FLEXURAL PROPERTIES, INTERNAL BOND STRENGTH, AND DIMENSIONAL STABILITY OF MEDIUM DENSITY FIBERBOARD PANELS MADE FROM HYBRID POPLAR CLONES

Jun Li Shi

Ph.D. Candidate

S. Y. Zhang†*

Senior Scientist/Adjunct Professor
Forintek Canada Corp.
319, rue Franquet,
Québec, Canada, G1P 4R4

Bernard Riedl

Senior Professor
Département des sciences du bois et de la forêt
Université Laval
Québec, Canada, G1K 7P4

Gilles Brunette

Manager
Department of Composite Products
Forintek Canada Corp.
319, rue Franquet,
Québec, Canada, G1P 4R4

(Received May 2004)

ABSTRACT

Flexural properties, internal bond strength, and dimensional stability of medium density fiberboard (MDF) panels made from three hybrid poplar (*Populus* spp.) clones with codes 915303, 915311, and 915313 were studied. Analysis of variance (ANOVA) and analysis of covariance (ANCOVA) were both performed in this study to test the differences in modulus of rupture (MOR) and modulus of elasticity (MOE) of MDF panels made from the three poplar hybrids. Results indicate that MOR of MDF panels made from clone 915311 was significantly higher than those of panels made from clones 915303 or 915313; however, there was no significant difference in MOR between panels made from clones 915303 or 915313. MOE of MDF panels made from clone 915311 was the highest value, which was significantly different from those of panels made from either clones 915303 or 915313; MOE of panels made from clone 915303 was the smallest and significantly lower than those of panels from clone 915313. MDF panels made from both clones 915303 and 915311 were superior to those panels made from clone 915313 in internal bond (IB) strength; but there was no significant difference in IB between panels made from clones 915303 or 915311. Dimensional stability of MDF panels was evaluated by linear expansion (LE), thickness swell (TS), and water absorption, and no significant differences were found among the three types of panels. This study shows a significant effect of hybrid poplar clonal variation on flexural properties and internal bond strength. This suggests that improvements in MDF panel flexural properties and internal bond strength may be made through tree breeding. Additionally, panel density was a factor influencing MDF panel MOR and MOE considerably; as significant linear relationships between MOR, MOE and panel density were determined.

Keywords: Fiberboard, hybrid poplar, modulus of rupture, modulus of elasticity, internal bond, linear expansion, thickness swell, water absorption.

† Member of SWST.
* Corresponding author (Tony.Zhang@QC.Forintek.ca)

INTRODUCTION

An increase in the production of composite panels in recent years has demonstrated a growing market with a constant and huge demand for raw material. The materials for papermaking and composite panel manufacturing have been primarily and conventionally coming from softwood species such as pine, spruce, fir, etc. However, a shortfall in softwood supply is currently being faced by these industries. Recently, forest products companies in Canada and the United States have become interested in fast-growing species as potential replacements for softwood chips to sustain raw material supply.

Hybrid poplar (*Populus* spp.) is a hardwood species with a high growth rate and short rotation, which can be expected to produce a promising wood fiber source with high yields (Dix et al. 1999; Cisneros et al. 2000). In Alberta, five major pulping projects have been conducted recently using aspen resources (Cisneros et al. 2000). Hybrid poplar has also been studied for its potential as a raw material substitute in composite panel products. In fact, the advantages of using hybrid poplar as softwood substitution for composite panel making include not only high wood fiber yields, but also good performance of the end products. Geimer (1986) studied the properties of structural flakeboard panels manufactured from poplar, tamarack, and pine. Results indicate that modulus of rupture (MOR), modulus of elasticity (MOE), thickness swell (TS), and linear expansion (LE) of the flakeboards made from tamarack and pine were inferior to those of panels made from poplar. Short rotation and intensively cultured hybrid poplar was also investigated as a possible raw material source for hardboard (Myers and Crist 1986). Hardboard panels were tested for strength properties and dimensional stability, and results indicate that hybrid poplar is a suitable raw material for hardboard manufacturing. Moreover, high bending and internal bond (IB) strength and low TS of MDF panels made with 19-year-old poplar wood bonded with either a melamine-reinforced urea-formaldehyde (UF) resin, a tannin-formaldehyde resin, or a polymeric diisocyanate (PMDI) resin were also reported (Roffael and Dix 1994). The better performance of composite panels made from poplar wood may be due to its wood and fiber characteristics. As we know, poplar wood is low in density, thus causing relatively high compaction ratio that has been reported to lead to superior panel strength properties (Maloney 1993; Hsu 1997; Peter et al. 2002; Shi et al. 2005). The thin-walled fiber can be packed better during pressing, which will result in more gluelines per unit panel thickness.

