlier. In addition one “control” mat was made without steam at

the platen temperatures used for each of the four pressure settings. The control mats were held at target thickness for 4 min to permit the core line temperature to approach platen temperature. The control mats were likewise tested for TS by submerging in water. All mats were fabricated to a target OD specific gravity of 0.640 and pressed to a target thickness of 13 mm. Moisture content of mats was 5% when they were placed in the press.

RESULTS AND DISCUSSION

Thickness swelling in a resin-bonded composite board is characterized as either recoverable or nonrecoverable. Recoverable TS refers to that increase in board thickness with moisture adsorption that diminishes when the board is dried. Nonrecoverable TS, on the other hand, is that portion of thickness expansion that is retained in the board upon subsequent drying. The literature on composites often attributes the nonrecoverable portion of TS to compression forces set into the board during pressing. The forces result from the resistance of the individual fiber or flake to forces tending to crush the wood cells or to bend the fiber or flake over adjacent particles. The concept is that these forces are trapped or “set” into the board when the adhesive cures. From a theoretical standpoint, it would seem that “compression-set” forces are responsible for most of the out-of-press TS, or initial springback as it is often called. In all commercial pressing operations, the out-of-press board thickness is governed by adjusting press position. Increased initial springback caused by intentional or unintentional changes in such variables as density, furnish type, moisture content, adhesive amount or properties, or press temperature is compensated by reducing the distance between adjacent platens. This, of course, increases wood damage and often introduces even greater compression-set forces. We eliminated this variable by pressing all mats to the same press position. Any resistance to release of compression-set forces in the resinless mats must be limited to weak ad-

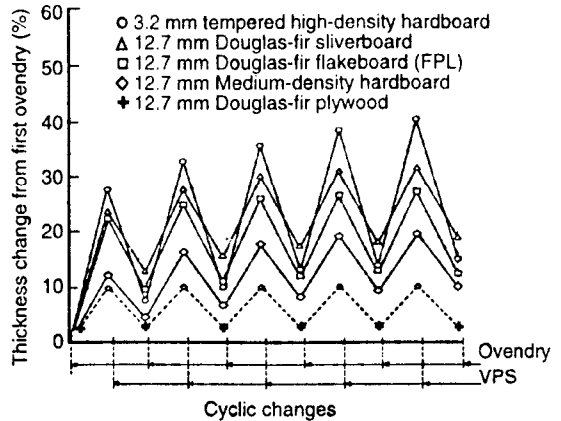


FIG. 5. Thickness swelling of various composite boards when subjected to cyclic oven-dry, vacuum-pressure-soak treatments (Heebink and Hefty 1968).

hesive bonds associated with “lignin flow,” hydrogen bonding, or even weaker wood-to-wood (Van der Wall force type) attractions.

Heebink and Hefty (1968) showed that the majority of nonrecoverable TS in resin-bonded composites is usually apparent after a single vacuum-pressure-soak (VPS) treatment. Their work also indicated that nonrecoverable TS may increase in a gradual fashion during successive exposures to OD-VPS cyclic moisture changes (Fig. 5). This suggests that under less severe in-service conditions where the relative humidity can cycle between 50% and 90%, the level of compression-set forces may determine the rate at which nonrecoverable TS is incurred. However, considering that crushed or bent cells exhibit tremendous forces in returning to their normal shape upon adsorbing water, it is difficult to rationalize that the presence or lack of compression-set forces can alter *maximum* TS in a resin-bonded board that has been saturated. More than likely, maximum TS in a conventionally pressed resin-bonded board is controlled by species, density, vertical density gradient, particle geometry, the associated packing factor, and the extent and quality of adhesive bonds. The gradual increase in board thickness with successive exposures to saturated conditions, which was observed by Heebink and Hefty, is probably the

result of successive degradation of resin bonds. Certainly, in our study with resinless mats, there is no reason to believe that compression-set forces affect maximum TS.

