PROPERTIES COMPARISON OF NORTH AMERICAN MANUFACTURED PARTICLEBOARD AND MEDIUM DENSITY FIBERBOARD

by

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Abstract

A survey of Canadian and US particleboard (PB) and medium density fiberboard (MDF) manufacturers was performed to identify potential candidates for the mechanical and physical properties comparison study. Sixty-three plants across Canada and the United States were contacted and 19 plants participated in the survey. In order to obtain and compare data on mechanical and physical properties of boards from PB and MDF manufacturers, samples were collected from 10 different manufacturing facilities across Canada and the United States (5 PB and 5 MDF). The performed tests included internal bond (IB), bending and elastic moduli (MOR/MOE), thickness swell (TS), linear expansion (LE), vertical density profile (VDP), and face and edge screw withdrawal resistance (SWR). Each manufacturing facility provided 5 full-sized (2440 by 1220 mm) panels that were tested according to North American standards. For particleboard, 4 out of 5 press lines exceeded the American National Standards Institute (ANSI) A208.1-2009 recommendation for IB. Only one of the tested particleboard sets reached the recommended ANSI standard for MOR. Results for the edge SWR showed that none of the tested particleboard manufacturers reached the ANSI recommended value. For MDF, all but one press line exceeded the ANSI standard A208.2-2009 recommended minimum value for MOE. The results for the modulus of rupture for MDF showed two manufacturers exceeding the recommended value, and three failing to meet the recommended value.

Preface

This dissertation is original, unpublished, independent work by the author, J. Dettmer.

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Acknowledgments

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1 Introduction

1.1 Background

Non-structural panels such as medium density fiberboard (MDF) and particleboard (PB) are commonly used interior building materials, which offer good dimensional stability, and a smooth surface that can be painted, laminated or veneered. They are widely used in shelving and other cabinetry and furniture applications, as well as sub-flooring (mainly PB). In North America, PB and MDF are the most used non-structural engineered wood products for furniture and furniture parts (Tabarsi et al. 2003).

These wood composite panels (WCP) are manufactured of wood fibers or wood particles mixed with thermoset resins and other additives such as wax and dyes. The mixture, referred to as furnish, is formed into a mat and pressed to target thickness under pressure of 2-3 MPa at temperatures between 160 °C and 200°C. They are made up of between 88-94% wood and about 12 - 6 % resin and additives depending on composite type, resin, and application (Papadopoulos, 2006).

Since its introduction in approximately 1940, the properties of particleboard have been researched extensively. Burrows (1960) defines resin efficiency as the "application of a minimum quantity of adhesive to wood particles, with resulting optimum physical properties in a pressed board". It relates to the quantification and optimization of resin distribution on individual wood particles or fibers throughout the panel profile for a given resin loading (Maloney, 1993). While determination of the overall resin content in panel products is

relatively easy, the irregular shape of the wood particles and fibers makes the direct quantitative measurement of resin distribution in PB and MDF products difficult (Kelly, 1977). Knowledge of the factors affecting the interaction between wood and resin in panel production, existing resin delivery technologies, and the technological understanding of micro-distribution of resin on and between furnish particles is imperative for increased resin efficiency. This could enhance panel properties and reduce resin consumption, leading to reduced production costs and ultimately the survival of some of the non-structural wood composites companies in North America.

Commonly used resins in the MDF and PB industry are urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF) and polymeric diphenyl-methane diisocyanate (pMDI) (Ruffing et al. 2010b). Resin is a major portion of the total production cost of wood composites. Most resins are produced from fossil fuel derivatives, the price of which has been on a steady increase, and this has put board manufacturers under significant pressure to reduce manufacturing costs (Winchester, 2006). For decades, UF and MUF resins have been the binders of choice. Their relative low cost, fast cure times, good bond strength, adaptability for various curing conditions, and transparency of cured resin makes them favorable for the production of MDF and PB. Their disadvantages are low moisture resistance and relatively high level of free formaldehyde left over from the resin polymerization reaction that may be emitted into the environment (Ruffing et al., 2010a). This free formaldehyde is a volatile organic compound (VOC) and is a known chemical irritant. Although free formaldehyde at low concentration is commonly present in the natural environment (background level), formaldehyde vapor at concentrations above 1 ppm causes

eye, nose, throat and lung irritations (Pilato, 2010). The US Environmental Protection Agency (EPA) classification for formaldehyde is “probable human carcinogen” (www.epa.gov, 2012). The fact that high exposure levels of formaldehyde cause sensory irritation of the eyes nose and throat, as well as the probable carcinogenic effect, causes regulatory agencies to closely monitor the allowed formaldehyde emission rates. Starting in the 1970s, UF resin bonded wood composite panels were identified as a major source for formaldehyde emissions. Even though the release of formaldehyde from UF resins was reduced by 80 - 90% between 1978 and 2006, more stringent formaldehyde regulations are being established (Marutzky, 2008). The pressures from agencies like the California Air Resources Board (CARB) combined with the resin cost challenge the wood composites panel industry to improve the resin efficiency and reduce the formaldehyde emissions in their products.