The requirements of wood fiber characteristics for diverse end uses are different (Zhang et al. 1997). For some applications such as lumber, construction, and plywood, low density wood is not preferred because of the low strength properties of such wood. On the contrary, some studies showed advantages of using light wood species for fiberboard making (Nelson 1973; Woodson 1976). On the other hand, it has been known that wood and fiber properties (e.g. wood density, and fiber cell-wall thickness) can be affected by genetic control on hybrid poplar trees (Ivkovich 1996; Law et al. 1997; Xing 2000; Cisneros et al. 2000; Savita 2001). Nevertheless, very little attention has been paid to genetic manipulation and selection of poplar trees just right for specific end uses. Only few studies on using wood and fiber produced from genetically manipulated poplar trees as raw material for composite panels manufacturing were found in the literature. Geimer and Crist (1980) investigated the properties of structural flakeboard panels made from five hybrid poplar clones. It was found that the clonal variation had an effect on structural flakeboard panel properties; some panels performed better than the others depending on furnish origins. Peter et al. (2002) studied the flexural properties, IB, density, water absorption, and TS of OSB panels made from eleven hybrid poplar clones. The flexural properties of OSB panels made from some clones appeared superior to those of panels made from others. It was concluded that poplar hybrids showed great promise for use in structural panel products because of superior flexural and IB properties.

Generally, wood density is believed to be the most important wood characteristic in determining final panel properties; the basic requirement of raw materials for making panels with acceptable properties is a relatively low wood density (Maloney 1993; Hsu 1997; Woodson 1976). Basically, low density wood is easier to consolidate into target thickness. As a matter of fact, at the same panel density, compaction ratio of panels made from low density wood is always higher than that of panels made from heavier wood. Compaction ratio is of importance as well-bonded panels are primarily associated with high compaction ratios (Maloney 1993; Hsu 1997). Shi et al. (2005) reported that properties of MDF panels made from black spruce juvenile wood were significantly superior to those of panels made from mature wood, explained that it was due to the low density of juvenile wood.

In this study, laboratory MDF panels were manufactured from three hybrid poplar clones and these panels were evaluated for flexural properties, internal bond strength, and dimensional stability. We intend to examine differences existing in properties of MDF panels made from these three clones. The information derived from this study is essential to assist in poplar genetic and breeding programs.

MATERIALS AND METHODS

Material collection and preparation

The material for this study came from a hybrid poplar clonal trial established by the Forest Research Branch of the Québec Ministry of Natural Resources in St-Ours, Southern Québec, Canada in 1993. The poplar trees were planted at 1.5- × 3.5-m spacing at this site, which is a part of the Champlain marine deposit with a rich salty-clay soil (40% clay). A systematic thinning was carried out in the spring of 1996 and the spacing after the thinning was 2.5 × 3.0 m (Zhang et al. 2003). Four trees from each of three clones with codes 915303, 915311, and 915313, coming from a hybrid family of *P. maximowiczii* and *P. balsamifera*, were harvested from this site in December 2002 at an age of 9 years. Butt logs of the three poplar hybrids were selected and debarked, and subsequently chipped using a portable chipper. Wood chips were collected, pooled by poplar clone, and then refined in a pressurized disc refiner located at the pilot plant of Forintek Canada Corp. Refining was processed without wax and resin injection. Moisture contents of the wood chips in the pre-steaming bin for clones 915303, 915311, and 915313 were 39.0%, 44.0%, and 40.0%, respectively. Specific refining energy for clones 915303, 915311, and 915313 were 134 kWh/t, 121 kWh/t, 125 kWh/t, respectively. To prevent fibers converted from different clones from mixing, 30 min of transition time was allowed between the three types of clonal wood materials while refining, and the fibers produced in the transition time period were discarded.