Exploratory studies

A lengthy series of exploratory trials were conducted with resinless mats to establish the press schedules and steam injection programs used in this experiment. Excerpts from this preliminary work are given in Table 2. In addition to TS data, Table 2 provides pertinent pressing time and temperature relations. Steam dwell time refers to the period of the press schedule during which press closure was stopped and maintained at a constant opening of 50 mm while steam was injected (in the case of steamed mats) (Fig. 6). Press dwell time refers to the time that the press remained at the target thickness of 13 mm. Total press time refers to the time from press closure to beginning of decompression.

In the exploratory portion of this study, TS was at first calculated for the target board thickness of 13 mm, that is

$$\text{TS} = \frac{(\text{measured thickness (mm)} - 13)}{100/13}$$

It is obvious from the negative (out-of-press) TS, calculated in this manner for mats F, J, and N (Table 2, footnote e), that final press position was actually less than 13 mm. To compare results in this and related experiments (to be described in later publications), we calculated TS on a common 10.75-mm initial thickness basis. This value is the minimum out-of-press thickness measured on a resin-bonded board made with 10 sec of steam at 1,950 kPa (Geimer and Kwon 1998).

Control mats A and B (Table 2), pressed without steam, established the maximum (24 h submerged) TS to be in the range of 362% to 397%. Exploratory experiments using steam were initially conducted at a manifold steam pressure of 700 kPa corresponding to a saturated steam temperature of 170°C. Introduction of 10 sec of steam at an early stage of closing (mat C) had only a slight effect on

final TS when the steam pressure was reduced by venting the cauls to atmosphere prior to closure to target thickness (Fig. 6). Extension of steam time from 10 to 90 sec (mat D) did not improve results. In both cases, mat-core temperature during steaming was quite high (167°C and 178°C, respectively), but dropped to approximately 110°C before the press reached target thickness. Out-of-press TS in mat C (10 sec of steam) was still high when compared to that in the conventionally pressed mat (190 sec of steam) (97% compared to 63% TS). Out-of-press TS increased to 227% for mat D (90 sec of steam), along with a sharp rise in out-of-press moisture content.

Delaying steam injection until after the press was closed to the final position was more effective than preclosure steaming (Table 2). When the postclosure steam period was 30 sec (mat E), 24-h TS was reduced to 281%. Increasing postclosure steam time to 90 sec and total press time from 99 to 219 sec (mat F) decreased 24-h TS even further, to 199%. Out-of-press TS was well below that experienced in mats steamed prior to press closure.

Data for mat G show the effect of the higher steam pressure (1,900 kPa) used in preclosure steam treatments (Table 2). Although a maximum mat temperature of 214°C was recorded, the temperature had dropped to 106°C by the time the press reached final position. Out-of-press TS and 24-h TS remained relatively high—241% and 262%, respectively. Delaying high-pressure steam injection until after press closure (mat H) produced some interesting results. Mat-core temperature rose relatively slowly, but it had climbed to 155°C by the end of the pressing schedule. When the mat was removed from the press, it had expanded in the center but was held together by a narrow band of flakes around the circumference (Fig. 7a). When the top and bottom halves were separated (Fig. 7b), it was obvious from the color differential that the center flakes had not experienced the same degree of heat as had the outer flakes. This was attributed to the entrapment of air. The fact that the edge and surface flakes had been bonded to-