1.2 Research Objectives and Structure of Work

The motivation for this study was the constantly changing wood composites market. Fluctuation in raw material costs, new formaldehyde emissions regulations, and advancements in the production process of PB and MDF suggest that the boards produced today have different properties than panels that were produced a decade ago. The key objectives of this study were to perform an industry survey of North American PB and MDF manufacturers to identify panel characteristics, furnish compositions, resin delivery systems, and mechanical and physical board properties, and to evaluate the panel properties from different board manufacturers and compare these to one another and previous studies.

The structure of this dissertation is as follows: A literature review that summarizes the correlations between manufacturing parameters and board properties and quality, compares formaldehyde emission regulations of different geographic regions, and concludes with the review of different resin systems and methods to reduce the formaldehyde emissions of wood composite panels. Further, the development and execution of the industry survey will be presented, as well as the properties evaluation of panels from 10 different North American PB and MDF manufacturers.

2 Literature review

2.1 Parameters Affecting Panel Properties and Board Quality

This section chronologically reviews articles and research papers that investigated the influence of resin efficiency and manufacturing parameters on board properties and the overall quality of PB and MDF.

Burrows (1960) performed a series of experiments in which the resin atomization produced by a spray nozzle was varied by changing the atomizing air pressure from 60 to 80 psi and properties of particleboard furnish coated with these different degrees of resin atomization were measured. The objective of his study was to investigate the factors that were suspected of influencing resin efficiency of phenol-formaldehyde (PF) bonded boards. He examined furnish characteristics such as a function of moisture content, surface roughness and wood growth rate, as well as resin atomization. He used 1" x 4" Douglas-fir boards that were cut into 4" x 4" blocks and randomly separated into 2 groups. The first set of blocks was conditioned at 90°F and 90% RH. The other group was immersed in water and stored at 35°F. At the time of reducing the blocks to flakes, the first group had an average MC of 26% and the second group 116%. After flaking (cutting strands from the radial edge of blocks, with a maximum of 1" in length and width and an average thickness of 0.015"), the furnish was dried to a MC of 9% and screened on a 2-mesh screen. After screening, the flakes were further divided into subgroups and 2 sub-groups were further air dried.

Wet flaked (MC 116%) – dried to 9% MC – 2% resin

Dry flaked (MC 26%) – dried to 9% MC – 2 % resin

Wet flaked (MC 116%) – dried to 6% MC – 6% resin

Dry flaked (MC 26%) – dried to 6% MC – 6% resin

Burrows arranged the resin content/MC ratio as shown above to achieve a uniform MC of the mats. The furnish was blended in a batch-type mixer and the mats were hand-formed and pressed to 18" x 18" x 0.5" at 350°F and 250 psi. The thickness of the panel was controlled using metal stops. No distinct differences in flake damage at different moisture contents at the time of flaking were found. No significant differences in surfaces quality were found for different moisture contents. However, it was found that flakes obtained from fast growing wood showed a smoother surface than flakes from slow-growth wood. Analyzing the glue bond of the pressed boards showed that some of the resin did not do any bonding, as it was embedded in fissures and cracks on the flake surface. Modulus of Rupture (MOR) and Internal Bond (IB) were measured and statistically evaluated to identify possible correlations to moisture content of the flakes at the time of flaking, degree of resin atomization and resin content. Burrows found that increasing the resin content from 2% to 6% increased MOR and IB but did not indicate if the increase was significant. MOR was not significantly influenced by the degree of atomization. The results for IB were more complex. At 2% resin content the boards made with a fine spray had higher values than those made with the coarse spray; at 6% resin content the absolute value of IB was essentially twice that at 2%, but there was no significant difference between the IB values of samples made with either, coarse or fine spray.