Panel manufacturing

Fibers generated from the three poplar clones were dried in a laboratory-scale dryer until the moisture content reached 2–3%. Then, fibers were passed through a hammer mill to fully separate the fibers from each other. Since almost all panel properties can be improved by means of increasing resin content (Maloney 1993), therefore in this study, resin was blended into the fibers at a relatively low level so as not to conceal any effect of clonal variation on MDF panel properties. Thus, 10% (by weight of dry fiber) Borden 302 urea-formaldehyde (UF) resin (65% solid content, no catalyst added) was first diluted, and then slowly sprayed onto the fibers using a laboratory-scale blade blender. At the same time, 0.5% wax was blended together with the fibers. No other additives were added into the furnish. Resin- and wax-blended fibers were passed through the hammer mill once again to disperse fiber balls. The average moisture contents of the fibers after wax and resin blending were 10.7%, 11.7% and 12.3% for the clone order listed previously, respectively. Mats were hand-formed immediately in a wood frame with size 610 by 610. All panels were manufactured at a target density of 740 kg/m^3 at the pilot plant of Forintek Canada Corp. Target panel thickness was 12 mm. Panels were pressed under the same schedule, which consisted of a closing period of 160 s, maintained pressure for another 160 s, and gradual relief of pressure over 40 s. The temperature of the two platens was set at 135°C. Due to the fact that panel density profile through thickness is one of the most important factors in determining properties of composite panels (Suchsland and Woodson 1974; Kelly 1977; Harless et al. 1987; Winistorfer et al. 1996; Wang et al. 2001), the press schedule was designed to realize flatter and similar panel density profiles, which can result in reduction of variations in panel properties caused by different density profiles. Three replicate panels were made for each poplar clone. Panels were trimmed immediately after pressing.

Panel property testing

All MDF panels were kept for conditioning in a chamber at 22°C and 65% relative humidity (RH) for at least 4 weeks until the panels reached a constant moisture content equilibrium. Testing of MOR, MOE, IB, LE, TS, and water absorption was carried out in accordance with the standard methods of ASTM D 1037-99 (2001) for evaluating properties of wood-based fiber and particle panel materials and ANSI A208.2-2002 (2002) for evaluating MDF for interior application. Flexural properties were determined on specimens of 338 by 75 mm. Three specimens were cut from each panel for flexural properties testing, producing nine specimens in total for each clone. Ten IB specimens of 50 by 50 mm were taken from each panel, resulting in thirty specimens for each clone. LE was measured from two specimens of 305 by 76 mm taken from each panel, for a total of six per clone. Specimens of 152 by 152 mm were used for both TS and water absorption assessment; two were cut from each panel, making six specimens in total for each clone. LE specimens were first stored in a conditioning chamber at 22°C and 50% RH for 4 weeks until their weight became constant, and after being measured then kept in another chamber at 22°C and 80% RH for another 4 weeks until the moisture content of specimens was checked to be constant equilibrium. LE was obtained by the linear variation of the specimens divided by the length measured at 50% RH. TS was calculated as the increase in thickness after a 24-h water immersion divided by the thickness measured on the specimens that have reached constant equilibrium moisture content under a condition of 22°C and 65% RH. Water absorption was calculated as the percentage of water absorbed in the specimens after 24-h water submersion based on the weight of specimens that have reached constant equilibrium moisture content at 22°C and 65% RH. About 1.5 mm was sanded from both surfaces of all IB specimens before they were glued to blocks. The weights and dimensions of all specimens for panel flexural properties, internal bond strength, and dimensional stability were measured before testing, and densities of these specimens were calculated for the purpose of analysis of covariance (ANCOVA). Panel density refers to the density of specimens calculated from the weight and volume obtained from the specimens at 22°C and 65% RH after 4 weeks of RH conditioning. Moisture contents of the three types of panels were measured on the moisture content equilibrated MOR/MOE specimens after conditioning while following the methods described in ASTM D 1037-99 (2001). Panel density profiles were determined from the ten IB specimens before they were sanded and glued to blocks, and the collected data were averaged for the three types of panels. The surface and bottom of each IB specimen were marked clearly to ensure that the directionality of the surfaces was maintained during density profile testing.