TABLE 2. *Exploratory studies.*

Mat	Press and steam conditions				Time and temperature conditions					Thickness swelling				
	Steam pressure (kPa)	Steam time (sec)	Steam dwell time ^a (sec)		Total press time (sec)	Time to 100°C (sec)	Close temp ^d (°C)	Time to max temp (sec)	Max temp (°C)	Out of press moisture content (%)	Out of press ^e (%)	Out of press ^f (%)	500-sec ^g (%)	24-hr ^h (%)
			at	after										
A	—	0	32	64	130	—	32	130	74	3.4	83	121	391	397
B	—	0	32	120	190	171	26	190	108	3.3	35	63	356	362
C	700	10	10	30	80	20	108	32	167	8.3	63	97	308	326
D	700	90	92	30	160	21	111	31	178	18.7	170	227	328	351
E	700	30	0	60	99	71	33	99	114	6.7	20	45	252	281
F	700	90	0	180	219	61	31	125	148	6.7	-9	10	184	199
G	1,900	30	30	34	100	20	106	27	214	10.6	113	158	241	262
H	1,900	30	0	60	99	62	33	99	155	24.5	91	131	222	229
I	700	20	0	30	70	27	169	31	171	18.1	34	62	172	188
J	1,900	20	0	53	89	28	192	51	192	13.6	-11	8	51	61
K	1,900	20	20	29	92	21	107	30	211	19.7	150	202	249	270
L	1,900	20	10	30	83	21	108	30	213	9.2	45	75	195	214
M	1,900	20	5	29	77	20	144	28	212	10.0	13	37	155	167
N	1,900	20	0	30	73	21	189	27	209	8.9	15	3	78	91

^a Press position is held at 50 mm while steam is injected.
^b Steam is injected; at 50-mm position hold; following 50-mm position hold, but prior to 13-mm position, after press closure to 13 mm target thickness. Press closure rate from 80 to 13 mm is 2 mm/sec.
^c Press position is held at 13-mm target thickness.
^d Temperature measured when press reaches 13-mm target thickness.
^e Percentage of TS = (measured thickness / 13)/13.
^f Percentage of TS = (measured thickness / 10.75)/10.75.
^g Steam injected at 28 mm press opening.

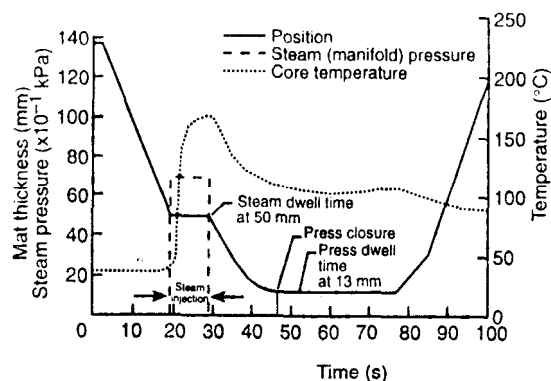


FIG. 6. Typical press schedule used in exploratory study, showing steam and press dwell times.

gether sufficiently to counteract the swelling forces in the center portion of the mat indicates that "lignin flow" or similar activity is one of the factors that reduce TS in a steam-injection-pressed mat.

The term "lignin flow" is qualified because (1) lignin, as used in this report, includes hemicelluloses, free sugars, and extractives, and (2) the flow of these substances can affect TS in a number of ways. What we envision is a softening of the noncrystalline cellular material and its movement to surround, conform to, and perhaps invade the deformed cellular structure. We also extend this in a macroscopic manner to the formation of a coating or partial coating on the exterior surface of the wood particles that comprise the composite furnish. The lignin, hemicelluloses, and free sugars that constitute the noncrystalline cellular material have the ability, above their glass-transition temperature, to fill gaps, strengthen damaged areas, and act as an adhesive on both the micro and macro scale.

Several trials confirmed that substantial improvements in reducing mat TS were possible if steam was injected while the press was closing and if steam injection was continued until the press had closed to target thickness (mats I and J). Twenty seconds of steam at 1,900 kPa was sufficient to reduce the 24-h TS measured in a conventionally pressed mat by a factor of 6.5. Both out-of-press and 24-h TS were significant-

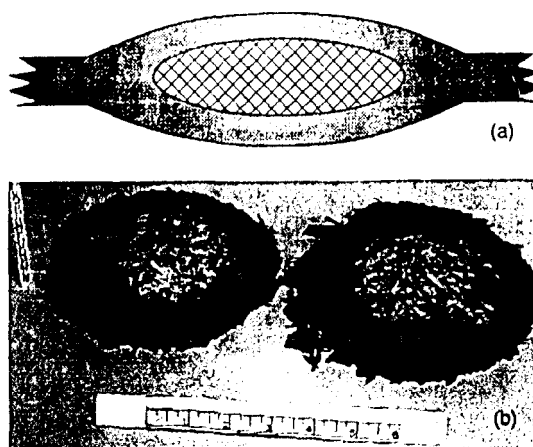


FIG. 7. Schematic and photograph of mat H: (a) cross-sectional diagram; (h) interior view (half sections).

