MEDIUM-DENSITY FIBERBOARD PRODUCED USING PULP AND PAPER SLUDGE FROM DIFFERENT PULPING PROCESSES

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Abstract. Pulp and paper sludge can be recycled in the manufacture of medium-density fiberboard (MDF) because it contains wood fibers. A comparative study was conducted to evaluate the properties of MDF made from virgin fibers mixed with different pulp and paper sludge sources. A factorial design was used in which factors were mill pulping processes, thermal–mechanical pulping (TMP), chemical–thermal–mechanical pulping (CTMP), and kraft pulping, and percentage of sludge mixed with virgin fibers (0, 25, 50, and 75%). Virgin fibers were obtained from paper birch wood, an underutilized species. Chemical

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composition, physical characteristics, pH, and buffer capacity of sludge were measured. MDF properties decreased mostly linearly with sludge content. Panel properties negatively correlated with the proportion of nonfibrous material such as ash and extractives. TMP and CTMP sludge sources produced panels of similar quality, and kraft sludge produced the lowest quality. It was concluded that the amount of sludge that can be incorporated into MDF without excessive decrease in panel quality depends on the pulping process. At 25% sludge content, all panels met ANSI quality requirements for MDF used for interior applications.

Keywords: Paper mill sludge, recycling, composite panels, wood fibers, paper birch wood.

INTRODUCTION

Environmental protection is increasingly a priority for the forest products industry (AF&PA 2006;UNECE/FAO 2008; Industry Canada 2009). Solid waste disposal costs are rising almost everywhere because of decreasing landfill space, public opposition, and stricter regulatory pressure (Amberg 1984; AF&PA 2006; Mahmood and Elliott 2006). For this and other reasons, many companies have adopted strategies to develop beneficial uses for solid waste.

Sludge is the largest byproduct of the pulp and paper industry (Smook 2002). It contains papermaking fibers as the principal organic component as well as papermaking fillers, pitch, lignin byproducts, inert solids rejected during chemical recovery processes, and ash (Smook 2002; Geng et al 2007a; Ochoa de Alda 2008). Sludge generated by the European pulp and paper industry accounts for about 4.3% of final mill production (Ochoa de Alda 2008). Similarly, in the province of Québec, Canada, sludge production accounted for about 4.8% of mill production in 2006 (MDDEP 2007; MRNFQ 2007). Given the size of the pulp and paper industry, large amounts of sludge are generated.

Between 1995 and 2007, global production of medium-density fiberboard (MDF) increased by an average of 18%/yr (FAO 2009). Because of its increasing production capacity and decreasing forest resources, the MDF industry needs new and more cost-efficient fiber supplies (Xing et al 2006a, 2006b, 2007; UNECE/FAO 2008; Industry Canada 2009). Pulp and paper sludge contains wood fibers and could therefore be recycled for MDF manufacturing. However, variation in fiber sources affects MDF processing and properties (Xing et al 2006a, 2006b, 2007).

Recent studies have proposed recycling pulp and paper sludge in wood-based panels (Davis et al 2003; Geng et al 2006, 2007a, 2007b; Taramian et al 2007). Geng et al (2007a) manufactured MDF with different sludge-to-virgin fiber mass ratios. Two sludge sources were compared: deinking and combined (mixed primary and secondary sludge) from a mill that used a thermomechanical pulping (TMP) process. Panel mechanical properties decreased with increasing sludge proportion. At the same sludge proportion, better mechanical properties were produced with combined than deinking sludge. The addition of deinking sludge positively impacted dimensional stability. These results were attributed to differences in fiber length, ash content, and acidity characteristics of the sludge. Taramian et al (2007) compared properties of particleboard made with different sludge-to-virgin fiber mass ratios. Sludge was collected from a mill using chemimechanical and neutral sulphite semichemical pulping processes. They found that sludge proportion had a negative impact on mechanical properties and, in some circumstances, a positive impact on dimensional stability. Davis et al (2003) investigated the properties of MDF with added deinking pulp and paper sludge. They evaluated the effect of three sludge components on the mechanical and physical properties of panels: fine content, kaolin coating clay content, and calcium carbonate content. Coating clay content was the primary factor affecting mechanical properties and water immersion performance, exhibiting a negative linear effect.

The pulping process has an important impact on pulp chemical composition and therefore fiber properties (Clark 1985; Smook 2002). For example, the chemical composition of fibers from high-yield pulping processes such as TMP is roughly similar to that of nonprocessed wood. Low-yield pulping processes such as the chemical kraft process remove most of the lignin from the cell wall. This produces high-quality cellulose-rich fibers used in high-quality and high-resistance papers. The quality of fibers from intermediate-yield pulping processes such as chemical–thermomechanical pulping (CTMP) lies between those of TMP and kraft fibers in terms of chemical composition and properties.