Fiber size measurement

It was reported that fibers with different size distribution may affect MDF panel properties (Groom et al. 1999). Thus, a Bauer-McNett Classifier was used to determine the fraction distribution of fibers generated from the three poplar clones. The procedures described in TAPPI T 233 cm-95 were followed for the measurement.

Data analysis and statistical methods

Statistical Analysis System (SAS) (1990) software package was used for data analysis in this study. Analysis of variance (ANOVA) was employed to compare the mean property values of MDF panels made from three poplar clones. Since the influence of panel density on panel properties, especially on flexural properties, has been reported in several studies (Maloney 1993; Olson 1996; Peter et al. 2002; Shi et al. 2005), ANCOVA was also performed using panel density as a covariate for the purpose of adjusting the mean MOR and MOE values, which were partly attributed to panel density. The removal of panel density influence on panel properties can improve the precision of the analysis and meanwhile reduce the error. Before performing ANCOVA, assumptions such as homogeneity and linearity of within-group regression, randomization, statistical independence of covariate and treatment, etc, must be tested to be sure that they are met; otherwise, the analysis will lead to misleading results (Huitema 1980). All pairwise multiple comparison procedures were conducted to compare the adjusted means using the PDIFF option in SAS with an α level of 0.05.

Simple linear regression analysis was also performed as a consequent statistical technique to develop equations describing the relationships between MOR, MOE, and panel density.

RESULTS AND DISCUSSION

Fiber size analysis

The size distributions for the three types of fibers are shown in Table 1. Since fibers distributed in 0–14, 14–28, 28–48, 48–200 and >200 mesh ranges for the three clones were similar, we assumed that the refining process produced fibers with similar size for the three clones. Therefore, fiber size had the same effect on the properties of the three types of panels.

TABLE 1. *Size distribution of fibers produced from three poplar hybrids measured by Bauer McNette classifier.*

Clone code	0–14 Mesh	14–28 Mesh	28–48 Mesh	48–200 Mesh	>200 Mesh
915303	0.95	1.90	3.10	2.38	1.67
915311	1.04	1.39	2.94	2.84	1.79
915313	1.02	1.25	2.97	3.59	1.17

Note: Numbers in column '0–14', '14–28', '28–48', and '48–200' were respectively weights of fibers retained on 14, 28, 48, and 200 mesh screens. Numbers in column '>200' were weights of fibers passed 200 mesh screen.
Methods in Tappi 223 cm-82 were followed.

Wood density, compaction ratio, and density profile

Panel average densities and compaction ratios are presented in Table 2. In this study, the relationships between compaction ratio and panel properties were not apparent because only a very narrow range of wood basic density was involved in the experiment; nevertheless, the adjusted MOR and MOE of the three groups appeared statistically different because the precision of the analysis was improved with the use of ANCOVA.

Slight differences existed among the average density profiles of MDF panels made from the three poplar clones as shown in Fig. 1 even though we made these panels under the same press schedule. Small difference in mat moisture content (10.7%, 11.7%, and 12.3%) seemed not to be a cause of different panel properties. So the slight difference in density profile might result from fiber origin while panels were compressed under heat and pressure. Since the density profiles of the three types of panels were nearly comparable, it is assumed that differences in panel properties were not a cause of density profile. However, the flatter density profile with large face layer thickness may lower the flexural properties of all types of panels.