ly reduced. To ascertain the importance of lignin flow and bonding, a series of mats were made using high pressure steam introduced prior to and during mat closure (mats K through N). The same 50-mm steam entry point and the same 20-sec duration of steam were used for all the mats. However, the steam dwell time was progressively shortened, reducing the time between steam cessation and press closure to target thickness, successively from 18 sec to 8, 3, and -2 sec. Press dwell time was maintained at 30 sec. Although maximum mat temperature was similar (approximately 210° C) in all cases, the closing temperature increased from 107° C to 189° C and maximum TS declined from 270% to 91%. The shift through the lignin's glass-transition point is apparently rapid, and in the case of early steam cessation, effective lignin flow, stops before the press reaches target thickness.

Further experiments on presteaming the mat during closure and maintaining steam pressure at least until final press-target thickness was attained) showed that consistent reductions in maximum TS below, 200% could be achieved using 700 kPa of steam. Increasing steam pressure and duration reduced TS even further. Exploratory studies also indicated that extension of the hold time at final position, after the manifold pressure was reduced to atmospheric, had little effect on final TS. It

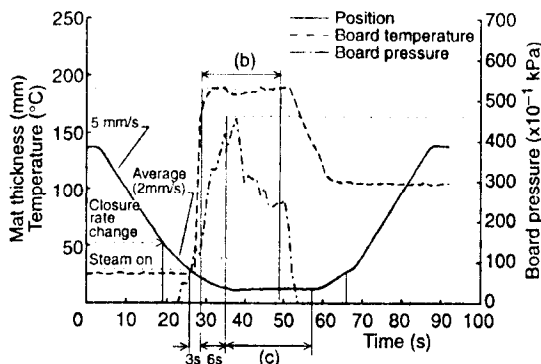


FIG. 8. Press schedule for mats exposed to 1,500 kPa steam (a) for 20 sec (b). Press dwell time was 20 sec (c).

is of interest to note that TS followed the same pattern for all mats, with the majority of swelling occurring within the first 500 sec after submergence.

Mat thickness swelling

The basic steam injection pressing schedule found to be most effective in reducing TS, i.e., steam injected into a mat during press closure and maintained at least until the press has closed to target thickness, is also the optimum schedule to achieve short press times (Geimer 1983). A general press schedule was used to delineate the effect of specific press variables on TS (Table 1). Press conditions recorded for a mat pressed with 1,500 kPa of steam pressure for 20 sec are plotted in Fig. 8 and are described as follows. After an initial adjustment period of 2 sec, the press was closed at a linear rate of 5 mm/sec. Upon reaching a position corresponding to a mat height of 50 mm, the press was scheduled to continue closing to 13 mm following a parabolic rate curve at an average rate of 2 mm/sec. When the mat had been compressed to 28 mm, a 1-sec burst of steam was used to purge the manifold. Steam was directed to the top platen and exhausted from the bottom platen for 2 sec to purge the mat of air. Steam was then directed into both the top and bottom platens. Manifold pressure was maintained at 1,500 kPa for 20 sec, resulting in an internal board temperature of 188°C. The manifold was immediately

vented to the atmosphere following the 20-sec specified steam period, allowing the board temperature to rapidly decrease to approximately 110°C.

The press closed to target thickness in 9 sec following initiation of the steam purge, and it was held at this position for 20 sec. This allowed a period of 6 sec to exhaust the steam prior to the decompression stage. Following decompression at 2 mm/sec to 30 mm, the press opened at a rate of 6 mm/sec to the starting position.