The results of a 1970 study by Lehman (Lehmann, 1970) using urea-formaldehyde (UF) resin with a furnish consisting of a mixture of 50% flakes and 50% particles of Douglas Fir

(#9 Tyler mesh with a screen opening of 2 mm) were similar to the findings of Burrows' earlier work. For the experiment Lehmann produced 24 particleboards with the following variables: board density (650 kg/m³, 750 kg/m³), degree of resin atomization (fine at 60 psi and coarse at 20 psi), and resin content (2, 4 and 8%). For each experimental combination, 2 boards were produced. Lehman found that the MOR and modulus of elasticity (MOE) of boards increased when the resin content was increased from 2 to 4%. For the coarse spray the MOE increased from 336 Mpsi at 2% resin content to 458 Mpsi at 4% resin content and 517 Mpsi at 8% resin content. A similar increase was found for the MOR (1463 psi, 2557 psi, 2859 psi). The effect of resin atomization and board density showed that fine atomization produced boards with stronger bending properties (MOE: 532 Mpsi at 8% RC and MOR: 3213 psi at 8% RC) and higher IB (fine: 230 psi, coarse: 200 psi). He concluded that resin efficiency is highly affected and controlled by degree of atomization of resin, resin content, and board density. The first two factors primarily control the distribution and coverage of wood particles by the resin binder whereas density contributes to the efficiency of bonding. Regardless of resin efficiency, in the density range studied, static bending and thickness swelling approached optimum levels below 8 percent resin content, but IB continued to increase with increasing RC.

In 1974 (Halligan & Schniewind 1974), Halligan and Schniewind evaluated the effect of moisture content on MOR, MOE and IB of UF bonded particleboard. For their study they manufactured 3-layer particleboard panels at 3 densities of 600 kg/m^3, 700 kg/m^3, and 800 kg/m^3 with face/core resin levels of 4%/6%, 6%/9%, and 10%/10%, for a total of 9 combinations. They cut bending and IB samples from these panels and conditioned them at a

range of different relative humidities ranging from 13 to 97% corresponding to moisture contents of 3 to 20%. Once the samples reached equilibrium the bending properties and internal bond strength were measured. Maximum MOE values were observed over a range of 2.5 to 5% MC followed by decreasing MOE with increasing MC. They performed a regression analysis of their data and fit cubic equations to be able to predict MOE, MOR and IB as a function of density and moisture content. The internal bond strength increased with resin content and density. Interestingly, boards with low resin content showed no meaningful difference in IB at the three different density levels. However, the IB values for the high resin content/low density boards showed a notably lower IB values for the low-density boards. These boards had only half the IB strength of the higher density boards. Based on the data from Halligan and Schniewind, Figure 3 illustrates the IB as a function of density and face/core resin content.

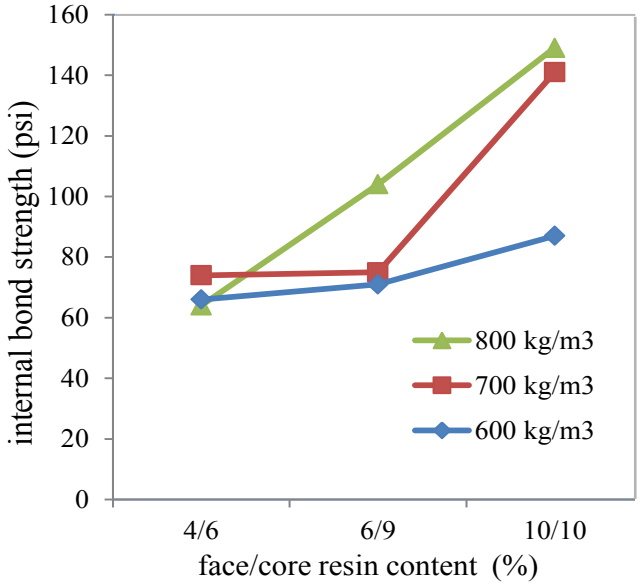


Figure 3: Internal bond strength at different face/core resin contents and indicated densities (based on data from Halligan and Schniewind 1974).

The authors concluded that the higher density boards were using the resin more efficiently. A higher densification of the furnish increased the inter-particle contact and thus required less resin to achieve the same bond strength as the low-density boards. Increasing the resin content resulted in an increased IB (highest of 149 psi at MC=3.9%, Density = 800kg/m³, RC face/core = 10/10%). They found that density was also the main factor affecting the MOR at low moisture contents (MC) and concluded that MOR and MOE increased with density. The highest MOE of 826 Mpsi was found at MC = 2.1%, Density = 800kg/m, RC=10/10% (face/core). The highest MOE (4570 psi) was found at MC=5.1%, Density = 800kg/m³, RC = 10/10% (face/core). Summarizing the effects of relative humidity, there were two main factors:

1. Higher density increased the degrading effects of moisture on MOR and MOE due to higher thickness swelling.
2. Higher resin contents reduced the degrading effects.

In regards to bending properties, the combination of high resin content and high density offered the best balance. For the IB at high moisture content, > 15%, this rule did not apply as low density and high resin content lead to the highest IB.