Flexural properties

Modulus of rupture (MOR).—The unadjusted mean MOR of MDF panels made from the three poplar clones are shown in Table 2. No significant difference was found in MOR among the panels from the three clones by Duncan's mul-

TABLE 2. *Mean modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), linear expansion (LE), thickness swell (TS), and water absorption of MDF panels made from three hybrid poplar clones.*

Clone code	Basic density of wood chips (g/cm^3)	Panel moisture content (%)	Average panel density (kg/m^3)	Compaction ratio	MOR (MPa) Unadjusted	MOR (MPa) Adjusted	MOE (MPa) Unadjusted	MOE (MPa) Adjusted	Unadjusted IB (MPa)	Unadjusted linear expansion (%)	Unadjusted 24 h thickness swell (%)	Unadjusted 24 h water absorption (%)
915303	0.29	8.6	762	2.63	22.2*a*	22.1*B*	1789*a*	1780*C*	0.75*a*	0.18*a*	24.6*a*	81.2*a*
					S = 1.7		*S* = 159		*S* = 0.12	*S* = 0.02	*S* = 3.4	*S* = 15.8
915311	0.29	8.5	751	2.59	22.0*a*	23.1*A*	1833*a*	1920*A*	0.74*a*	0.19*a*	26.3*a*	92.6*a*
					S = 2.0		*S* = 175		*S* = 0.10	*S* = 0.04	*S* = 1.2	*S* = 2.6
915313	0.31	8.4	770	2.48	23.3*a*	22.3*B*	1912*a*	1833*B*	0.66*b*	0.19*a*	26.0*a*	88.5*a*
					S = 2.9		*S* = 229		*S* = 0.10	*S* = 0.02	*S* = 2.1	*S* = 8.7

Note: Unadjusted means with the same small letter were not significantly different by Duncan's multiple-range test ($p = 0.05$). Adjusted means with the same capital letter were not significantly different by multiple comparison procedures for all pairwise comparisons using the PDIFF option in SAS ($p = 0.05$). Methods for panel density and moisture content determination were in accordance with ASTM D 1037-99. Panel moisture content refers to the moisture content of panels after conditioning. Compaction ratios were based on panel equilibrium density and basic density of wood chips.
S represents standard deviation.

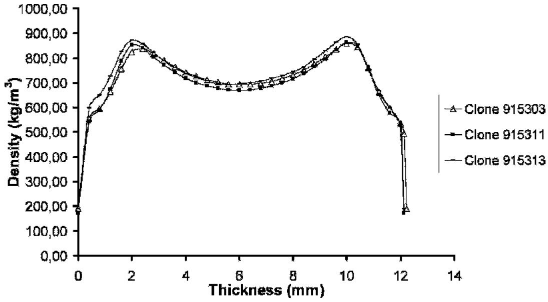

FIG. 1. Average density profiles of MDF panels made from three hybrid poplar clones

tiple-range test at the 0.05 of significant level if the effect of panel density was not taken into account. However, as mentioned previously, panel density is a factor in determining panel properties considerably (Maloney 1993; Olson 1996; Peter et al. 2002; Shi et al. 2005). Panel density was then analyzed as a covariate using ANCOVA in order to eliminate its effect on MOR and adjust mean MOR values. First, the assumptions of ANCOVA such as linearity and homogeneity of within-group regressions were tested to ensure the data fit the ANCOVA model. All the assumptions were met. A statistical comparison of ANOVA and ANCOVA for MOR is presented in Table 3. $F = 0.78$ ($P = 0.4702$) was obtained from ANOVA, showing that there were no significant differences in panel MOR among the three types of panels. With the use of ANCOVA, $F = 4.50$ ($P = 0.0236$) was acquired, which was to say that here, the clonal variation effect on panel MOR was significant ($\alpha = 0.05$). The results from regression analysis indicate a significant linear relationship between MOR and panel density for all three types of panels. The effect of panel density on MOR was indicated by a significant linear regression test, where $F = 96.99$ ($P < .0001$) was calculated (Table 3, Fig. 2). The adjusted mean MOR for the three types of poplar panels are listed in Table 2. MOR of MDF panels made from clone 915311 was significantly higher than that of panels from clones 915303 and 915313; there was no significant difference in MOR between panels made from clones 915303 and 915313.

