THERMAL DEGRADATION OF WOOD FIBERS DURING HOT-PRESSING OF MDF COMPOSITES: PART I. RELATIVE EFFECTS AND BENEFITS OF THERMAL EXPOSURE

Jerrold E. Winandy†
Supervisory Research Wood Scientist

and

Andrzej M. Krzysik
Forest Products Technologist
USDA Forest Products Laboratory
One Gifford Pinchot Drive
Madison, WI 53705-2398

(Received March 2007)

ABSTRACT

This research evaluated the potential of wood fiber to chemically decompose during hot-pressing. We evaluated changes in carbohydrate composition and structure as a function of multiple press temperatures (180°, 200°, and 220°C) and an array of hot-pressing durations from 180 to 2500 s. Results show how this thermal degradation in chemical composition directly results in changes in moisture sorption characteristics, physical and mechanical properties, and aboveground durability. For most mechanical properties, it appears that very little degrade occurs until mat temperatures exceed 150°C. Changes in the chemistry of medium density fiberboard seem to result in measurable changes in hygroscopicity, decay, strength, and stiffness. Control of hot-press temperature and duration appears a potential method to heat-treat medium density fiberboard and enhance its serviceability. This heat-treatment effect appears to be related to cumulative thermal load/exposure; subsequent analysis and computational modeling is currently underway.

Keywords: Medium density fiberboards, thermal degradation, process conditions, compositional changes, carbohydrate structure, physical and mechanical properties, profile density.

INTRODUCTION

Particleboard and medium density fiberboard (MDF) consumption exceeds 618 million m^2 on a 19-mm-thick basis, with approximately 25% of that being MDF (Howard 2001). A great majority of this material uses urea-formaldehyde resin and is not intended for the structural engineered wood marketplace (Suchsland and Woodson 1968). For MDF to have real potential to compete in this engineered wood market, it will require more moisture-resistant resins and it will need to overcome several issues related to moisture sorption, structural performance, and durability. The systematic use of phenolic or isocyanate resins could address the resin issue, but even then additional resistance to moisture may also be required.

Heat treatments offer the potential to modify the hygroscopicity of wood fiber. Because a hot-press process is already used in manufacturing MDF, our opinion is that enhanced serviceability could be achieved in the hot-press through extended cycles to create controlled heat-treatment processes. Further, this could be done without substantial costs in infrastructure upgrades at MDF mills. This is the first phase of a systematic study on the effects of heat treatments on wood composites as they affect moisture sorption, mechanical properties, and dura-

† Member of SWST.

Wood and Fiber Science, 39(3), 2007, pp. 450–461

bility of MDF. The second phase will include theoretical modeling of these complex relationships.

BACKGROUND

It has long been known that controlled exposure of woody material to high temperatures can enhance resistance to moisture absorption and ultimately durability (Scheffer and Eslyn 1961; Stamm 1964). Militz (2007) provided a recent review of the technical literature on heat treatments. Over the last 10 to 15 years, several heat-treating processes have been commercialized in Europe (Rapp 2001). Winandy and Smith (2007) recently summarized the effects of heat treatments on wood composites related to moisture sorption, mechanical properties, and durability.

Tests on hardboards without a resin binder, made by an alkaline process, showed that heat treatment decreased water sorption and swelling and increased bending strength (Voss 1952). Increasing the press temperature (up to 175°C) of particleboard with phenol-formaldehyde (PF) resin improved strength properties of the board and reduced thickness swelling (Liiri 1969). Press time also affected board properties at outer and middle layer moisture contents (MCs) of 18% and 9–11%, respectively, and PF resin contents of 7–10%. Post-pressing heat treatment immediately after pressing was also found to be beneficial (Liiri 1969). It is possible to improve the hygroscopic properties of self-bonded boards by modifying the physico-chemical properties of the spruce particles by thermal treatment (Antoine et al. 1971). Dry-felted boards were given various thermal treatments (150°–180°C for 1.5–5 hr); although the treatments had little effect on board strength, they did improve moisture resistance (Szymankiewicz 1971). As with solid wood, water absorption and thickness swelling of composites decreased progressively with increasing exposure at temperatures of 50°–175° (Andre and van Oost 1964). For MDF, the time–temperature effect is related to moisture environment just as previously noted for solid wood (van Houts et al. 2001a, b).

Steam-injection treatments (0.6–1.0 MPa) during hot-pressing of binderless particleboards caused considerable degradation of hemicelluloses, lignin, and cellulose; conventional hot-pressing of dry material caused less degradation of the chemical components (Widyorini et al. 2005).

More research has been conducted on the ability of heat treatment to impart dimensional stability and strength than on its durability effects. Thickness swelling of particleboard decreased with an increase in the time and temperatures of post-heat treatment (Zhang et al. 1997). Dimensionally stable wood-based composites also have a better inherent ability to withstand severe exposure conditions compared to regular boards (Hsu et al. 1989). Prolonged heating at 175° and 218°C for 0.5–2 h improved the dimensional stability of the boards; the improvement increased with increasing severity of treatment, but with a slight reduction in strength (Suchsland and Enlow 1968). Heat treatment of hardboard increases its stiffness, bending strength, and modulus of elasticity (MOE) (Ogland and Emilsson 1951). Static bending properties and moisture absorption of particleboards were improved more by hot oil treatments than by dry heat treatments (Gupta et al. 1980). Nishikawa et al. (1979) found that the strength properties of 12-mm-thick fiberboards with a density of 0.70 g/cm^3 were related to manufacturing conditions. The optimum conditions were (1) the use of phenolic resin; (2) hot-pressing with 30 kg/cm^2 at 190°C for 15 min with distance bars; and (3) heat-treatment at 150°C for 2 h. Pulp freeness and heat treatment had substantial effects on modulus of rupture (MOR) and internal bond (IB). The addition of phenolic resin and the MC of the wet mat were important for screw holding. Heat treatment caused a considerable decrease in thickness swelling and water absorption and a small reduction in bending and tensile strength (Roffael and Rauch 1973). As particleboard density was reduced, a smaller benefit in terms of increased bond strength and reduced swelling was noted (Roffael et al. 1973). Results suggested that two processes or zero-order reactions proceeded independently: (1) physical strengthening of the bonds between wood fibers, begin-