Kelly's (1977) "Critical Literature Review of Relationships between Processing Parameters and Physical Properties of Particleboards" is a review article that is an extensive summary of the work that has been done to that date. He mentions that the resin is a major material cost and that achieving "optimum board properties with minimum adhesive consumption is the goal of all WCP manufacturers" and refers to this concept as *resin efficiency*. He points out that resin, deposited in inter-particle voids, does not contribute to the bonding of the

particles. Minimizing these voids by increasing the density improves the board properties at a constant resin loading. Kelly also cites work by Carroll and McVey (1962) who examined the effect of prolonged post-mixing of the mixtures of resinated and unresinated furnish. They found that it had a relatively limited impact on improving the resin distribution.

Cassens et al. (1994) studied variations in selected properties of industrial grade particleboard. They measured and compared the IB, MOR, MOE, and face and edge Screw Withdrawal Resistance (SWR) of 3/8" thick M2 grade particleboard from 7 different production lines, representing 4 different manufacturers. All testing was done in accordance with ASTM D1037. One production line was located in the Western United States and used mostly ponderosa pine for furnish. The remaining 6 lines were located in the south-east and used southern yellow pine as the main furnish source. The samples, 2 boards per production line, were provided by a kitchen cabinet manufacturer that used a supplier certification program to ensure internal quality requirements. These included sanding marks, chatter, smoothness, large particles, and pits. For quantitative screening, the board density was monitored and IB tests were performed if the material was questionable. The samples for each test were conditioned at 35% RH and 75°F. For the static bending tests 4 samples per board (2 parallel and 2 perpendicular to the machine direction) were cut. Samples for board density were cut from the ends of the static bending samples after bending tests were completed. Four samples per board were conditioned to equilibrium at 72°F and 36 % RH, measured and weighed. The face SWR specimens were prepared by gluing three 3" by 6" pieces together which resulted in a total thickness of 1-1/8". A total of 6 specimens per board were produced and tested, using a 1-inch No. 10 wood screw. For the edge SWR test, 6

samples per board (2.5” x 4.5”) were tested by withdrawing 1-inch long No. 6 sheet metal screws from the 4.5” long edges of each specimen. For MOE the range was 434×10^3 psi as the highest value to a low of 317×10^3 psi, corresponding to a range of 37% of the mean value. Similarly, a 39% increase from lowest to highest was discovered for the MOR (highest: 2590 psi, lowest: 1860 psi). The average values for face SWR ranged from a low of 293 pounds to a high of 422 pounds, a difference of 44%. The means for the edge SWR ranged from 95 to 160 pounds, a difference of 60%. The equilibrium MC of the samples averaged 8.8% at 39% RH and 79°F to 12% at 68% RH and 79°F. The samples of one supplier showed a significantly higher linear expansion of 0.34% at 68% RH. The IB was the only board property that did not show a significant difference among the sourced samples, which according to the authors, is the one property that is used as a board strength indicator and most commonly monitored among furniture manufacturers.

In 2004, Cai et al. (2004) studied the mechanical and physical performance of particleboard made from eastern red cedar. They evaluated VDP (vertical density profile), MOR, MOE, IB, Thickness Swell (TS), surface hardness and SWR with the processing variables being density (400, 500, 650 and 750 kg/m^3), furnish (whole tree and pure wood) and mat construction (single- and three-layer). The furnish was made from small-diameter (average 28 cm) eastern red cedar logs from Oklahoma. For one furnish type, the whole trees, including bark, branches and needles were hammer milled through an 8mm screen and dried to 4% MC. To produce the second furnish type (pure wood), the pure wood logs (no bark, branches, or needles) underwent the same procedure. For the three-layer boards, the pure wood chips (8 mm screen) were further screened at 2 mm mesh size to separate fine and

coarse particles. The particles were then mixed in a drum type blender with 1 % wax emulsion and 7 % UF resin (based on oven dry wood particle weight). Mat forming was done manually using a forming box. The face-to-core ratio for the 3-layer boards was 60:40. All boards were pressed for 6 minutes at 180°C. One board each (55.88 cm long x 50.8 cm wide) was pressed for the following combinations:

1. Whole tree, single layer, SG=0.5
2. Whole tree, single layer, SG=0.65
3. Pure wood, single layer, SG=0.4
4. Pure wood, single layer, SG=0.5
5. Pure wood, single layer, SG=0.65
6. Pure wood, single layer, SG=0.75
7. Pure wood, three layers, SG=0.65

After conditioning the boards for one week at 25°C and 65% RH the following samples were cut according to ASTM D 1037 (ASTM 1999): 2 VDP, 4 MOE & MOR, 4 IB, 4 surface hardness, face SWR, and 1 TS.