TABLE 3. *Comparison of analysis of variance (ANOVA) and analysis of covariance (ANCOVA) of modulus of rupture (MOR) and modulus of elasticity (MOE) of MDF panels made from three hybrid poplar clones.*

Statistical methods	Variations	MOR(MPa)				MOE (MPa)			
ANOVA	Source	DF	SS	F-value	Pr > F	DF	SS	F-value	Pr > F
	Model	2	8.03	0.78	0.4702	2	69646.52	0.97	0.3948
	Error	24	123.67			24	864891.78		
	Corrected total	26	131.70			26	934538.30		
ANCOVA	Source	DF	SS	F-value	Pr > F	DF	SS	F-value	Pr > F
	Model	5	122.06	53.21	<.0001	5	904321.06	125.69	<.0001
	Error	21	9.63			21	30217.23		
	Corrected total	26	131.70			26	934538.30		
	Source	DF	Type I SS	F value	Pr > F	DF	Type I SS	F value	Pr > F
	Clone	2	4.13	4.50	0.0236	2	84785.87	29.46	<.0001
	Density	1	117.92	257.01	<.0001	1	814560.74	566.09	<.0001
	Density*clone	2	0.01	0.01	0.9869	2	4974.46	1.73	0.2019
	Source	DF	SS	F-value	Pr > F	DF	SS	F-value	Pr > F
	Regression	1	122.05	96.99	<.0001	1	899346.60	195.93	<.0001
	Adjusted treatment	2	4.13	4.92	0.0166	2	84785.87	27.71	<.0001
	Error	21	9.65			21	35191.69		

Note: SS is sum of square. DF is degree of freedom. F values were significant at $p = 0.05$.

Modulus of elasticity (MOE).—The same analytical procedures were employed for MOE data. According to ANOVA, no significant differences were found between panels made from the three hybrids by Duncan's test (Table 2). Consequently, ANCOVA was performed in order to eliminate the effect of panel density on MOE. ANCOVA assumptions were tested by verifying linearity and homogeneity of within-group regressions. A linear regression test was significant, and the slopes of within-group regression were all equal, meaning that there were no interactions existing among the three groups (Table 3, Fig. 3). The adjusted mean MOE were calculated by using the same regression slope for the three types of panels, and the results are presented in Table 2. MOE of MDF panels made from clone 915311 was significantly higher than that of panels made from clones 915303 and 915313, while MOE of panels made from clone 915303 was the smallest and significantly lower than that of panels from clone 915313 (Table 2). The precision of testing was greatly improved and error was reduced by using ANCOVA.

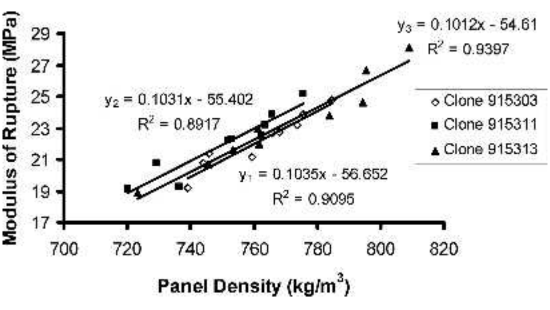

FIG. 2. Relationship of modulus of rupture (MOR) to panel density. Note: y_1, y_2, y_3 correspond to modulus of rupture (MOR) of MDF panels made from hybrid poplar clones 915303, 915311, and 915313, respectively; x refers to panel density.

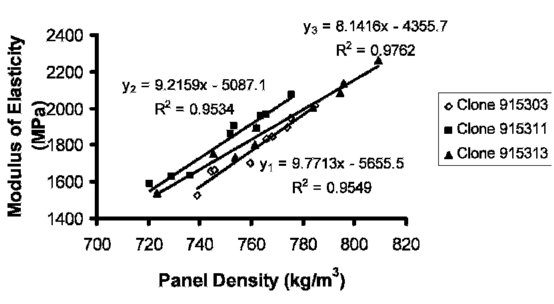

FIG. 3. Relationship of modulus of elasticity (MOE) to panel density. Note: y_1, y_2, y_3 correspond to modulus of elasticity (MOE) of MDF panels made from hybrid poplar clones 915303, 915311, and 915313, respectively; x refers to panel density.