Previous studies on the recycling of pulp and paper sludge for MDF were conducted on deinking sludge and/or sludge from a single mill (Davis et al 2003; Geng et al 2007a). Differences in the pulping processes and the resulting pulps among mills are expected to have a substantial influence on sludge chemical composition. To better evaluate available sludge sources in the pulp and paper industry, the effect of specific pulping processes must be considered. In this study, the properties of MDF made from virgin fibers mixed with different contents of sludge from three pulping processes (TMP, CTMP, and kraft) were compared. The overall objective was to evaluate the effect of pulping process on MDF properties and to better understand the relationship between sludge characteristics and panel properties.

MATERIAL AND METHODS

Material Collection and Refining

Pulp and paper sludge was collected from three mills using different pulping processes: TMP, CTMP, and kraft. TMP sludge was collected from the White Birch Paper, Stadacona Division pulp and paper mill in Québec City (Québec, Canada). CTMP sludge was collected from the Abitibi-Bowater pulp and paper mill in Dolbeau–Mistassini (Québec, Canada). Kraft sludge was collected from the SFK Pulp Fund commercial pulp mill in Saint-Félicien (Québec, Canada). Primary and secondary sludge are generally combined in the dewatering process (Smook 2002), and the primary-to-secondary ratio varies across and within mills. For better comparison, all sludge sources were combined to a constant primary-to-secondary sludge mass ratio of 9:1. Thus, the sludges used in this study are made of 90% primary and 10% secondary sludge. High primary sludge content was selected because secondary sludge contains very few fibers (Smook 2002). All three mills use softwood chips from similar species (mainly spruce and/or balsam fir and/or pine). Paper birch chips were collected for use as virgin fibers. Paper birch (*Betula papyrifera*) was selected because it is currently one of the most available and underutilized species in Québec's public forests (CEGFPQ 2004; MRNFQ 2007). Because of its availability, it is considered by the wood industry to be an important species for years to come.

The pH of raw sludge varies 5.5-7.5 with the exception of kraft sludge, which has a pH over 12. Because urea–formaldehyde resin used in MDF manufacturing may not polymerize adequately in this very alkaline environment (Rowell 2005), kraft sludge was neutralized using sulphuric acid. The pH was lowered to a level similar to that of other sludge sources with about 200 mL of 20% volume sulphuric acid solution/kg of wet sludge (at about 30% consistency).

Sludges were then refined using an Andritz 0.56-m single-disc refiner at the MDF pilot plant at FPInnovations–Forintek Division, Québec City (Québec, Canada). Material was preheated for 1.5 min at a steam pressure of 750 kPa in a cooking screw (digester) and then refined at a disc plate speed of 2000 rpm. A large gap between refiner disc plates (1.5 mm) was used to not damage sludge fibers. The refiner energy level was 720 MJ/odt. When kiln-dried, sludge has a tendency to form clumps (Davis et al 2003). The mechanical refining process separates these clumps into individual fibers (Geng et al 2007a) permitting resin to be applied evenly on sludge particles. The refining also transforms wood chips contained in primary sludge into individual fibers. More importantly, a TMP refiner is available in all MDF plants. Refined sludge was then discharged through a blowline and dried by a flash tube dryer at 150°C for 8 s to a moisture content (MC) of about 15 ± 5%. Refined sludge was then further dried in a rotary dryer at 70°C for 15 min to a MC of 3 ± 1%. White birch chips were processed using the same methods as those for sludge but using a smaller gap of 0.5 mm between refiner disc plates.

Sludge and Fiber Characterization

Dry samples were ground in a Wiley mill fitted with a 35-mesh screen. Material was then placed in an airtight container to homogenize moisture content for subsequent chemical analysis. Cellulose content was determined by Kürschner and Hoffer's nitric acid method (Browning 1967). Pentosans content was obtained according to TAPPI T 223 cm-84. Total lignin content was determined by the Klason method according to TAPPI T 222 om-98 (acid-insoluble lignin) and quantified by absorption spectroscopy at 205 nm according to TAPPI useful method UM-250 (acid-soluble lignin). Total extractive content was determined by successive extractions with an organic solvent mixture (ethanol/toluene) followed by hot water according to TAPPI T 204 cm-97 and T 207 om-93, respectively. Ash content was determined by combustion in a muffle furnace at 525°C according to TAPPI T 211 om-93. Two replicates were conducted for chemical analysis.

Fiber length distributions were measured using an OpTest Equipment Fiber Quality Analyzer. Each length distribution was obtained from five samples of 5000 fibers each. Bulk density was determined by sifting refined and dried sludge through a 5-mesh screen into a 3-L container and weighing (Xing et al 2006b).