The compaction ratio of the panels was between 0.88 and 1.67 and the VDPs of the different boards showed a similar curve at different mean densities. As expected, board 7 showed a more distinctive U-shaped density profile. The MOR and MOE increased with panel density. Cai et al. concluded that density is a major factor affecting the mechanical and physical properties of the manufactured particleboard. For the furnish type, the linear expansion (LE) was the only property that was significantly affected. Three-layer particleboard performed

better than single-layer particleboard in regards to MOE, MOR, IB and surface hardness. At 7% resin loading (UF resin), the boards did not meet the requirements for M3 grade particleboard for bending stiffness. The investigators suggested that improvements on the process parameters (e.g. resin loading and density) and processing techniques that deal with the high-silica content of the furnish could potentially be employed to use the low value eastern red cedar trees to produce marketable particleboard.

In 2004, Xing et al. (2004) investigated the effect of UF resin pre-cure on the IB of MDF. Differential scanning calorimetry (DSC) was used to quantify the degree of resin pre-curing after blending. For this study, dried unresinated softwood fibers were mixed with 20% UF resin (based on oven dry wood fiber weight) in a lab sized rotary drum blender equipped with an internal spray nozzle. According to the authors, DSC scanning required a high resin content in order to identify the polymerization peak of the resin. MC of the mat was 20%, which is related to the high resin content. Immediately after blending, the first sample was retrieved from the blender to perform a DSC analysis and to press the first MDF panel. The remaining resinated fibers were sealed in a bag and stored at 25±3°C. At pre-set time intervals, 24 h, 48 h, 120 h, 168 h, and 216 h, resinated fibers were taken to produce one MDF panel and one DSC sample per time interval. To produce the MDF panels at different stages of resin pre-cure, the mats were formed with a target density of 600 kg/m³ using a molding frame (460 mm x 560 mm). For the DSC, 10 measurements for each sample were scanned. For IB testing, all MDF panels were kept at 25°C and 65% RH prior to cutting.
It was found that the pre-cure process after blending at room temperature (23°C) happened in 3 stages, where stage 1 (the first 24hrs) and stage 3 (48 to 216 h) showed a comparable rate

of pre-cure reaction. The second stage (24 to 48 h) showed a significantly higher pre-cure reaction. Xing et al. explained that the water in the UF resin lowered the concentration of reactants. Over time, the water diffused into the fiber cell wall, which increased the reaction rate (stage 2). Larger molecular chains were formed during the advancing curing process. This might have been responsible for the lower rate of resin cure reaction (stage 3). The results of the IB testing showed, that the IB decreased significantly during the first 24 hours. After 24 h, the IB in relation to time showed a linear decrease. The authors speculate that the UF penetration of the fiber cell walls during the first 24 h was responsible for the steep decrease of IB. Once the cell wall penetration was completed, the sole factor for the IB decrease was the resin pre-cure. Based on their results, Xing et al. derived the relationship between resin efficiency (R_e) and pre-cure degree (P from 0-100%) as:

$$\mathrm{IB} = -0.0041\,\mathrm{P} + 0.4414 \ \ (\mathrm{MPa}) \qquad (1)$$

and resin efficiency as:

$$R_e = \frac{IB_i}{IB_0} \text{ x } 100\% \qquad (-) \qquad (2)$$

where IB_0 is the IB at 0 hr after blending. Substituting Eqn. 1 into Eqn. 2 and rearranging produces an expression for resin efficiency in terms of resin pre-cure only (Eqn 3), i.e.,

$$R_e = -0.93\mathrm{P} + 100 \qquad (-) \qquad (3)$$

Semple et al. (2005b) tested IB, MOR, MOE, density, and SWR (face and edge) of 5/8" M2 grade PB from 6 press lines of 4 different Canadian suppliers. They evaluated the effects of

press line, machine direction and screw type on the physical and mechanical properties of particleboard. For each press line 5 replicate sheets were acquired and cut into sub-panels. These panels were then conditioned for 2 weeks at 20 ± 1°C and 65 ± 5 % relative humidity (RH). In order to avoid any location bias, the test specimens for each test were randomized for each sub-panel.

The results showed that there was a highly significant effect of press line on panel density and strength properties. The density ranged from 650 kg/m^3 to 710 kg/m^3. For IB, samples from all press lines, except one, met the ANSI A208.1 standard, ranging from 0.42 MPa to 0.73 MPa. Semple et al. concluded that the low IB of one press line was not related to insufficient compaction ratio, which is a common cause of low IB. This conclusion was based on the fact that the measured core density of the particular press line was within a tight range of 530 to 545 kg/m^3. They suggest that other factors such as inadequate curing, non-homogenous resin distribution in the core furnish and/or resin content variation should be considered as a cause for the low IB.

2.2 Formaldehyde Regulations

In this section, various international formaldehyde emission regulations are reviewed and compared.

