

EFFECTS OF HOT-PRESSING PARAMETERS AND WAX CONTENT ON THE PROPERTIES OF FIBERBOARD MADE FROM PAPER MILL SLUDGE

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ABSTRACT

Primary sludge combined with 20% secondary sludge was used for the manufacture of fiberboard. A factorial design was carried out to determine the effects of panel density, pressing temperature and time, and wax level on the panel properties of fiberboard. Two levels were employed for each of the four variables, and the panel dimensional stability and mechanical properties were analyzed using Design-Expert software. The statistical analysis indicated that internal bonding (IB) was significantly affected by panel density, pressing temperature, and their interaction. Pressing time and wax level were not directly related to IB. Similarly, modulus of rupture (MOR) was dependent strongly on panel density, pressing temperature, and their interaction, but was not affected by pressing time and wax level. The effect of panel density on modulus of elasticity (MOE) was as strong as on MOR, but the effect of pressing temperature was weaker on MOE than on MOR. MOE was also related to pressing time, but not to wax level. Thickness swelling (TS) was not affected by panel density, but it was significantly dependent on pressing temperature and time. Unexpectedly, wax level did not have significant impact on TS.

Keywords: Paper mill sludge, fiberboard, panel density, pressing temperature, pressing time, wax content.

INTRODUCTION

The pulp and paper industry is very raw material intensive and processes a considerable amount of water. The production of pulp and paper generates a large quantity of wastewater. Before it is discharged into the receiving water bodies, the wastewater undergoes several treatment processes (Henry 1991). Primary treatment

removes suspended solids from the effluent, and the following secondary (biological) treatment reduces biological oxygen demand (BOD) level in the effluent. Primary treatment produces primary sludge (PS), while the secondary treatment process generates secondary sludge (SS, active sludge). In many paper mills, SS is combined with PS during the dewatering process. Another kind of sludge, deinking paper sludge (DPS), is generated from paper recycling processes. Consequently, sludge is the largest by-product of the pulp and paper industry and disposal of sludge is

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a major solid waste problem for the industry (Battaglia et al. 2003).

Most sludge is currently landfilled or incinerated (Beauchamp et al. 2002). However, landfill costs are increasing, and there exists the potential of contaminating the landfill sites. Incineration is also costly and might cause air pollution problems (Pridham and Cline 1988). The development of technologies to make beneficial use of paper mill sludge has interested forest products researchers. Paper mill sludge is primarily composed of short cellulose fibers, clay filler material, and residual chemicals used in the paper mill's water treatment and deinking facilities. DPS and PS have higher fiber content than does SS (Pridham and Cline 1988), but the fibers are too short to be converted into a finished paper product. However, it is possible to use DPS and PS to manufacture fiberboards, and many previous reports have dealt with the characterization and utilization of DPS in this capacity (Latva-Somppi et al. 1994; Davis et al. 2003). Recent research has demonstrated that PS combined with 20% SS is more suitable as a raw material for the manufacture of fiberboard than is DPS (Geng et al. 2005). In previous publications, phenol-formaldehyde or urea-formaldehyde resins were used for manufacturing fiberboard from paper mill sludge. These synthesized resins are dependent on petrochemicals and some of them release formaldehyde, which is a suspected carcinogen (Li and Geng 2005).

The present study outlines attempts to manufacture fiberboard from PS combined with 20% SS. A factorial design was applied for screening the impact factors of panel density, wax level, and pressing temperature and time on the dimensional stability and mechanical properties of the fiberboard panels.

MATERIALS AND METHODS

Material

Primary sludge, which was combined with about 20% SS during the dewatering process, was collected from Papiers Stadacona Ltée. in Quebec City, Canada. The sludge was from the

treatment process of thermo-mechanical pulping effluent of spruce and balsam fir.

Refining and drying of sludge

The sludge at a moisture content of 193% was preheated for 3 min with steam pressure of 7.5 bar in a cooking screw and then was refined in a refiner at speed of 2500 rpm and specific energy of 200kWh/odt at the MDF Pilot Plant of Forintek Canada Corp. (Quebec City, QC, Canada). The refined fiber was discharged through a blowline and dried by a flash tube dryer to a moisture content of 15% (oven-dried fiber basis). The fiber was then dried further in a rotary dryer to a moisture content below 5% before panel manufacturing.