Buffering capacity and pH were measured as described in Xing et al (2006b). An aqueous extract was prepared by refluxing 6.25 g of dry furnish in 125 mL distilled water for 20 min. Extract solution was then passed through a filter paper using a vacuum, cooled at room temperature, and diluted to 250 mL. Two extract solutions were prepared for each furnish type. The extract (50 mL) was titrated to a pH of 3 using 0.025-N H_2SO_4 solution for alkaline buffering capacity or to a pH of 8 using 0.025-N NaOH solution for acid buffering capacity. Two titrations were conducted for each titration solution for a total of 16 measurements.

Panel Manufacturing and Testing

MDF panels were processed according to a 3^2 factorial design in which factors were mill pulping process (TMP, CTMP, and kraft) and dry mass percent of sludge mixed with virgin fibers (0, 25, 50, and 75%). Three MDF panels were made for each experimental condition (three repetitions). Panel target density was 800 kg/m^3, pressing temperature was 180°C, and pressing cycle was 5.5 min (including closing and opening times). The pressing schedule was optimized to obtain similar density profiles for all panels (Figs 1 and 2). Density profiles, with higher face than core density, are similar to those of many commercial MDF products. Target thickness was 10 mm and panels were sanded to a final thickness of about 9.5 mm. Twelve percent of urea–formaldehyde resin (UF) (dry-mass resin on dry-mass sludge and fiber mixture) (UL 232, Arclin Canada, Sainte-Thérèse), 0.5% of dry-mass sludge and fiber mixture of emulsion wax (EW58A, Hexion Canada, Lévis), and 0.25% ammonium chloride as a catalyst (dry-mass catalyst on dry-mass resin) were mixed and diluted to 50% consistency to

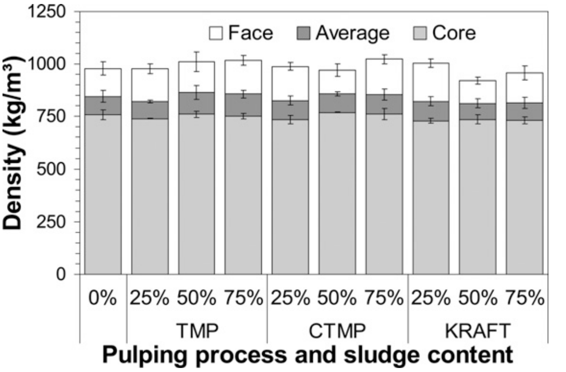

Figure 1. Average, core, and face density of medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes.

reduce viscosity. The mixture was applied to dry sludge and fiber mixtures in a conventional rotary drum blender mounted with a spray nozzle. Total furnish MC was 11%. Mats were manually formed in a 460 × 560-mm wood box and pressed in a Dieffenbacher hydraulic press having 1000- × 1000-mm plates.

Physical and mechanical properties of panels were measured according to ASTM D1037-99.

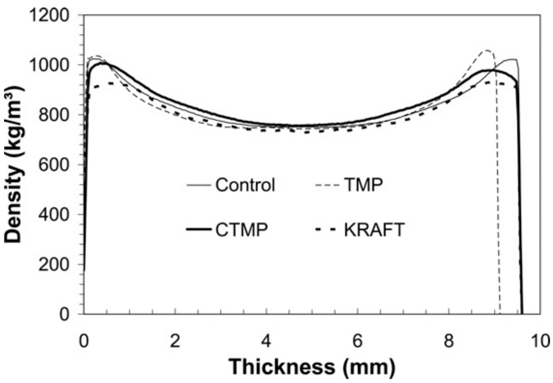

Figure 2. Examples of density profiles of medium-density fiberboard made from virgin fibers mixed with 50% pulp and paper sludge from three pulping processes (each curve is an average for 12 samples from the same panel).

Before testing, panels were conditioned to constant mass at 65% RH and at 20°C. For each panel, two thickness swell (TS) specimens, 12 internal bond (IB) specimens at panel center, four specimens for bending modulus of rupture (MOR) and modulus of elasticity (MOE), and two linear expansion (LE) specimens (152 × 76 mm) were cut. Finally, an analysis of variance with multiple comparisons (contrasts) was conducted using SAS (SAS 9.2). To include the control panel in the statistical analysis, a Waller-Duncan multiple comparison test (5% significance level) was conducted.

RESULTS AND DISCUSSION

Sludge and Fiber Properties

Chemical composition. Chemical compositions of sludge samples are presented in Table 1. Chemical composition of white birch is also presented. Typical values for softwoods are given for comparison with sludge (sludge is from softwood mills) (no softwood virgin fibers were used in panel formulations). Cellulose, pentosans (part of the hemicelluloses), and lignin contents are roughly similar for the three

Table 1. Chemical composition, physical characteristics, and pH characteristics of the different materials.