ning at about 150°C; and (2) chemical depolymerization of cellulose chains in the fibers, accelerating above 170°C (Pulikowski 1975). A model was presented for predicting the strength of tempered hardboard. Burmester and Deppe (1973) found that a 3-hour heat treatment reduced thickness swelling of boards made with isocyanate or phenol resin after immersion in water. Heat treatment reduced IB and bending strength, the effect depending on duration of heat treatment and the binder used. This reduction was less for isocyanate resin than for phenol resin. Burmester (1981) reviewed the results of 12 of his German-language studies on heat and/or formaldehyde treatments, which showed that the extent of enhanced dimensional stability was more related to heat than to formaldehyde addition.

Youh et al. (2000) found they could improve the physical-mechanical properties of board products by applying the technique of high-frequency heating when compared with similar hot-platen heating. Goroyias and Hale (2002a) found that heat treatment of wood strands to greater than ~235°C prior to pressing imparted a noticeable increase in their resistance to moisture, but also decreased strength and stiffness. Garcia et al. (2006) found that heat treatment of fiber prior to pressing could substantially enhance dimensional stability of MDF. With high press temperatures, there was less strength loss when pressing occurred in a nitrogen atmosphere compared to a steamed atmosphere, which was in turn less than in an air environment (Brauns and Strand 1958).

When particleboards made with an isocyanate binder were exposed to decay, boards made from heat-treated chips showed improved decay resistance and remained below the 16% MC necessary for fungal growth (Burmester 1974). Goroyias and Hale (2002b) found that several heat treatment scenarios for composites could substantially enhance dimensional stability, but decay resistance was enhanced to a far lesser extent. Deng et al. (2006) found that refining conditions (heat, pressure), resin content, and in-service MC affected subsequent susceptibility of MDF to mold. To ensure a high degree of decay resistance for situations such as direct outdoor exposure or ground contact, chemical treatment of strands prior to composite manufacture would be necessary (Goroyias and Hale 2004).

Hemicellulose is hydrolyzed during heat treatment (200°C for 20 min) and these changes cause reduced hygroscopity of heat-treated fiberboard (Solecnik and Siskina 1964). Fiberboards made of lignin-free material display the same increase due to heat treatment as those made of a non-delignified material; therefore, it is concluded that lignin does not play an important role in strength increase (Klauditz and Stegmen 1951). Higashihara et al. (2004) found that hemicelluloses began to measurably degrade after steaming for 60 min and both hemicelluloses and cellulose were considerably decreased after 720 min of heating at 180°C.

Lebow and Winandy (1999) and Winandy and Lebow (2001) found that cumulative thermal effects on strength and chemical composition, respectively, were not only related to exposure duration but also to the pH of the environment in which the biomaterials were exposed during processing and in service. Thus, any discussion of heat treatments of biocomposites must also include consideration of the pH effect from urea-formaldehyde (UF), PF, polymeric diphenylmethane diisocyanate (pMDI), or binderless systems. Poblete and Roffael (1985) found that thermal treatment alone in particleboard hot-pressing led to decreased wood pH. They also found that the magnitude of pH-mediated hydrolysis of UF-bound particleboard was more severe in the hotter face layers than the cooler core layer.

From this summary, it is clear that previous literature considering the influences of thermal treatments has closely studied temperature, but has not systematically considered the complex interdependent relationships of heat, duration of exposure, changing resin and wood chemistry, interactive moisture relationships, and wood strength/stiffness. Until recently, most previous studies that have considered heat-treatment effects on solid wood have also very accurately defined the absolute magnitude of the thermal environment, but they have not systematically

considered other critical issues such as duration and chemical environment. For composites, a critical need exists for a more systematic approach to the problem.

OBJECTIVES

The objective of this research was to initiate a systematic study of the effects of thermal or thermo-chemical processes relative to multiple issues (e.g., temperature, time of exposure to those temperatures, pH of environment). In this first effort, we evaluated the potential of wood fiber to chemically decompose, resulting in changes in moisture sorption characteristics, physical and mechanical properties, and durability as they relate to compositional changes in carbohydrate structure as a function of multiple press temperatures and hot-pressing durations. In a later report, we will quantify these relationships where possible.