Results of the submergence tests are given in Table 3. Out-of-press thickness of mats varied greatly between treatments—from 10.85 mm for the mat treated with 40 sec of steam at 1,950 kPa to 19.67 mm for the mat treated with 20 sec of steam at 600 kPa. Use of the 10.75-mm common-base thickness allowed us to compare TS between mats receiving different treatments.

The press schedule for control mats pressed without steam was the same as that for the steam injection pressed (SIP) boards, with the exception that press dwell time at target thickness was extended to approximately 245 sec. This permitted core temperatures to rise between 123°C and 136°C depending on platen temperature (Table 3). Out-of-press moisture content of these control mats was relatively low (below 3.2%) (Fig. 9). Out-of-press TS was moderate, ranging between 18% and 31% (Fig. 10). However, 24-h TS of the conventionally pressed boards was quite high, setting the upper range of mat TS between 351% and 361% (Table 3). No effect of platen temperature could be discerned on 24-h TS of control mats.

Maximum TS in a SIP mat was 205%, measured in the mat exposed to 20 sec of steam at 600 kPa (Table 3, Fig. 11). Mat TS decreased with increasing steam pressure and steam duration to 32% in the mat exposed for 40 sec at 1,950 kPa steam.

Conventionally pressed mats did not show as much out-of-press TS as mats pressed with 600 kPa of steam and yet exhibited more TS after 24 h under water (Table 3, Figs. 9 and 10). Obviously, a number of factors influenced

TABLE 3. *Mat thickness swelling.*

Press conditions					Mat conditions						
Steam pressure (kPa)	Steam time (sec)	Platen temp (°C)	Total time (sec)	Press dwell time (sec)	Time to 100 °C (sec)	Close temp (°C)	Time to max temp (sec)	Max temp (°C)	Out-of-press MC (%)	TS (10.75-mm basis)	
										Out of press (%)	24-h (%)
600	20	175	54	24	29	148	51	155	19.7	82	205
	40	175	74	39	29	157	66	163	17.5	60	191
	80	175	114	80	29	156	56	163	20.4	52	173
	160	175	194	159	29	159	154	163	23.4	55	158
1,050	10	190	50	15	28	164	42	173	13.6	30	164
	20	190	57	23	28	171	47	177	15.4	29	147
	40	190	77	43	28	172	66	180	17.1	28	129
	80	190	120	86	29	172	101	181	21.7	20	101
1,500	5	205	44	10	28	196	36	207	10.4	13	148
	10	205	49	19	28	201	33	202	13.1	13	118
	20	205	59	25	28	188	44	190	15.7	13	87
	40	205	79	45	28	184	58	192	18.4	9	63
1,950	5	220	44	9	29	208	38	233	13.1	19	114
	10	220	49	14	28	214	37	234	12.0	5	90
	20	220	59	25	28	183	51	194	14.7	5	61
	40	220	77	43	28	190	71	201	15.9	1	32
—	—	175	278	244	153	32	278	123	3.2	31	351
—	—	190	279	245	133	30	279	129	2.1	20	352
—	—	205	279	245	121	31	279	136	1.6	18	361

TS behavior of the mats. We attribute the greater out-of-press TS of the 600-kPa SIP mats to their higher moisture content.

Out-of-press mat moisture content increased as steam duration lengthened, but it was not significantly altered by steam pressure (Fig. 9). However, the tendency for out-of-press TS to increase with increased moisture content was often hidden by reductions attributed to either greater flake plasticization or lignin flow. Out-of-press TS was directly correlated

with 24-h TS in most SIP mats (compare Figs. 10 and 11). We believe that there are at least two mechanisms by which maximum TS is reduced in a SIP resinless mat. The first is lignin flow. As explained earlier, we believe that lignin flow occurs on both a micro- and macroscopic level. A second factor is a change in the molecular structure of the sugars, lignin, or cellulose components in the presence of steam. The mechanism by which this change