	Birch virgin fibers	Softwood virgin fibers[b]	Sludge from TMP	Sludge from CTMP	Sludge from Kraft
Chemical composition					
Cellulose (%)	45[a]	44.4 ± 1.5[c]	34.8	42.8	39.2
Pentosans (%)	23[a]	12.3 ± 1.0[c]	5.0	6.3	7.6
Lignin (%)	18[a]	28.5 ± 1.5[c]	26.3	25.3	21.9
Extractives (%)	5.0[a]	6.3 ± 1.5[c]	16.1	2.78	1.15
Ash (%)	0.3[a]	0.3 ± 0.1[c]	18.8	29.0	48.3
Physical characteristics					
Bulk density (kg/m^3)	30.2	25.5[d]	44.6	29.2	25.1
Average fiber length (mm)	1.19	—	0.39	0.45	1.09
Fines percent (length less than 200 m)	2.0	—	17.3	14.2	2.5
pH characteristics					
pH	3.86	3.86[d]	5.83	4.90	5.30
Alkaline buffering capacity (mmol H_2SO_4/100 g oven-dried sample)	1.94	1.62[d]	5.94	3.88	2.44
Acid buffering capacity (mmol NaOH/100 g oven-dried sample)	3.94	4.51[d]	2.06	2.85	1.75

[a] Paper birch wood, from Rowell (2005).
[b] For comparison only (not used in panel formulations).
[c] Average (wood): spruce-pine-fir, from Rowell (2005).
[d] Average (fibers): spruce and pine, from Xing et al (2006b).
TMP, thermal–mechanical pulping; CTMP, chemical–thermal–mechanical pulping.

pulping processes. Higher cellulose and lower lignin contents were expected from kraft sludge because the kraft process removes most of the lignin from the cell wall (Clark 1985). This result could be explained by the fact that sludge contains many undefibrated fibers such as shives which suggests that lignin byproducts are found in kraft sludge. It should be noted that these methods were designed for wood substance, not sludge, and therefore results may have been interfered with by other phenol-like molecules not found in wood, resulting in a total material slightly higher than 100% in the case of kraft sludge (Table 1). In all cases, ash content is much higher than typical values found in softwoods. For CTMP and kraft sludge samples, extractive content is lower than typical values found in softwoods, and the TMP sludge sample contains a very high extractive proportion. These values (ash and/or extractives) show that all sludge samples contain large proportions of nonfibrous material. Assuming that these nonfibrous materials would have a negative impact on panel properties, TMP and CTMP sludges would be better candidates for panel manufacturing than kraft sludge. Cellulose, pentosans, and lignin contents are slightly lower than typical softwood values because sludge contains a large proportion of nonfibrous material. The greatest difference between softwood and sludge is ash content.

Physical characteristics. Physical characteristics of the different sludge samples are presented in Table 1. In terms of fiber length, kraft sludge is the best candidate for MDF manufacturing because it has the highest average fiber length and the lowest fine proportion. This was expected, because chemical defibration produces fewer fines and longer fibers than mechanical defibration (Clark 1985). The average kraft sludge fiber length is acceptable, because it is similar to that of birch fibers used as virgin fibers in panel formulations. Sludge bulk density varies with pulping process (Table 1). Differences in bulk densities may be explained by pulp yield, fiber length, and nonfibrous proportion. Bulk density decreases with decreasing pulp yield because part of the fiber cell wall is dissolved in chemical cooking (Clark 1985). Bulk density also decreases with increasing fiber length and decreasing fine content because long fibers increase void volume, whereas fines have the opposite effect. The substantial differences in bulk densities demonstrate the influence of the pulping process on the physical characteristics of sludge. It also illustrates the large physical differences between the three sludge sources. Increased bulk density with increasing nonfibrous proportion (mainly ash) would be expected but was not observed. Apparently, the effects of pulping process and fiber length were greater. Bulk density has practical implications for MDF processing in terms of mat thickness, and it also impacts MDF properties (Xing et al 2006b).

pH Characteristics

The pH characteristics of the different samples are presented in Table 1. An acid furnish is required for the UF resin to polymerize and build a strong crosslinked network (Rowell 2005). A pH value of about 4-5 or lower is recommended to obtain a reasonable pressing time (Maloney 1993; Rowell 2005). Virgin birch fiber pH level is acceptable. Sludge pHs are higher than softwood virgin fibers and are in the high end or higher than recommended values. Of the sludge sources, CTMP sludge is the best candidate in terms of pH for panel manufacturing, and TMP is the worst. The use of a resin catalyst (such as ammonium chloride) is required with sludge because of its unfavorable pH. In this case, a low alkaline buffering capacity is preferable. A high alkaline buffering capacity would not allow the catalyst to decrease the furnish pH. In terms of buffering capacity, kraft sludge is the best candidate for panel manufacturing and TMP the worst. All sludges showed inferior pH characteristics compared with softwood virgin fibers. The effect of the unfavorable pH characteristics of sludge on UF performance might be reduced by mixing them with virgin fibers.