2.2.1 US Housing and Urban Development Agency

The first regulation to limit the indoor formaldehyde exposure in manufactured homes in the United States was enacted in 1985. Until 2007, the US Housing and Urban Development Agency (HUD) was the only national regulatory agency restricting the formaldehyde

emissions from WCPs. The emission limits set by the HUD standard do not include MDF panels and apply only to residential manufactured homes (Ruffing, 2010a).

2.2.2 CARB

In March 1992, the California Air Resources Board (CARB) identified formaldehyde as a toxic air contaminant. Formaldehyde resin bonded WCPs were identified as a major source for formaldehyde emissions. As a result, emission standards were implemented in 2 phases. Phase 1 (enacted 1 January 2009) and Phase 2, with more stringent emission limits, enacted 1 January 2011. Table 1 shows Phase 1 and Phase 2 Formaldehyde Emission standards. Because of California's important WCP market role, the CARB legislation is already affecting the US and international wood composite panel industry, as well as resin suppliers.

2.2.3 European Formaldehyde Release Regulations

Since 1988, the European Standardization Organization began to develop emission limits for WCPs in compliance with existing regulations in Austria, Germany, Denmark, and Sweden. There are two classes for wood composite panels, E1 and E2. The emission limits are also shown in Table 1 (Ruffing, 2010a).

2.2.4 Japan

The Japanese building standard laws were updated in 2003. Emission class of the panel product, the type of habitable room, and the ventilation frequency form the base of the use restrictions. If a building component consists of multiple building materials, like doors, windows, or cabinets the testing is conducted on the finished product. That allows the use of high-emitting panel products for the panel core, if the surface is sufficiently sealed to restrict

formaldehyde emissions (Ruffing, 2010a). This method can reduce formaldehyde emissions from WCPs by up to 95% (Barry & Corneau, 2006).

Table 1: Comparison of international formaldehyde emission restrictions for various board types (Ruffing et al., 2010a). Note the asterisks in the Japanese grades refer to F3-Star and F4-Star, usually written as a capital F followed by 3 or 4 asterisks.

Standard	Product	Numeric value (mg/m^3)	Approx. US large-chamber value (mg/m^3)
CARB Phase 1	HWPW	0.08	0.08
	PB	0.18	0.18
	MDF	0.21	0.21
	Thin MDF	0.21	0.21
CARB Phase 2	HWPW	0.05	0.05
	PB	0.09	0.09
	MDF	0.11	0.11
	Thin MDF	0.13	0.13
US (HUD)	HWPW	0.2	0.2
	PB	0.3	0.3
Europe E1/E2	All	0.12	0.14 (for HWPW and PB)
	E1: PB, MDF, OSB	≤ 8 mg/100g	0.1 (for MDF)
	E2: PB, MDF, OSB	≤ 30 mg/100g	
Japan F***	All	0.5 mg/L	0.07
F****	All	0.3 mg/L	0.04

CARB: California Air Resources Board; HUD: Home and Urban Development; HWPW: Hardwood Plywood; MDF: Medium Density Fiberboard; OSB: Oriented Strand Board; PB: Particleboard

A telephone survey conducted in 2008 (Ruffing et al., 2010b) showed, that the major North American resin suppliers consider regulatory institutions like CARB as the main driving force for the resin manufacturers' "green resin programs".

2.2.5 Discussion

A study on formaldehyde emissions from solid wood (Meyer & Boehme, 1997) investigated 5 different native German wood species regarding their formaldehyde emissions (Table 2).

Table 2: Formaldehyde emissions of solid wood at different moisture contents (Meyer & Boehme 1997).

	Moisture content (%)	Testing period (hrs)	HCHO (ppm)
Beech	53	360	0.002
	7	336	0.003
Douglas-fir	117	384	0.004
	9	240	0.005
Oak	63	360	0.009
	8	360	0.004
Spruce	42	384	0.003
	7	336	0.004
Pine	134	240	0.003
	8	360	0.005

Comparison of these values showed that the highest emission rate, Oak at 0.009 ppm for an MC of 63%, is already one quarter of the maximum value of 0.04 ppm permitted by the Japanese F**** formaldehyde emission restriction.

The issue of carcinogenic effects of formaldehyde on humans is controversial. The International Agency for Research on Cancer (IARC) rated formaldehyde as “carcinogenic to humans (Group 1)” based on “sufficient evidence in humans and sufficient evidence in experimental animals for the carcinogenicity of formaldehyde” (IARC, 2006). Golden (2005) argues that the IARC’s decision to re-evaluate the cancer rating for formaldehyde is based on

30-60 year old studies. Figure 4 shows the reduction of formaldehyde release of resins that are used in the WCP industry between 1978 and 2006 (Marutzky, 2008).