Internal bond strength

The mean IB of MDF panels made from clones 915303 and 915311 was significantly higher than that of panels from clone 915313; but there was no significant difference in IB strength between the panels made from clones 915303 and 915311 by Duncan's multiple-range test (Table 2).

Dimensional stability

LE, TS, and water absorption of MDF panels made from the three poplar clones were not significantly different at a significance level of 0.05 (Table 2). Therefore, the clonal variation effect on MDF panel dimensional stability was not significant.

Panel density versus MOR/MOE

Panel density affected panel flexural properties considerably. Significant linear relationships between panel density and panel MOR and MOE for all three types of panels were found as mentioned previously. Equations describing the relationships were developed using simple linear regression from the model $Y = a + bX$, where Y represents panel MOR or MOE, and X is panel equilibrium density. The equations are shown in Fig. 2 and Fig. 3. The equations apply only to the panels made from hybrid poplar fibers with processing and manufacturing techniques similar to those used in this study.

Panel density is one of the most important factors in determining MDF panel flexural properties. Panel MOR and MOE can be improved by increasing panel density. This is due to more fibers being used in heavier MDF panels and more resistance against mechanical loads (Maloney 1993).

CONCLUSIONS

The following conclusions can be made from this study:

1. MOR of MDF panels made from clone 915311 was significantly higher than those of panels from clones 915303 and 915313; however, there was no significant difference in MOR between panels made from clones 915303 and 915313.
2. MOE of MDF panels made from clone 915311 was the highest and was significantly different from those of panels from clone 915303 and 915313; MOE of panels from clone 915303 was the smallest and was significantly lower than that of panels from clone 915313.
3. MDF panels made from either clone 915303 or 915311 were superior to panels from clone 915313 in IB strength; there was no significant difference in IB between panels made from clone 915303 and 915311.
4. No significant differences were found in LE, TS, and water absorption among panels made from the three poplar hybrids; the effect of clonal variation on the dimensional stability of hybrid poplar MDF panels was not appreciable.

This study shows that clonal variation had a significant effect on the flexural properties and internal bond strength of hybrid poplar MDF panels; however, its effect on panel dimensional stability was not significant. Thus, it is likely that improvement in panel flexural properties and internal bond strength can be achieved through tree breeding.

ACKNOWLEDGMENTS

The authors wish to thank the financial support provided by Forintek Canada Corp., Natural Sciences and Engineering Research Council of Canada (NSERC) and Université Laval. The Québec Ministry of Natural Resources is acknowledged with thanks for providing the materials for this study.

REFERENCES

American National Standards Institute (ANSI). 2002. Medium Density Fiberboard (MDF) for Interior Application. ANSI A208.2–2002. Composite Panel Association, Gaithersburg, MD.

American Society for Testing and Materials (ASTM).

2001. Evaluating properties of wood-based fiber and particle panel materials. ASTM D 1037–99. Vol. 04.10. ASTM, Philadelphia, PA. Pp. 141–170.

Cisneros, H. A., L. Belanger, W. Y. Gee, P. A. Watson, and J. V. Hatton. 2000. Wood and fiber properties of hybrid poplars from southern British Columbia. TAPPI J. 83(7):60.

Dix, B., V. Thole, and R. Marutzky. 1999. Poplar and eucalyptus wood as raw material for wood-based panels. Pages 93–102 *in* Eurowood Technical Workshop Proc. Industrial End-uses of Fast-grown Species. CNR/IRL and CNR/ITL. Florence, Italy.

Geimer, R. L. 1986. Properties of structural flakeboard manufactured from 7-year-old intensively cultured poplar, tamarack, and pine. Forest Prod. J. 36(4):42–46.

———, and J. B. Crist. 1980. Structural flakeboard from short-ratation, intensively cultured hybrid *populus* clones. Forest Prod. J. 30(6):42–48.