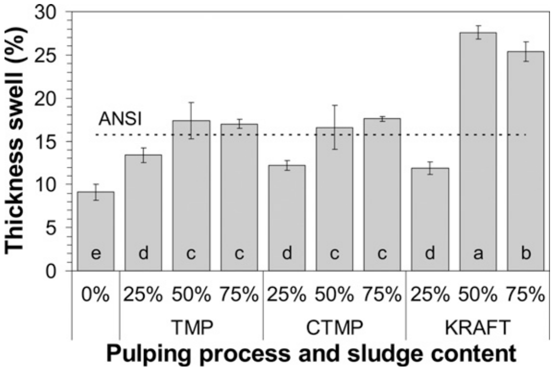

Figure 3. Thickness swell after 24 h soaking of medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes (ANSI (2002) (means with the same letter are not significantly different at the 5% probability level).

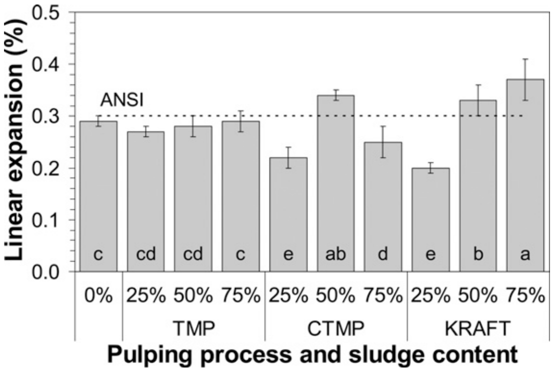

Figure 4. Linear expansion (from 50-80% RH) of medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes (ANSI (2002) (means with the same letter are not significantly different at the 5% probability level).

Effects of Sludge Content on MDF Properties

Physical properties. TS (Fig 3) and LE (Fig 4) increase mainly linearly with increasing sludge content with some higher-order effects (Table 2). Increasing sludge content has a negative impact on TS for the three pulping processes. Comparing the effect of sludge content on TS with previous reports is difficult given the diverging and conflicting results (positive, negative, and no effect) (Geng et al 2007a; Taramian et al 2007). Statistical interactions between pulping process and sludge content reveal that the effect of sludge content varies with pulping process. Thus, the amount of virgin fibers that can be replaced by sludge with acceptable TS or LE increase varies with the pulping process. TS increases with 0-50% sludge content, but little variation is observed with further increase.

Because the only difference between panel formulations is the type of sludge and fiber used, significant differences in physical properties must be explained by differences in sludge and fiber characteristics. The greater difference between the sludge sources in terms of chemical composition is proportional to the nonfibrous materials content (ash and/or extractives) (Table 1). Ash content strongly correlates with TS, showing a positive correlation coefficient of 0.87 (Table 3; Fig 5). LE correlates better with fiber extractive content than with ash content (Table 3). It should be noted that total fiber

Table 2. Analysis of variance results and selected contrasts (F values) in medium-density fiberboard properties.

Source of variation	TS	LE	IB	MOE	MOR
Pulping process	74**	4.5*	268**	13**	18**
TMP vs CTMP	<1^{NS}	1.3^{NS}	42**	<1^{NS}	<1^{NS}
TMP vs kraft	93**	3.3^{NS}	506**	18**	28**
CTMP vs kraft	118**	8.7**	258**	20**	26**
Sludge content	123**	47**	39**	66**	114**
Linear effect	171**	60**	74**	132**	227**
Residual effects	68**	35**	3.2^{NS}	<1^{NS}	<1^{NS}
Pulping process × Sludge content	25**	19**	15**	16**	9.3**

** Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
^{NS} Not significant at the 0.05 probability level.
TS, thickness swell; LE, linear expansion; IB, internal bond; MOE, modulus of elasticity; MOR, modulus of rupture; TMP, thermal-mechanical pulping; CTMP, chemical–thermal–mechanical pulping.

Table 3. Correlation coefficients between medium-density fiberboard properties and fiber and sludge chemical composition.

	TS	LE	IB	MOE	MOR
Cellulose	−0.447	0.520	0.159	0.524	0.561
Pentosans	−0.629	−0.004	0.418	0.768	0.841
Lignin	0.317	−0.190	−0.030	−0.483	−0.573
Extractives	−0.230	−0.817	0.559	0.161	0.126
Ash	0.869	0.457	−0.915	−0.903	−0.919

Note: Chemical compositions were obtained from mass weighted sums of white birch and sludge chemical compositions from Table 1.

TS, thickness swell, LE, linear expansion; IB, internal bond; MOE, modulus of elasticity; MOR, modulus of rupture.