Panel-making experiment design

To determine the effects of four variables, namely panel density, wax dosage, and pressing temperature and time, on dimensional stability and mechanical properties, two levels of each factor were selected and a 1/2 fractional factorial design was carried out with Design-Expert® version 6.0.5 software (Stat-Ease, Inc., MN, USA). The experimental design resulted in 8 panel-making conditions (Table 1). The fiber mat was manually formed and then pressed with a Vice-roy Press (platen dimension 610 mm × 610 mm). The pressing time in Table 1 included the closing and de-gasing time, in which the closing time was 1 min. Two panels were made with dimensions of 457 mm × 457 mm × 9.5 mm under each condition.

Panel properties evaluation

The panels were conditioned at a relative humidity of $65 \pm 1\%$ and $20 \pm 3^\circ\text{C}$ for two weeks before property testing. Two thickness swelling (TS) specimens (150 mm × 150 mm), 12 internal bonding (IB) specimens (50 mm × 50 mm) at the central of panels, and 3 specimens (75 mm × 280 mm) for bending modulus of rupture (MOR) and modulus of elasticity (MOE) were cut from each

TABLE 1. Two levels and 1/2 fractional factorial design with Design-Expert® software and responses.

Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3	Response 4
Density (kg/m ³)	Temperature (°C)	Time (min.)	Wax (%)	IB (MPa)	TS (%)	MOR (MPa)	MOE (MPa)
750	210	6	1.5	0.13	33.5	2.8	506
1100	210	8	1.5	1.25	24.3	13.5	2165
1100	180	8	0	0.19	51.7	8.9	1770
750	180	8	1.5	0.03	59.0	2.4	372
750	210	8	0	0.21	24.8	3.4	652
1100	210	6	0	1.00	27.4	11.6	1998
750	180	6	0	0.04	59.8	2.2	332
1100	180	6	1.5	0.25	75.2	9.2	1554

panel and all properties were evaluated in accordance with ASTM D 1037-99 (ASTM 1999).

Statistical analysis and confirmation run

The four measured responses, namely TS, IB, MOR, and MOE were analyzed with the same software. A model describing the data was generated, and equations in terms of actual factors were derived. The optimal panel-making condition was also identified by the software. To confirm the optimization and to determine the parameters for manufacturing panels with the desired properties, panels (457 mm × 457 mm × 9.5 mm) were made at an optimal condition (Table 2).

RESULTS AND DISCUSSION

Thickness swelling analysis

The collected data on TS were statistically analyzed using Design-Expert® software. Panel density did not affect TS within a wide range of 750 to 1100 kg/m³. Values of “Prob > F” on pressing temperature and time were less than 0.0500. This response indicates that pressing temperature and time were the significant model

terms. Based on a previous report (Chow et al. 1996), the addition of wax was expected to considerably improve dimensional stability. However, the TS results showed that increasing the wax level (from 0 to 1.5%) did not cause much difference. Although the wax level did not affect TS as significantly as did pressing time and temperature, it was still related to TS because the value of “Prob > F” was 0.0935 (less than 0.1000) (Table 3). Considering pressing time, pressing temperature, and wax level as important factors, the derived regression equation describing the relationship between TS and the three factors (in terms of actual factor) is as shown in Eq. (1) and model “Prob > F” was 0.0018.

$$TS = 293.03 - 1.13 * \text{temperature} - 4.51 * \text{time} + 4.72 * \text{wax} \quad (1)$$

Internal bonding analysis

Statistical analysis of measurement data revealed that pressing time in the tested lengths of 6 and 8 min and the wax level at 0 and 1.5% did not show considerable effects on IB, whereas panel density, pressing temperature, and their interaction were significant model terms (Table

TABLE 2. Comparison of the predicted and tested dimensional stabilities and mechanical properties of panels made with the selected optimized parameters (density 1100 kg/m³, pressing temperature 210°C, pressing time 8 min and wax 0.99%).

	TS (%)	IB (MPa)	MOR (MPa)	MOE (MPa)
Predicted panel properties	24.1	1.13	12.56	2104
Tested panel properties	17.0	1.17	12.41	1891
ANSI A208.1-2002 (Grade 210)	21.1	0.35	21.0	N/A

TABLE 3. Analysis of variance (ANOVA) for the selected factorial model.