EXPERIMENTAL DESIGN

This experiment examined single-layer fiberboard panels with a density of 720 kg/m^3 and target thickness of 12.5 mm. There were 2 controlling experimental factors: (1) press temperature (180, 200, and 220°C); and (2) hot-press duration, from 5 to 11 at each press temperature. At 180°C, the 11 press durations were 180, 270, 360, 450, 540, 720, 900, 1080, 1500, 2000, and 2500 s. At 200°C, the 11 press durations were 180, 270, 360, 450, 540, 630, 720, 810, 1500, 2000, and 2500 s. At 220°C, the five press durations were 180, 650, 1000, 1500, and 2000 s. Panels produced at different press temperatures and durations were compared using physical, mechanical, and chemical evaluations of the MDF. A total of 27 MDF panels were made and evaluated in this experiment, one for each press temperature–duration combination, with all other factors constant.

MATERIALS AND METHODS

Materials

The experimental MDF panels were manufactured from commercial mixed hardwood fiber (thermomechanical pulp) obtained from the GP Lionite Plant in Phillips, Wisconsin. The species mix was approximately 60% aspen, 10–15% each oak and maple, and <10% pine. After defibration, the fibers were commercially dried to a final MC of 3–4%, compressed to reduce the volume during transportation, and shipped to the Forest Products Laboratory in Madison, Wisconsin. The pre-compression process caused the fibers to form clumps. Thus, the dry clumped fibers were run through a hammermill without a screen to make the fibers more suitable for blending with resin. The purpose of the hammermilling process was to separate the clumps, not to shorten fiber length. This procedure resulted in a high quality fiber furnish with few noticeable fines.

Board fabrication

A water-soluble, liquid PF resin (Borden, Cascophen OS-707) with a solids content of 57% was sprayed onto the wood fiber (~5% MC) as it rotated in a drum-type blender using a single atomizing spray gun. Resin content was 5% solids; wax was not used. Some balling of the wood fibers occurred during resin application as a result of the tackiness of the resin and the tumbling action in the rotating drum. A powerful industrial vacuum cleaner mounted on top of a 190-L metal container was used to break up the balls. The blended furnish was vacuum-transferred back to the metal container prior to board fabrication.

Loose fiber mats were hand-formed in a 460- by 460-mm deckle box placed on an aluminum caul. Initial fiber MC was ~8% and mat height was approximately 320 mm. When all the fiber had been put into the deckle box, the mats were pre-compressed by hand to reduce the height and to pre-densify the mat prior to hot-pressing. This allowed for easy insertion of the mat into the hot-press and helped prevent edge crumbling that resulted from physical stresses imposed on the edges during mat compression or edge blow-out caused by internal gas-pressure developing within the mat during initial heating of the mat in the hot-press.

Panels were consolidated in a 915- by 915-mm oil-heated press using a single-step to target thickness closure scenario that developed maximum pressing pressures of ~3.5–4.0 N/mm^2 depending on press temperature. A thermocouple–gas pressure sensor was inserted into the geometric center of each mat to monitor evolving gas pressure and core temperature. Computerized press control assured that all ancillary pressing factors (e.g., closure rate, opening rate) were virtually identical except for platen temperature and time at target thickness. Following pressing, all MDF panels were stored in a hot box for 12–18 h to finalize resin cure. They were then weighed and measured to determine specific gravity.

Tests

The panels were cut into specimens for physical, mechanical, and chemical testing as shown in Table 1. Prior to testing, the specimens were conditioned at 50% relative humidity (RH) and 21°C. Three-point static bending tests to determine MOR and MOE and IB strength tests were performed in accordance with ASTM D 1037 (ASTM 2005). Results were compared to MDF limits stated in the ANSI A208.2 Standard (2002). Thickness swell and water absorption measurements were made by immersing the specimens in water in a horizontal position for both 2 h and 24 h at ambient temperature in accordance with ASTM D 1037. The effects of extended humidity exposure on specimen weight and thickness were assessed after equilibration at 27°C and 30, 65, or 90% RH.

A newly developed test was used to evaluate the potential resistance of these MDF composites to non-ground-contact decay when exposed in a warm damp environment (Micales-Glaeser 2006). In this new method, 25- by 25- by 12.5-mm-thick MDF blocks were first oven-sterilized for 4.5 h at 170°C. The MDF blocks were first weighed, then aseptically transferred in sets of four blocks onto wire screens suspended by metal pegs about 5 mm above (without contacting) a 5-mm-deep reservoir containing a 50/50 mixture of water and vermiculite in the bottom of each 100-mm-diameter, deep petri dish. The four MDF blocks in each exposure chamber were arranged so that they were not touching each other. Each set of MDF blocks was allowed to equilibrate in the exposure chambers at 65% RH and 27°C for 4 days before inoculation. The inoculum was made using 2-week-old liquid cultures of *Gloeophyllum trabeum* (Pers. Ex Fr) Murr (Mad 617) grown at 25°C in 250-mL Erlenmeyer flasks containing 25 mL of 2.5% malt extract broth. The inoculum was prepared by taking two of these cultures, draining the culture medium, adding 100 mL of sterile distilled water and blending for 15 s. Each block was uniformly inoculated with 0.5 mL of hyphal suspension. The composite blocks soaked up the inoculum quite rapidly, eliminating the need to swab the surface of the block. Lastly, additional sterile distilled water was added to the underlying vermiculite (up to the 5-mm level) to assure a saturated environment with free water just above the surface of the vermiculite.