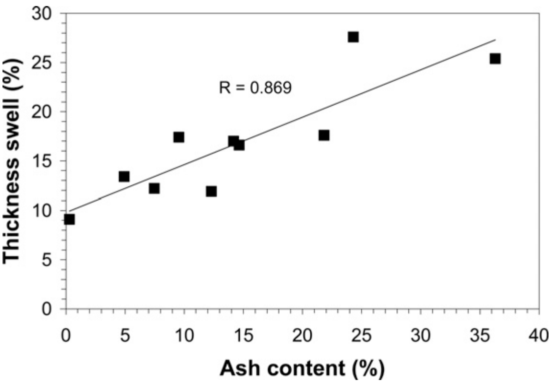

Figure 5. Correlation between thickness swell and ash content.

content in panels (virgin fibers plus fibers in sludge) decreases as ash content increases.

The nonfibrous part of sludge may affect TS by two mechanisms: mechanical interference with UF bonds between fibers and chemical affinity of ash and polar extractives with water molecules. Ash contains atoms having strong affinity with water such as Na^{+}, Ca^{2+}, Al^{3+}, and Mg^{2+} (Davis et al 2003). Sludge also has unfavorable pH and buffering capacity compared with virgin fibers, which may reduce the quality of the UF resin crosslinking network, thereby decreasing dimensional stability. Cellulose and pentosan contents show a moderate and negative correlation with TS (Table 3). In fact, most of the furnish characteristics show low correlation with MDF properties. One explanation for this result is that sludge and virgin fibers have similar chemical composition, and only the ash and extractives contents differ greatly (Table 1).

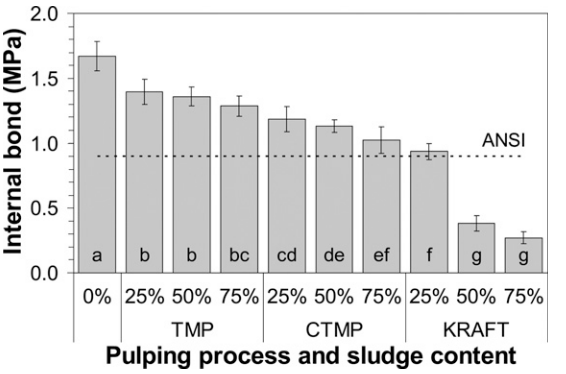

Figure 6. Internal bond strength of medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes (ANSI (2002) (grade 150; means with the same letter are not significantly different at 5% probability level).

Thus, panel chemical composition varies greatly only in terms of ash and extractive contents.

Mechanical properties. MDF mechanical properties (IB, MOR, MOE) decrease linearly with increasing sludge content (Table 2) as previously reported (Geng et al 2007a; Taramian et al 2007). Statistical interactions between pulping process and sludge content reveal that the effect of sludge content varies with the pulping process (Table 2). Thus, the amount of virgin fibers that can be replaced by sludge with acceptable mechanical property reduction varies with the pulping process.

IB strength values are presented in Fig 6. In good agreement with previous reports (Davis et al 2003; Geng et al 2007a; Taramian et al 2007), replacing fibers by sludge adversely affects IB strength. For TMP and CTMP panels, IB reduction is abrupt from 0-25% sludge content and then relatively low and progressive with further sludge content increase. For kraft panels, IB strength dramatically decreases from 25-50% sludge content. Variations in bending MOE and MOR with sludge origin and content are shown in Figs 7 and 8. The effect of sludge content on bending is lower than for other properties. In fact, panel flexural properties are known to be less dependent on adhesive performance than IB and dimensional properties. The MOE of the

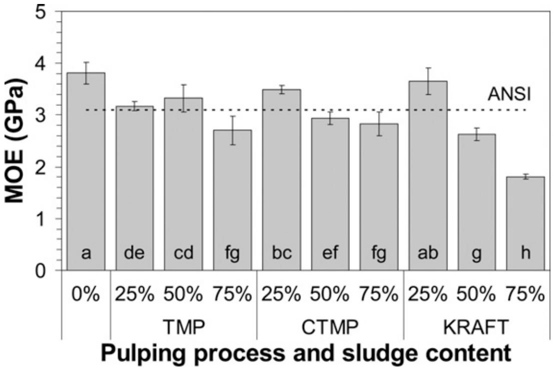

Figure 7. Modulus of elasticity (MOE) in bending of the medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes (ANSI (2002) (grade 150-160; means with the same letter are not significantly different at the 5% probability level).