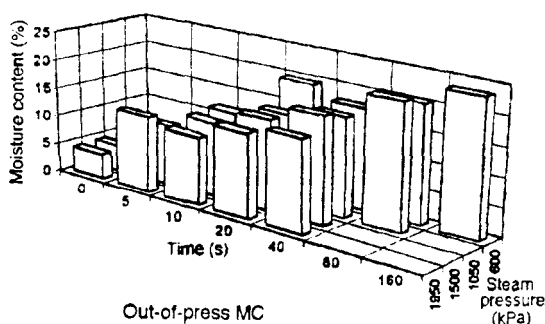


FIG. 9. Out-of-press mat moisture content

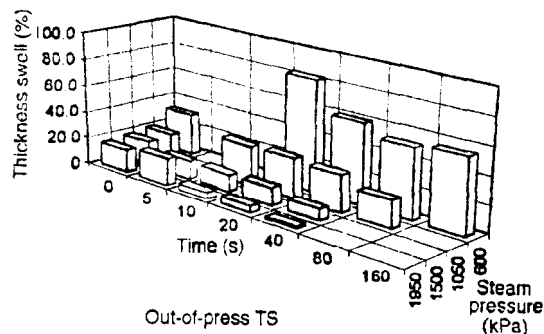


FIG. 10. Out-of-press mat thickness swell (10.75 mm basis).

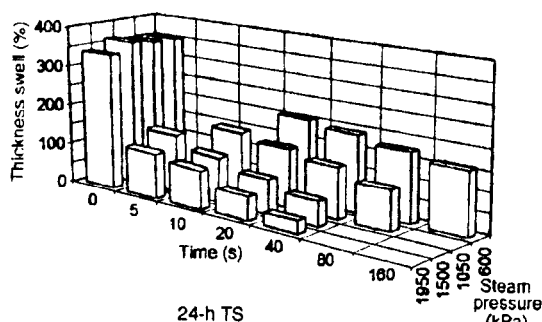


FIG. 11. Twenty-four hour mat thickness swell (10.75 mm basis).

affects TS is not well understood, but it may involve cross-linking of the amorphous regions and crystallization of the microfibrils in addition to relaxation of stresses in these areas (Dwianto et al. 1996). A forthcoming report will document chemical analysis of the steam-treated wood and further explore the relationship with TS.

Maximum mat TS decreased with increasing steam pressure and steam duration (Fig. 11). Exposure to the high steam pressure (1,950 kPa) for 5 sec reduced 24-h TS to 114%, even though the cessation of the short steam period occurred 3 sec prior to press closure. Increasing steam time to 40 sec at this high pressure lowered the TS to 32%, a greater than tenfold reduction of TS measured in the conventionally pressed mats.

This relative time dependency is of interest since conditions change so rapidly during steam injection. A major reduction in compressive-set forces occurs very soon after steam injection, as evidenced by the two- to three-fold reduction in pressure needed to close the press. A thermocouple embedded in the core of a partially compressed flakeboard mat registers temperatures above 100°C within half a second following injection of steam. This time is primarily dependent on the expulsion rate of air. However, as the mat rapidly absorbs heat, an additional 2 to 20 sec are required for the temperature to approach that of the saturated steam. In an unsealed press, this time is also dependent on press closure, which

controls the rate of increase in mat density and ultimately steam pressure. The additional time needed for the heat to raise the temperature in the center of each wood particle above the glass-transition point of lignin depends to a large part on the thickness of the particle and the steam pressure. This time would be rather short, considering the average flake thickness of 0.762 mm and the reduction in the glass-transition point accompanying a steam-induced increase in moisture content. Note, however, that further reductions of TS were obtained by extending steam time from 80 to 160 sec in the 600-kPa SIP mats. Even greater TS reductions were observed in the 1950-kPa SIP mats when exposure time was lengthened from 20 to 40 sec. Improvements in TS performance during these extended periods are attributed to changes in the molecular structure of the lignin, hemicellulose, and related sugars and/or crystallinity of the microfibrils.