Groom, L. H., L. Mott, and S. M. Shaler. 1999. Relationship between fibre furnish properties and the structural performance of MDF. Proc. 33rd International Particleboard/Composite Materials Symposium April 13–15, Washington State University, Pullman, WA.

Harless, T. E. G., F. G. Wagner, P. H. Short, R. D. Seale, P. H. Mitchell, and D. S. Ladd. 1987. A model to predict the density profile of particleboard. Wood Fiber Sci. 19(1):81–92.

Hsu, W. E. 1997. Wood quality requirements for panel products. Timber Management toward Wood Quality and End-product Value. Proc. CTIA/IUFRO International Wood Quality Workshop, Québec City, Canada.

Huitema, B. E. 1980. The analysis of covariance and alternatives. Wiley & Sons, New York, NY.

Ivkovich, M. 1996. Genetic variation of wood properties in Balsam poplar (*Populus balsamifera L.*). Silvae Genet. 45(2/3):119–124.

Kelly, M. W. 1977. Critical literature review of relationship between processing parameters and physical properties of particleboard. Gen. Tech. Rep. FPL-10. USDA Forest Serv., Forest Prod. Lab., Madison, WI.

Law, K., J. Valade, S. Rioux, and R. Lanouette. 1997. Wood and paper properties of five short-rotation poplar clones grown in Québec. Proc. Pulping Conference October 19, 1997 (TAPPI):847–856.

Maloney, T. M. 1993. Modern particleboard and dry-process fiberboard manufacturing. Miller Freeman Publications. San Francisco, CA.

Myers, G. C., and J. B. Crist. 1986. Feasibility of manufacturing hardboard from short-rotation intensively cultured *Populus*. Forest Prod. J. 36(1):37–44.

Nelson, N. D. 1973. Effects of wood and pulp properties on medium-density, dry-formed hardboard. Forest Prod. J. 23(9):72–80.

Olson, B. D. 1996. Developing wood composites using small diameter timber resources from dense, stagnant stands. M.S. thesis, Washington State University, Pullman, WA.

Peter, J. J., D. A. Bender, M. P. Wolcott, and J. D. Johnson. 2002. Selected properties of hybrid poplar clear wood and composite panels. Forest Prod. J. 52(5):45–54.

Roffael, E., and B. Dix. 1994. Mechanical-technological properties of MDF from poplar wood. Holz Roh-Werkst. 52(1):48.

SAS/STAT User's Guide. 1990. SAS Institute, Inc. Cary, NC.

Savita, G. 2001. Wood and paper properties of poplar clones. IPPTA. 13(4):35–37.

Shi, J. L., S. Y. Zhang, and B. Riedl. 2005. Effect of juvenile wood on strength properties and dimensional stability of black spruce medium density fiberboard panels. Holzforschung 59(1):1–9.

Suchsland, O., and G. Woodson. 1974. Effect of press cycle variables on density gradient of medium density fibreboard. Pages 375–396 *in* Proc. 8th Particleboard Symp.

Wang, S., P. M. Winistorfer, T. M. Young, and C. Helton. 2001. Step-closing pressing of medium density fibreboard; Part 1: Influences on the vertical density profile. Holz Roh-Werkst. 59(1–2):19–26.

Winistorfer, P. M., T. M. Young, and E. Walker. 1996. Modeling and comparing vertical density profiles. Wood Fiber Sci. 28(1):133–141.

Woodson, G. E. 1976. Properties of medium-density fiberboard related to hardwood specific gravity. Pages 175–192 *in* Proc. 10th Washington State University Particleboard Symposium. Pullman, WA.

Xing, X. 2000. Genetic variation in wood density of triploid clones of *Populus tomentosa*. Beijing Linye Daxue Xuebao 22(6):16–20.

Zhang, S. Y., R. Gosselin, and G. Chauret. 1997. Wood quality: its definition, impact and implication for value-added timber management and end uses. Timber management toward wood quality and end product value. Proc. CTIA/IUFRO international wood quality workshop, Québec City, Canada.

———, Q. Yu, G. Chauret, and A. Koubaa. 2003. Selection for both growth and wood properties in hybrid poplar clones. Forest Sci. 49(6):1–8.