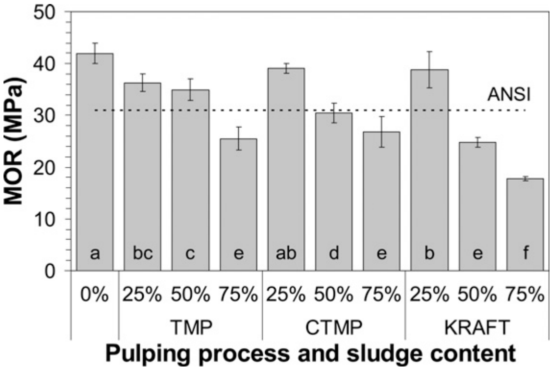

Figure 8. Modulus of rupture (MOR) in bending of the medium-density fiberboard made from virgin fibers mixed with different contents of pulp and paper sludge from three pulping processes (ANSI (2002) (grade 150-160; means with the same letter are not significantly different at the 5% probability level).

25% kraft sludge panel and the MOR of the 25% CTMP sludge panel are not significantly different than that of the control panel (Table 2). For TMP and CTMP sludge, bending strength reduction is relatively low and progressive. However, high kraft sludge content has a stronger effect on MOE and MOR.

Because the only difference between panel formulations is the type of sludge or fiber used, significant differences in mechanical properties

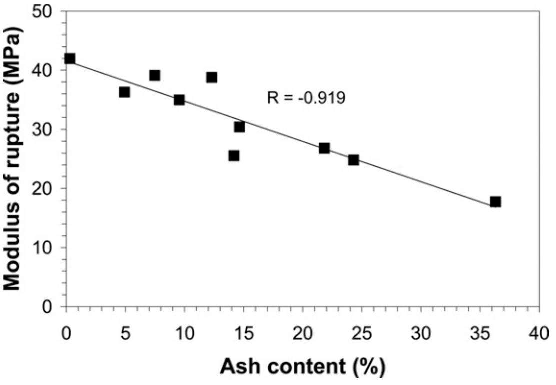

Figure 9. Correlation between modulus of rupture and ash content.

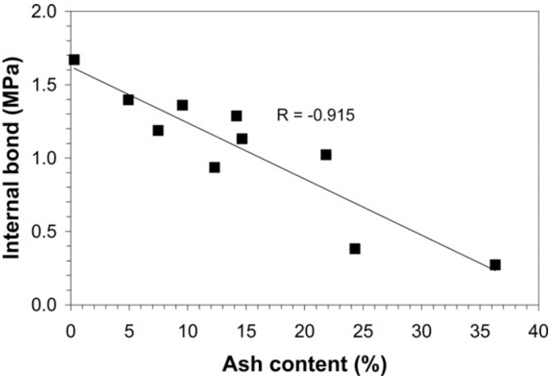

Figure 10. Correlation between internal bond and ash content.

are mainly explained by differences in sludge and fiber characteristics. Ash content strongly correlates with panel mechanical properties, showing correlation coefficients up to –0.92 (Table 3; Figs 9 and 10). As discussed previously, nonfibrous materials in sludge and their unfavorable acidity characteristics have negative impacts on UF resin crosslinking and bonding. Of all the sludge and fiber characteristics measured, only ash content (and extractives for LE) strongly correlates with panel properties (Table 3). In good agreement with previous reports (Davis et al 2003; Geng et al 2007a; Taramian et al 2007), this result suggests that nonfibrous content is the main factor affecting MDF properties.

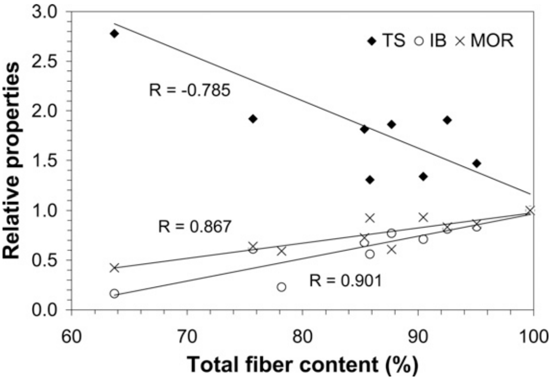

Figure 11. Variation of selected medium-density fiberboard relative properties as a function of total fiber content (total fiber content = 100 − % ash, relative property = panel property/control panel property).

High ash content involves less fibrous material and thus less wood surface for bonding. Figure 11 presents variation of selected relative properties (defined as panel property divided by control panel property) as a function of total fiber content. As expected, increasing fiber content has a positive effect on panel properties. This can be explained by the increase in total wood surface for bonding with increasing fiber content. Also, organic material mechanically interferes with the UF bonds between fibers.

Effect of Pulping Process on MDF Properties

Physical properties. Pulping process has a highly significant effect on TS and a significant effect on LE (Table 2). Significant interactions between pulping process and sludge content reveal that the effect of pulping process varies with sludge content (Table 2).