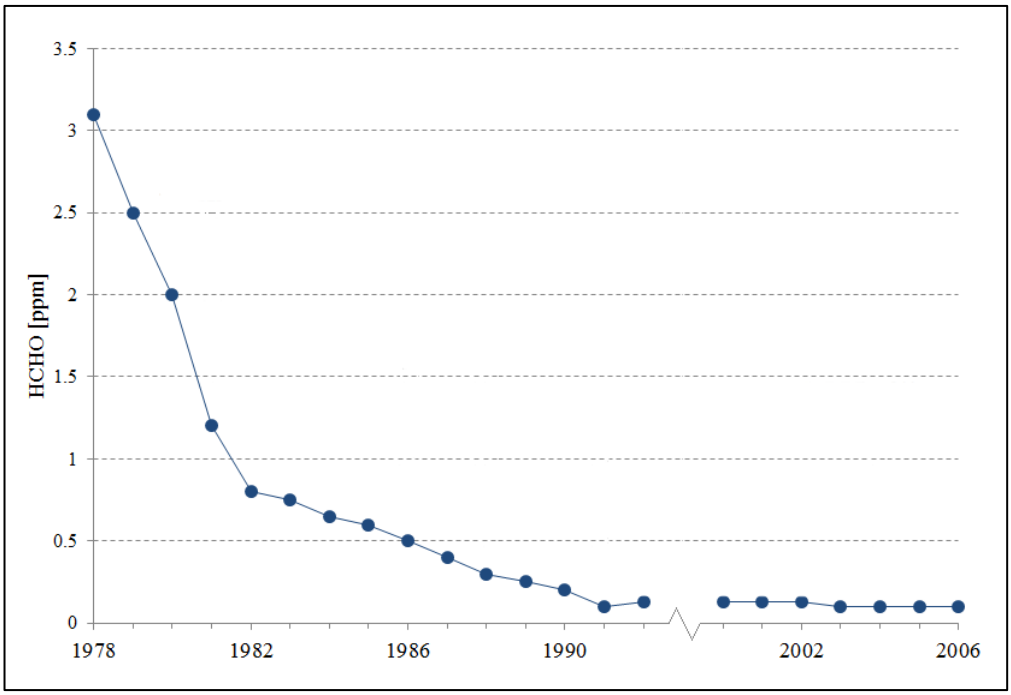


Figure 4: Formaldehyde reduction for particleboard resins between 1978 - 2006 (Marutzky 2008).

2.3 Trends and Other Resin Systems

In this section an overview of different resin systems and methods to reduce the formaldehyde emissions of wood composite panels is presented.

2.3.1 Urea Formaldehyde Resins

In North America, most of the resins currently used in the PB and MDF industry are formaldehyde based adhesives. These amino-plastic resins include urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), and combinations of these. Urea-formaldehyde bonded boards are mostly for interior use. The addition of melamine leads to better water and weather resistance, as well as the reduction of formaldehyde

emissions. Even though the use of MUF resins increase the production cost, they are generally more forgiving in terms of process variations.

2.3.2 PMDI

Polymeric diphenyl-methane diisocyanate (pMDI) is the third most commonly used resin in North America (Dettmer and Smith, 2011, unpublished results – Appendix B). Since its first introduction to the German particleboard market in the early 1970s, the importance of pMDI as a resin for the composite panels industry has grown tremendously. The capacity of the pMDI resins to form strong chemical bonds with wood results in several benefits when compared with UF resins: Reduced press temperatures, far better moisture resistance, low resin dosage, and superior physical properties of the panel. Negative aspects of using pMDI for composite panels production include higher cost, as well as health issues during the production of the resin (Papadopoulos et al., 2002). Although pMDI resins become inert once they are cured it is known that aerosolized liquid isocyanates can cause asthma and other respiratory problems.

2.3.3 Ultra-low Emitting Formaldehyde UF Resins (ULEF-UF)

Ultra-Low Emitting Formaldehyde UF resins form a new class of resins that are able to pass the CARB phase 2 emission limits. These ULEF-UF resins are chemically optimized to reduce the formaldehyde emissions. Mixing UF resin with certain additives, called scavengers that directly bind with the UF, can reduce the formaldehyde emissions from WCPs by 2 to 10 times. Typical additives are melamine and hexamine. The use of these additives is connected with higher resin cost (Athanassiadou et al., 2008) and it is uncertain if adding scavengers increases the time over which composite panels emit formaldehyde. A 2010 study raised concerns of higher formaldehyde emission rates from ULEF-UF resins at

higher temperatures and relative humidity (Frihart et al., 2010). The study investigated formaldehyde emissions of ULEF-UF at 25°C and 35°C and at different relative humidity levels (30%, 75%, and 100%). The results showed that the emissions far exceeded the CARB phase 2 limits at 100% relative humidity for both reference temperatures (25°C and 35°C).