The inoculated and control MDF blocks were exposed in near-saturated RH condition for 9 weeks in sealed 100-mm-diameter petri dishes that allowed air exchange but limited moisture

TABLE 1. *Tests and test specimen sizes and number.*

Test	Specimen size (mm)	Specimens per panel	Reference
Bending (MOR, MOE)	75 by 356	2	ASTM D 1037
Internal bond	50 by 50	3	ASTM D 1037
Density	405 by 405	1	ASTM D 1037
Thickness swell	150 by 150	2	ASTM D 1037
Water absorption	150 by 150	2	ASTM D 1037
Humidity exposure	25 by 25	3	—
Decay	25 by 25	4	Micales-Glaeser 2006
Chemical analysis	50 by 50	1	Davis 1998 and Effland 1977

loss (Fig. 1). The dishes were incubated at 27°C and 65% RH in an environment chamber. At the end of the 9-week exposure, each block was oven-dried and weighed to determine weight loss. The four blocks used in each exposure were pre-selected to provide 20 comparisons. These 20 pre-planned comparisons enabled us to directly compare the effects of various press durations at each temperature, or effect of temperature at matched times, or evaluations using 2 × 2 matched temperature-duration comparisons within the same petri dish. The use of pre-planned comparisons allowed us to account for the influence of uncontrolled variability from one petri dish to another in the biological exposures when assessing press temperature–duration performance. Only MDF specimens pressed at 1080 s or less were evaluated for decay potential.

Carbohydrate contents were determined by high pH anion-exchange chromatography with pulsed amperometric detection (HPAEC/PAD) (Davis 1998). The method of Effland (1977) was used to determine Klason lignin.

RESULTS AND DISCUSSION

Any interpretation of the data must recognize that the fiber within the consolidated MDF mat starts at some initial temperature (in our case ~20–22°C) and eventually comes to equilibrium with the platen temperature. For any press temperature, a unique set of core-temperature curves will exist depending on mat thickness, moisture, venting, and press closure rate. The critical component influencing the effect of any heat treatment on the wood material is the cumulative thermal exposure. As the MDF is hot-pressed, the wood fiber continually increases in temperature until it reaches an equilibrium with the particular hot-platen temperature. Thereafter, the exposure is a steady-state thermal load until pressing is discontinued. Accordingly, each press temperature and duration has a unique thermal exposure represented as an integrated summation of the cumulative time-temperature exposure resulting from an initial thermal-ramp load and a subsequent steady-state thermal load after the mat reaches the platen temperature. This cumulative thermal load is sometimes conceptualized as degree-days, degree-hours, or in our specific case degree-seconds. For our controlled experimental conditions, these temperature-ramping (i.e., progressive thermal load) curves are shown in Fig. 2. The predicted cumulative thermal loads from all 27 of our MDF press scenarios are given in Table 2.

Mechanical and physical property data for the three press temperatures and multiple press du-

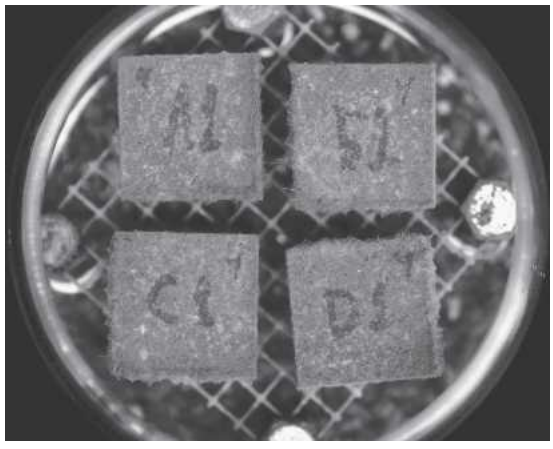

FIG. 1. Example of four non-ground-contact decay tests well underway using the 100-mm petri dish method of Micales-Glaeser (2006).

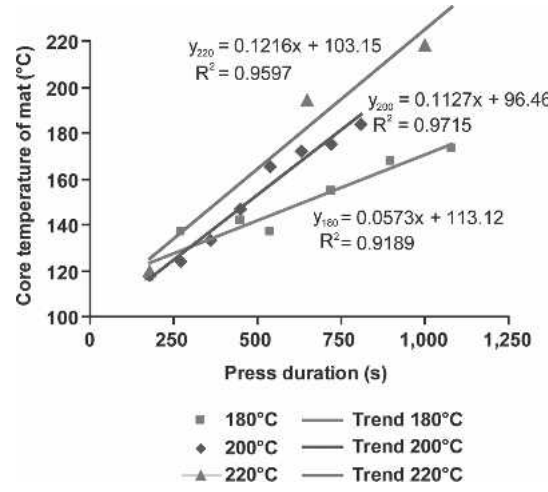

FIG. 2. Effects of press temperature and duration on mat temperature and simple linear estimates of trends.

TABLE 2. *Cumulative time-temperature exposures at the core of the consolidating MDF mats for each press temperature and duration using equations in Figure 2.*