In terms of TS (Fig 3), TMP and CTMP panels are similar (Table 2) and kraft panels have the lowest performance. For LE, TMP and CTMP panels show similar performance and kraft panels are less stable (Table 2; Fig 4). These differences are explained by differences in sludge and fiber characteristics. As discussed previously, the main differences in sludge characteristics are ash and extractive contents (Table 1). In contrast to a previous report (Geng et al 2007a), the highest ash content sludge has the highest TS. Kraft sludge may be more hydrophilic, affecting panel TS, because kraft defibration and the bleaching process remove most of the less hydrophilic cell wall component (lignin) and increase the proportion of more hydrophilic components (cellulose and hemicelluloses) (Clark 1985; Rowell 2005).

Mechanical properties. The pulping process significantly affects panel mechanical properties (Table 2). Statistical interactions between pulping process and sludge content reveal that the effect of pulping process varies with sludge content (Table 2).

TMP sludge presence in boards results in the highest IB strength, and kraft sludge presence in boards produces the lowest (Fig 6). In this study, IB does not vary according to the pH characteristics of sludge. For example, TMP sludge has the highest pH and buffering capacity (sum of alkaline and acid), but its presence in panels results in the highest IB, whereas the opposite trend would be expected. The high ash content of kraft sludge strongly affects IB by mechanically interfering with the UF bonds between fibers. IB shows good correlation with ash content (Fig 10). In terms of bending properties, panels made with TMP and CTMP sludges are similar (Table 2) and panels made with kraft sludge are weakest. However, differences in MOE and MOR between panels are very low at 25% sludge content. The effect of pulping process is lower on bending properties than on IB strength. This might be explained by the greater fiber length of kraft sludge, which helps develop bending strength (Suchsland and Woodson 1990).

Based on the pulping process, kraft sludge fibers are superior in terms of fiber quality. Kraft pulp produces stronger papers than mechanical pulps. However, it can be concluded that the properties of MDF made with sludge do not vary with fiber quality (or pulp yield), but rather with nonfibrous content (ash and extractives).

ANSI Grading

The MDF produced in this study was graded according to the American National Standard for MDF for interior applications (ANSI 2002) based on physical and mechanical properties (TS, LE, MOE, MOR, IB). According to average density (Fig 1), panels are expected to meet the requirement for the highest ANSI grades such as 150 or 160. As expected, control panels classify for grade 160. At 25% sludge content, TMP and CTMP panels also classify for grade 160, and kraft panels classify for grade 150. At 50% sludge content, none of the panels meets ANSI requirements because of insufficient dimensional stability performance (TS and LE). In terms of mechanical properties alone, only the 75% kraft sludge panel does not meet the minimum ANSI requirement (grade 110). These results show that pulp and paper sludge could be recycled in MDF, replacing up to 25% of virgin fibers. The main limitation to further sludge proportion increases is dimensional stability. This issue needs to be explored in future research.

Practical Implications

This study showed that recycling pulp and paper sludge as furnish for MDF manufacturing is feasible. Sludge could be used for MDF in a similar way as that of fibers without noticeable problems. Although increasing sludge proportion led to a consistent negative impact on all MDF physical and mechanical properties, the latter still meet most ANSI specifications. The best MDF physical and mechanical properties were at 25% sludge content.

Taking into account that sludge is rich in ash and inorganic matters, higher proportions of sludge might not be suitable for MDF manufacturing. Indeed, inorganic matters in MDF might cause premature wear of cutting and sanding tools. Thus, limiting sludge content up to 25% in the MDF furnish should be an acceptable alternative because all studied properties met ANSI standards and the total inorganic content in the fiberboard is lower than 8%.

Other than physical and mechanical performance of fiberboards made with sludge, some practical aspects are worthy of discussion. These include smoothness of the final product and sludge odor. Sludge MDF panels have a smooth and uniform texture, especially those made with high sludge content. This may be attributed to their small particle size compared with conventional MDF fibers. Sludge is known to have a bad odor mainly because of the production of volatile organic sulfur compounds (Wilson et al 2006). High temperature treatment of sludge is known to be effective to control odor in biosolids (Wilson et al 2006). In the present study, sludge was dried at high temperature (up to 150°C) and fiberboards were pressed at 180°C. As a result, the produced fiberboards were odorless.

CONCLUSIONS

To evaluate the potential of various pulp and paper sludge sources available in the industry for recycling in MDF manufacturing, properties of MDF made from virgin fibers mixed with three different pulp and paper sludge sources were compared. MDF panels were produced according to a factorial design in which factors were pulping process (TMP, CTMP, and kraft) and sludge content mixed with virgin fibers (0, 25, 50, and 75%). MDF properties (TS, LE, IB, MOE, and MOR) decreased mostly linearly with sludge content. Panel properties strongly correlated with the proportion of nonfibrous material such as ash and extractives. TMP and CTMP sludge sources produced panels of similar quality and kraft sludge produced the lowest quality panels. It can be concluded that the amount of sludge that can be incorporated into MDF without an excessive decrease in panel quality depends on the pulping process. At 25% sludge content, all panels met ANSI quality requirements for MDF for interior applications.

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