CONCLUSIONS

The steam injection schedule best suited for dimensionally stabilizing a flake mat was found to be one in which steam treatment is initiated prior to press closure and continued at least until the press attains target thickness. This procedure elevates the temperature above the glass transition of hemicelluloses and lignin ("lignin flow") during the time when flake position and geometry are changing and permits them to return to a gel or glass stage after the mat has reached a stable position. Using this pressing technique, we determined the effect of steam injection pressure and duration on thickness swelling (TS) of resinless flake mats subsequently submerged in water. Pressing a mat with 20 sec of steam at 600 kPa resulted in 205% TS compared to 350% TS in resinless mats pressed in a conventional fashion. Reductions in TS were proportionate to steam time and duration. Thickness swelling in a mat treated with 40 sec of steam at 1,900 kPa was reduced to 32%—tenfold improvement compared to the TS of conventionally pressed mats. Out-of-press TS or springback

was reduced with reductions in out-of-press moisture content and was strongly dependent on plasticization of the mat and consequent reductions in compressive set forces. Reduction in maximum TS at saturated conditions was dependent on lignin flow and changes in the molecular structure of the wood. Incorporation of these findings in the steam injection manufacturing process offers the potential for economical production of stabilized flakeboard, OSB, and composite lumber.

ACKNOWLEDGMENTS

Many persons have contributed to this research project since its inception in 1987. Special recognition must be given to Steve Hankel for machine design and construction, James Wood and Jim Muehl for technical assistance, and Richard Kinney and Gary Larson for computer programming and press control.

REFERENCES

- DWIANTO, W., F. TANAKA, M. INQUE, AND M. NORIMOTO. 1996. Crystallinity changes of wood by heat or steam treatment. *Wood Res. Bull.* 83:47-49. Wood Research Institute, Kyoto University, Japan.
- GEIMER, R. L. 1983. Method of pressing reconstituted lignocellulosic materials. U. S. patent 4393019, July 12.
- , AND J. H. KWON. 1988. Flakeboard thickness swelling. II. Fundamental response of board properties to steam injection pressing. *Wood Fiber Sci.* (in press).
- GORING, D. A. I. 1963. Thermal softening of lignin, hemicellulose and cellulose. *Pulp & Paper Mag. Can.* 64(12): 517-527.
- HEEBINK, B. G., AND F. V. HEFTY. 1968. Steam post treatments to reduce thickness swelling of particleboard (exploratory study). Research Note FPL-0187, USDA, Forest Serv., Forest Prod. Lab., Madison, WI. 27 pp.
- HSU, W. E., W. SCHWALD, AND J. A. SHIELDS. 1988. Chemical and physical changes required for producing dimensionally stable wood-based composites. Part 1. Steam pretreatment. *Wood Sci. Technol.* 22(3):281-289.
- , ———, AND ———. 1989. Chemical and physical changes required for producing dimensionally stable wood-based composites. Part 2. Heat post-treatment. *Wood Sci. Technol.* 23(3):281-288.
- KAMKE, F. A., AND L. J. CASEY. 1988. Fundamentals of flakeboard manufacture: Internal-mat conditions. *Forest Prod. J.* 38(6):38-44.
- OKAMOTO, H., S. SANO, S. KAWAI, T. OKAMOTO, AND H. SASAKI. 1994. Production of dimensionally stable medium density fiberboard by use of high-pressure steam pressure. *Mokazai Gakkaishi* 40(4):380-389.
- PRICE, E. W., AND R. L. GEIMER. 1986. Thick composites are technically feasible with steam-injection pressing. Pages 65-71 in *Proc., Composite Board Products for Furniture and Cabinets—Innovations in Manufacture and Utilization*. Nov. 11-13, Greensboro, NC. Forest Products Society, Madison, WI, 1989.
- RAZALI, A. K. 1985. Origins of thickness swelling in particleboards. Ph.D. thesis, University of Wales, Bangor.
- SHEN, K. C. 1973. Steam-press process for curing phenolic bonded particleboard. *Forest Prod. J.* 26(11):46-50.