Actual		Predicted		
Press temperature (°C)	Press duration (s)	Mat (at core) temperature (°C)	Cumulative time–temperature exposure (°C · s)	Cumulative time–temperature exposure (°C · min)
180	180	123	21295	355
180	270	129	32636	544
180	360	134	44447	741
180	450	139	56719	945
180	540	144	69455	1158
180	720	154	96319	1605
180	900	165	125040	2084
180	1080	175	155618	2594
180	1500	180	231003	3850
180	2000	180	321003	5350
180	2500	180	411003	6850
200	180	117	19199	320
200	270	127	30168	503
200	360	137	42050	701
200	450	147	54845	914
200	540	157	68553	1143
200	630	167	83173	1386
200	720	178	98706	1645
200	810	188	115153	1919
200	1500	200	252493	4208
200	2000	200	352493	5875
200	2500	200	452493	7542
220	180	125	20548	342
220	650	182	92775	1546
220	1000	220	163916	2732
220	1500	220	273916	4565
220	2000	220	383916	6399

rations at each press temperature are presented in Table 3. It is clear that appreciable loss in all mechanical properties eventually occurs from any extended hot-pressing scenario, with bending strength being the most affected property. We also noted that a discernible change in bending strength and MOE appeared at, or near, a mat core temperature of 175°C, but this should not be thought of as the "critical" value. The effect of thermal exposure on wood materials is clearly a cumulative process (Lebow and Winandy 1999). It is reasonable to assume that some changes in wood materials and the ensuing losses in various properties are initiating below this 175°C level. We evaluated the data set from the standpoint of effect as a function of cumulative time–temperature exposure and noted that most changes in properties appeared about 50,000°C · s after passing through about 150°C. In a hot-press scenario, our opinion is that the actual critical threshold for a noticeable loss in structural properties may be 200 to 300 s after passing through a mat core temperature of 150°C.

Increased press temperatures and durations clearly do not inhibit the ability of the MDF to absorb water, as shown in both 2- and 24-h soak tests (Table 4). However, even though the MDF absorbs moisture, the relative thickness swell is noticeably suppressed. This inhibition in thickness swell for the MDF–moisture absorption relationship is also evident when the MDF is exposed to higher levels of vaporous moisture at 27°C and RH levels of 30, 65, and 90% (Fig. 3). It is possible that the absorbed water occupies void space but is not directly associated with the fiber so it does not promote swelling.

For the results of our non-ground-contact de-

TABLE 3. *Static bending properties and IB strength of MDF specimens exposed to various press temperatures and durations.*

Press platen temp. 180°C					Press platen temp. 200°C					Press platen temp. 220°C				
Press duration (s)	MOE (GPa)	MOR (MPa)	IB (kPa)	SG	Press duration (s)	MOE (GPa)	MOR (MPa)	IB (kPa)	SG	Press duration (s)	MOE (GPa)	MOR (MPa)	IB (kPa)	SG
180	2.90	26.3	220	0.66	180	2.73	26.8	220	0.66	180	2.03	14.8	170	0.62
270	2.67	25.2	320	0.64	270	2.87	27.9	180	0.67	270	—	—	—	—
360	2.98	29.2	260	0.66	360	3.23	34.9	270	0.68	360	—	—	—	—
450	3.24	33.3	310	0.69	450	2.87	29.3	240	0.65	450	—	—	—	—
540	2.68	25.6	220	0.61	540	2.96	31.6	330	0.65	540	—	—	—	—
630	—	—	—	—	630	2.69	28.0	200	0.63	630	—	—	—	—
650	—	—	—	—	650	—	—	—	—	650	2.02	17.3	310	0.61
720	2.73	27.3	260	0.65	720	2.83	30.0	300	0.66	720	—	—	—	—
810	—	—	—	—	810	2.79	29.8	230	0.66	810	—	—	—	—
900	2.84	29.2	250	0.67	900	—	—	—	—	900	—	—	—	—
1000	—	—	—	—	1000	—	—	—	—	1000	1.62	13.0	280	0.56
1080	3.23	33.7	350	0.68	1080	—	—	—	—	1080	—	—	—	—
1500	1.74	15.2	188	0.60	1500	1.13	7.4	130	0.53	1500	1.39	9.0	180	0.55
2000	1.03	7.4	119	0.56	2000	0.96	6.0	142	0.50	2000	1.50	11.6	207	0.57
2500	1.32	10.9	127	0.57	2500	1.26	8.9	117	0.51	2500	—	—	—	—

TABLE 4. *Effects of press temperature and duration on 2- and 24-h thickness swell and water absorption of MDF specimens.*

		2-h water soak		24-h water soak	
Press temperature (°C)	Press duration (s)	Thickness swell (%)	Water absorption (%)	Thickness swell (%)	Water absorption (%)
180	180	30.1	105.0	32.4	103.3
180	270	24.7	98.9	26.8	102.6
180	360	24.8	99.6	27.4	100.7
180	450	23.7	98.8	26.2	108.5
180	540	23.3	102.8	25.2	115.0
180	720	23.0	114.1	23.8	116.7
180	900	21.1	101.2	24.1	95.7
180	1080	20.4	104.0	22.1	107.4
180	1500	23.3	103.7	26.0	115.2
180	2000	27.5	127.0	29.5	138.6
180	2500	22.8	117.3	25.1	127.8
200	180	26.0	106.3	28.0	110.2
200	270	27.4	113.1	29.7	120.4
200	360	25.1	112.2	26.2	112.9
200	450	22.3	111.1	23.1	111.9
200	540	20.9	96.6	21.9	101.6
200	630	21.8	107.7	22.4	110.0
200	720	20.4	100.8	21.4	112.9
200	810	20.5	105.8	21.6	114.4
200	1500	19.0	119.7	22.2	135.8
200	2000	17.9	109.2	22.3	128.6
200	2500	15.0	93.7	19.7	109.8
220	180	35.3	112.2	41.4	124.0
220	650	18.0	82.8	22.3	102.3
220	1000	12.6	57.5	20.2	95.5
220	1500	9.6	79.7	16.7	103.1
220	2000	6.8	62.9	14.9	111.9