	Source	F value	Prob > F	Significance
TS	Model	41.02	0.0018	Significant
	Temperature	110.43	0.0005	
	Time	7.82	0.0490	
	Wax	4.80	0.0935	
IB	Model	53.93	0.0011	Significant
	Density	70.19	0.0011	
	Temperature	59.40	0.0015	
	Density and temperature	32.19	0.0048	
MOR	Model	89.17	0.0004	Significant
	Density	243.76	<0.0001	
	Temperature	16.88	0.0147	
	Density and temperature	6.86	0.0589	
MOE	Model	210.37	<0.0001	Significant
	Density	593.68	<0.0001	
	Temperature	32.36	0.0050	
	Time	6.08	0.0693	

3). The derived regression equation describing the relationship between IB and the significant model terms (in terms of actual factor) is as shown in Eq. (2) and model “Prob > F” was 0.0011.

$$IB = 9.28 - 0.01 * density - 0.05 * temperature - 7.87E - 0.005 * density * temperature \quad (2)$$

It is well known that paper mill sludge is composed of fine fibers, inorganic fillers, and other residual chemicals from the pulp and paper and wastewater treatment processes. For dry-formed fiberboard, fine fibers in the sludge play an important role in the development of internal bonding (Suchsland et al. 1987). For the fine fibers to develop adhesive properties and act as bonding agents, high panel density and high pressing temperature are required. These requirements are consistent with the regression equation for IB. Secondary sludge combined with PS might be also advantageous for IB development (Lavrent'ev et al. 1979).

Bending strength analysis

From the statistical analysis carried out, panel density and pressing temperature were regarded as the significant model terms and the values of “Prob > F” were 0.0001 and 0.0147, respec-

tively (Table 3). These results indicate that bending strength (MOR) was strongly affected by both panel density and pressing temperature and in particular by panel density. Interaction of panel density and pressing temperature on MOR was not as significant as the individual factors, but its value of “Prob > F” was 0.0589, slightly higher than 0.0500. MOR was not affected by pressing time at the tested times of 6 and 8 min or by wax level at 0 or 1.5%. In terms of actual factors, the relationship between MOR and the three model terms was regressed as the following Eq. (3) and model “Prob > F” was 0.0004.

$$MOR = 19.42 - 0.03 * density - 0.18 * temperature + 2.79E - 0.004 * density * temperature \quad (3)$$

Fine fibers improve the total contact between fibers and might act as binders in binderless fiberboard panels. However, long fibers are essential in bending strength development (Suchsland et al. 1987). Previous research has found that the sludge used in this study was lacking in long fibers. Fibers longer than 1.00 mm accounted for less than 8.0% of the total fiber length (Geng et al. 2005).

Bending stiffness analysis

Bending stiffness (MOE) did not show any relationship with wax level. MOE was most sig-

nificantly related to the panel density as indicated by the value of "Prob > F" (<0.0001) (Table 3). MOE was also dependent on pressing temperature and time, but the dependence was not as significant as it was on panel density. The derived regression equation describing the relationship between MOE and the three factors (in terms of actual factor) is as shown in Eq. (4) and model "Prob > F" was 0.0001.

$$\text{MOE} = 4.31 * \text{density} + 10.78 * \text{temperature} + 71.16 * \text{time} - 5326.77 \quad (4)$$

Optimization of manufacturing conditions and confirmation run

The manufacturing conditions for fiberboard with desired properties made from the paper mill sludge were optimized using Design-Expert software based on the research data (Table 1). One of the optimized conditions giving a desirability quotient of 0.91 was selected (Table 3), and the expected panel properties were also tabulated. Two panels were made to confirm the selected solution. The tested IB and MOR were very close to the predicted values, although the tested TS and MOE varied slightly (Table 2). These results indicate that the optimization run by the software was reliable.

Compared with the requirements of ANSI A208.2-2002 for Grade 210 fiberboard (ANSI 2002), IB was much higher than the specified minimum value of 0.35 MPa, and TS was lower than the requirement. However, MOR did not meet the standard requirement (21.0 MPa) mainly due to lack of long fibers.

CONCLUSIONS

The effects of panel density, pressing temperature and time, and wax level on the panel properties of fiberboard made from primary sludge were investigated. Using Design-Expert® software, the experiment was designed with a 1/2 fractional factorial design using two levels of each of the four variables. This design resulted in eight different experimental conditions. The

data were statistically analyzed using the same software, and the results demonstrated that IB was significantly affected by panel density and pressing temperature. Similarly, MOR was also strongly dependent on panel density and pressing temperature, but especially on panel density. Pressing time and wax level were not directly related to IB or MOR. The effect of panel density on MOE was as strong as it was on MOR, but the effect of pressing temperature on MOE was weaker than it was on MOR. Modulus of elasticity was also related to pressing time, but not to wax level. Thickness swelling was not affected by panel density, but was significantly dependent on pressing temperature and time. Addition of wax from 0% to 1.5% did not result in a significant difference in TS. With the exception of bending strength, all panel properties of the fiberboard panels made from the sludge met the requirements of ANSI A208.2-2002 for grade 210.

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