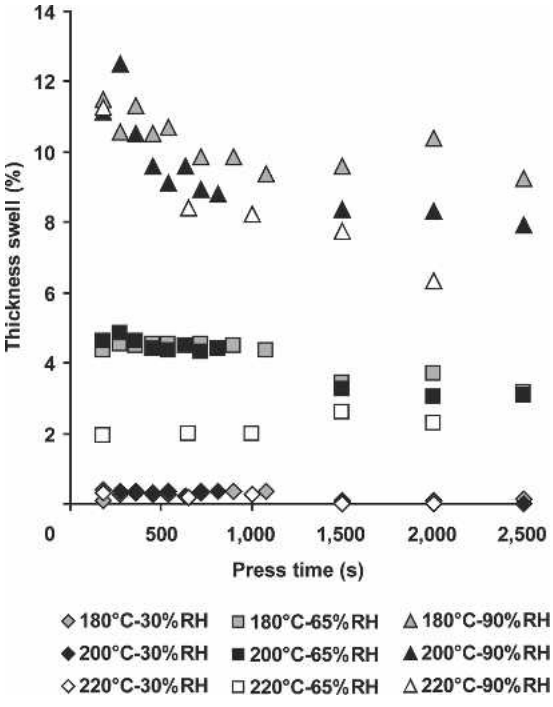

FIG. 3. Relationship between thickness swell at 27°C and RH levels of 30, 65, or 90% for 12.5-mm-thick MDF as affected by press temperature and duration.

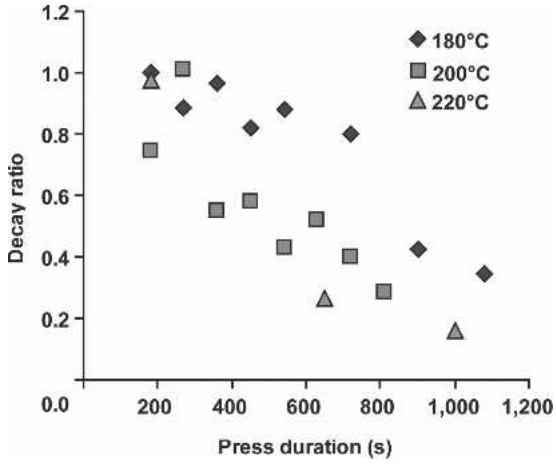

FIG. 4. Comparative decay ratio for non-ground-contact decay of 25- by 25- by 12.5-mm-thick MDF blocks assessed using the Micales-Glaeser (2006) petri dish method. A decay ratio of 1.0 represents the ~20% weight loss experienced by MDF controls.

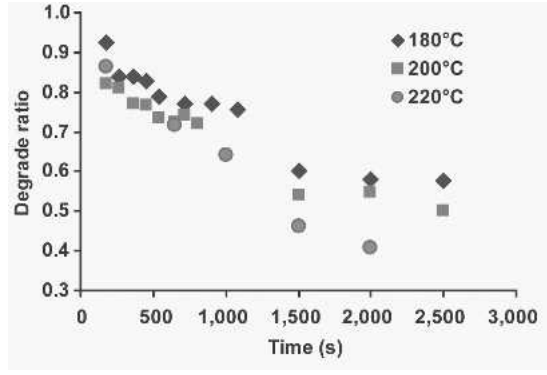

FIG. 5. Effects of press temperature and duration on arabinan content relative to controls.

cay tests, the control specimens generally experienced a weight loss of 20% after 9 weeks. When the variously hot-pressed decay results are compared to the control, we derive a decay ratio that is simply a ratio of heat-treated-to-control weight-loss results for MDF exposed to progressively higher hot-press temperatures and press durations. These decay ratios clearly show the relative benefits of progressively higher press temperatures and durations on the enhanced non-ground-contact decay resistance of MDF (Fig. 4).

The chemical composition of some of the constituents of wood fiber used to manufacture MDF is considerably altered by elevated temperatures and extended thermal durations. Chemical property data for the three press temperatures are presented in Figs. 5 to 7. It is clear from these data that arabinan and galactan, each a side-chain component of the hemicellulose, are dramatically reduced as both temperature and press duration increase. Mannan, a key component in the main-chain portion of the hemicellulose, is affected, but less so than arabinan or galactan (Fig. 7). Our results indicated little or no noticeable change in the initial concentrations of glucose, xylan, or Klason lignin.

It is clear from these results that cumulative thermal exposure in the hot-press alters the hemicellulose structure, especially arabinan and galactan. These changes in hemicellulose seem to reduce the hygroscopicity of the MDF fiber. This in turn inhibits moisture sorption, which eventually leads to thickness swell and additional loss in mechanical properties. While there

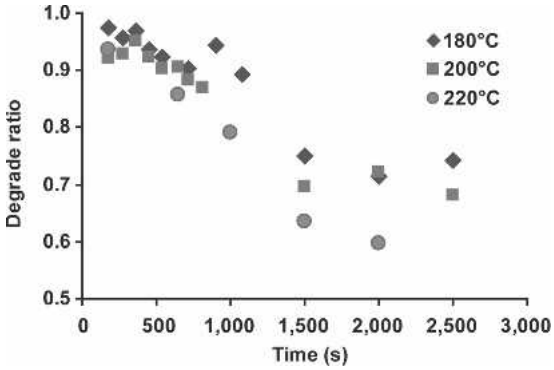

FIG. 6. Effects of press temperature and duration on galactan content relative to controls.

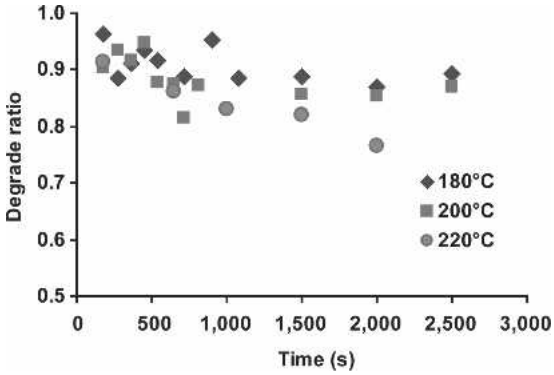

FIG. 7. Effects of press temperature and duration on mannan content relative to controls.

are major losses in mechanical properties for extended hot-pressing, there are also clear benefits. Learning to control one property while limiting another will be the critical next phase in our attempt to develop a practical method to heat-treat MDF and both enhance serviceability and retain strength. We now believe that the MDF-heat-treatment effect is related to cumulative thermal load/exposure. Subsequent analysis and computational modeling is currently underway.

CONCLUSIONS

- For most mechanical properties, it appears that very little degrade occurs until mat temperatures exceed 150°C.
- Changes in the chemical composition of MDF and MDF fiber parallel previous trends from evaluations of solid wood.
- Changes in MDF chemistry seem to result in measurable changes in hygroscopicity, decay, strength, and stiffness.
- Control of hot-press temperature and duration appears an effective method to heat-treat MDF and enhance its serviceability.
- Additional analysis and computational modeling will be needed and is currently underway.

REFERENCES

ANDRE, P., AND J. VAN OOST. 1964. A contribution to the study of condensation of lignocellulosic particles: The effect on the properties of boards made from spruce sawdust of heat treatment of the sawdust or of the boards themselves. Agricultura, Louvain Ser. 2. 12(3):516–41.

ANTOINE, R., P. ANDRE, AND H. P. NAVEAU. 1971. Thermal treatment and its influence on self-bonding of spruce particles (*Picea abies*). Holzforschung 25(1):8–15.

ASTM. 2005. ASTM Standard D 1037. *In*: Annual Book of Standards Vol. 4.10 Wood. American Society for Testing and Materials, West Conshohocken, PA.

ANSI. 2002. ANSI A208.2 Standard. American National Standards Institute. Washington, DC.

BRAUNS, O., AND A. STRAND. 1958. Heat treatment of hardboard (Varmebehandling av harda trafiberskivor). Svenskpapptidn. 61(14):437–444. (in Swedish)

BURMESTER, A. 1974. Simple methods of improving dimensional stability. (2) Treatment of wood-based materials, technology, economics. Holz und Kunststoffverarbeitung 9(9):610–617. (in German)

———. 1981. Dimensional stabilization of wood. IRG/WP/3171. International Research Group for Wood Protection, Stockholm, Sweden. 8 pp.

———, and H. J. Deppe. 1973. Experiments to improve dimensional stability of particle board by applying the FWD [moisture/heat/pressure] process to chips. Holzbearbeitung 20(7):24–30. (in German)

DAVIS, M. W. 1998. A rapid modified method of compositional carbohydrate analysis of lignocellulosics by high pH anion-exchange chromatography with pulsed amperometric detection (HPAEC/PAD). J Wood Chem. Technol. 18(2):235–252.

DENG, J., D. Q. YANG, AND X. GENG. 2006. Effect of process parameters on fungal resistance of MDF panels. Forest Prod. J. 56(3):75–80.

Effland, M. 1977. Modified procedure to determine acid-insoluble lignin in wood and pulp. Tappi 60(10):143–144.

GARCIA, R. A., A. CLOUTIER, AND B. RIEDL. 2006. Dimen-

sional stability of MDF panels produced from heat-treated fibres. Holzforschung 60:278–284.

GOROYIAS, G. J. AND M. D. HALE. 2002a. Heat treatment of wood strands for OSB production: Effect on mechanical properties, water absorption and dimensional stability. IRG/WP 02-40238. IRG Secretariat, Stockholm, Sweden. 18 pp.

———, and ———. 2002b. The effect of high temperature and long pressing time on dimensional stability and decay resistance of OSB. IRG/WP 02-40237. IRG Secretariat, Stockholm, Sweden. 20 pp.

———, and ———. 2004. The mechanical and physical properties of strand boards treated with preservatives at different stages of manufacture. Wood Sci. Technol. 38(2):93–107.

GUPTA, R. C., S. P. SINGH, AND S.-N. NAUTIYAL. 1980. Studies on tempering of phenolic bonded particle board. J. Timber Development Association of India 26(4):16–18.

HIGASHIHARA, T., T. MOROOKA, S. HIROSAWA, AND M. NORIMOTA. 2004. Relationship between changes in chemical components and permanent fixation of compressed wood by steaming and heating. Mokuzai Gakkaishi (J. Japanese Wood Research Society) 50(3):159–167.

HOWARD, J. 2001. U.S. timber production, trade consumption and price statistics 1965 to 1999. Research Paper FPL-RP-595. USDA Forest Service, Forest Products Laboratory, Madison, WI. 90 pp.

HSU, W. E., W. SCHWALD, AND J. A. SHIELDS. 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.

KLAUDITZ, W. AND G. STEGMAN. 1951. Fundamental chemical and physical processes in the heat treatment of wood-fibre boards (Uber die grundlegenden chemischen und physikalischen Vorgange bei der Warmevergutung von Holzfaserplatten). Holzforschung 5(3):68–74. (in German).

LEBOW, P. K. AND J. E. WINANDY. 1999. Verification of a kinetic model for the effects of FR on bending strength at elevated temperatures. Wood Fiber Sci. 31(1):49–61.

LIIRI, O. 1969. On the effect of pressing conditions and heat treatment on the properties of particle board bonded with phenolic resin. Tied-Valt-Tekn-Tutkimusl-Sarja-1-Puu. 48(27). (in Finnish).

MICALES-GLAESER, J. A. 2006. Personal communication. USDA Forest Service, Northern Research Station, Madison, WI.

MILITZ, H. 2007. Processes and properties of thermally modified wood manufactured in Europe. *In*: ACS Symposium Series #——. Wood protection and molds in homes. T. Schultz and D. Nicholas, eds. Am. Chem. Soc., Washington, DC. (in press).

NISHIKAWA, K., A. MATSUMOTO, AND O. NIIRO. 1979. The manufacturing of medium-density fibreboards by the wet process. J. Hokkaido Forest Products Research Inst. 327: 1–5. (in Japanese).

OGLAND, N. J., AND E. B. EMILSSON. 1951. The effect of heat treatment on the bending strength and elasticity of hardboards (Varmebehandlingens inverkan pa harda trafiberskivors bojhallfasthet och elasticitet). Sven Papperstidn. 54(17):597–600. (in Swedish).

POBLETE, H., AND E. ROFFAEL. 1985. On chemical changes in wood particles during pressing with urea-formaldehyde resins as binder. Holz Roh- Werkst. 43(1):57–62.

PULIKOWSKI, Z. 1975. Principles of the heat treatment of hardboard in heating chambers. Prace Instytutu Technologii Drewna 22(3/4):57–99. (in Polish).

RAPP, A. O. 2001. Review of heat treatments of wood. Proceedings of a seminar held 9 Feb., 2001 in Antibes, France. COST Action E22: Environmental Optimization of Wood Protection. 65 pp.

ROFFAEL, E. AND W. RAUCH. 1973. Influence of temperature and thermal after-treatment on some physical properties of di-isocyanate-bonded particle boards. Holz Roh-Werkst. 31(10):402–405. (in German).

———, ——, and K. Schaller. 1973. The manufacture of phenol-resin-bonded particle boards. Part 3. Thermal after-treatment of medium- or low-density boards. Holz-Zentralblatt 99:1500–1501. (in German).

SCHEFFER, T. C., AND W. E. ESLYN. 1961. Effect of heat on the decay resistance of wood. Forest Prod. J. 11(12):485–490.

SOLECNIK, N. J., AND A. P. SISKINA. 1964. The influence of decomposition products of wood constituents on the production technology and properties of wood fibreboards made by the dry and semi-dry methods. Lesn-Z,-Arhangelsk 7(3):144–152 (in Russian).

STAMM, A. J. 1964. Wood and cellulose science. Ronald Press, New York, NY. 549 pp.

SUCHSLAND, O., AND R. C. ENLOW. 1968. Heat treatment of exterior particleboard. Forest Prod. J. 18(8):24–28.

——— and G. Woodson. 1968. Fiberboard manufacturing practices in the United States. USDA Agricultural Handbook No. 640. USDA, Washington, DC. 263 pp.

SZYMANKIEWICZ, H. 1971. Changes caused by thermal treatment in the properties of dry-felted fibreboard made from scots pine wood. Prace Inst Tech Drewna 18(1):115–134. (in Polish).

VAN HOUTS, J., DEBES-BHATTACHARYYA, KRISHNAN-JAYARAMAN. 2001a. Reduction of residual stresses in medium density fibreboard. Part 1. Taguchi analysis. Holzforschung 55(1):67–72.

———, ———, ———. 2001b. Reduction of residual stresses in medium density fibreboard. Part 2. Effects on thickness swell and other properties. Holzforschung 55(1):73–81.

VOSS, K. 1952. Heat treatment of hardboards (Die Warmebehandlung von Holzfaser-Hartplatten). Holz Roh-Werkst. 10(8):299–305. (in German).

WIDYORINI, R., J. XU, T. WATANABE, AND S. KAWAI. 2005. Chemical changes in steam-pressed kenaf core binderless particleboard. J. Wood Sci. 51(1):26–32.

WINANDY, J. E. AND P. K. LEBOW. 2001. Modeling strength loss in wood by chemical composition: I. An individual

component model for southern pine. Wood Fiber Sci. 33(2):239–254.

———, and W. R. Smith. 2007. Enhancing composite durability using thermal treatments. *In* Vol. 7231, 201–215 Proc. International Wood Protection Conference. March 21–23, 2006, New Orleans, LA. Forest Products Society, Madison, WI.

YOUH, S. J., B. M. JO, AND J. S. OH. 2000. The improvement of physico-mechanical properties of MDF with high frequency heating technique. Mokchae Konghak (Journal of the Korean Wood Science and Technology) 28(4):83–93.

ZHANG, X. Q., R. S. LU, W. H. WANG, AND A. B. PU. 1997. Heat post-treatment to reduce thickness swelling of particleboard from fast-growing poplars. J. Forestry Res. 8(3):188–190.