2.3.4 Soy-based Systems

Soy based adhesives have been used to produce wood composite panels for more than 70 years. However, lower performance and high cost compared to formaldehyde-based resins, limited their use to niche products that did not require the physical properties that UF bonded composite panels offer (Informa Economics 2009).

Heartland Resource Technology developed a soy-based protein resin that has been marketed since 2009. The company lists environmental friendliness, renewability, reduced formaldehyde emissions, and reduced need for petroleum-based materials as the major advantages of their product. The main markets are Hardwood Plywood (HWPW) and Oriented Strand Board (OSB) (Pilato, 2010).

2.3.5 Crops Oil Derived Resins

A 2005 study by MDF Eisenreich (2005) showed, that modified vegetable oils, especially maleinized and epoxidized oils, can be used to produce formaldehyde-free bio-based MDF. In that study, a crop oil derived resin was used with wood, hemp, and flax fibers as the main fibers (75-85%) and hot-pressed into panels. The mechanical properties of these biocomposite panels were slightly lower than the required EN 6225 values.

2.3.6 Lignin

As a polyphenol, native lignin in wood has similar properties as phenol formaldehyde resin (PF). Technical lignin is mainly recovered as a byproduct in the pulp and paper industry. Thus far, the development of lignin-based adhesives has not had any commercial success. Currently, low chemical reactivity, dark color, long curing time, and high curing temperature make them impractical for the composite panel industry (Pizzi & Mittal 2003). However, lignin has been used as a partial phenol substitute in phenol formaldehyde resin (Papadopoulos et al., 2010). During this study, researchers successfully replaced 50% of phenol with lignin to produce particleboard that met the industry standards in terms of mechanical and physical properties.

2.3.7 Barriers Reducing Formaldehyde Emissions

Comparison of the regulations for formaldehyde emissions from WCPs on an international level shows that, except for the Japanese regulations, the emission rates are measured on raw (unfinished) panels. Most consumer products use composite panels with some sort of surface finish or coating, rather than in their raw form. A 2006 study (Barry & Corneau, 2006) investigated the emission barrier capacity of ten commonly used MDF and PB finishes. Results show that the most effective formaldehyde emission barriers are epoxy powder coatings. Epoxy powder coatings are commonly used for MDF panels and enable a 99% reduction of formaldehyde emissions to be achieved. A UV paint coated MDF sample reduced the formaldehyde emissions by 89%, whereas an acrylic paint reduced the emissions by 11%. The study also investigated the barrier effect of laminates such as HPL (High Pressure Laminate), a predominant laminate in the kitchen industry, where emissions were reduced by 99%.

2.4 Conclusion

Parameters that affect the board properties and quality have been studied extensively. Resin type and content, moisture content, particle size, and furnish composition are parameters that greatly affect board properties. Internal bond increases with increasing resin content, maximizing the inter-particle bond leads to more efficient use of the resin, MC influences IB and MOR/MOE, and furnish composition affects LE. Especially for PB, one of the oldest wood composites, a plethora of research articles and papers is available, but new manufacturing technologies and emission regulations constantly create new research opportunities.

The CARB regulation and the IARC formaldehyde cancer rating has led to new studies in the area of formaldehyde-free resin systems, as well as optimizing currently used UF resin systems. Resin manufacturers already offer alternatives to UF resins and modified UF resin systems that comply with the various international emission regulations. However, problems with existing alternatives have to be addressed. The additional cost for alternative resins is a concern for the wood composites manufacturers. Resins that can be used with existing resin dispersion systems should be taken into consideration. The improvement of physical and mechanical properties of panels produced with alternative resins is another aspect that should be investigated.

Resin manufacturers have to further the research on ULEF-UF resins that increase the formaldehyde emissions at higher temperatures and humidity. Results of new studies regarding the carcinogenic effect of formaldehyde on humans will affect the cancer rating of

organizations like EPA and IARC that will also, down the line, affect the use of urea formaldehyde resins and their alternatives.

3 Industry Survey

3.1 Introduction

Surveys on the properties of PB and MDF produced in the US and Canada were performed in the past. Semple et al. (2005b, 2005c) surveyed six Canadian plants that produce 5/8" M2 grade, as well as a comparison study of MS and M2 grade PB from two Canadian manufacturers. In 1994, Bautista (1994) and Zhang (1994) compared the mechanical properties of PB from 25 mills. Also in 1994, Cassens et al. (1994) measured and compared the properties of 3/8" thick M2 grade particleboard from 7 different production lines, representing 4 different manufacturers.

With advancements in the production technology of PB an MDF, e.g. resin and resin delivery systems, it is likely that the properties of the boards have changed compared to those in the earlier studies. A key objective of this survey was to identify panel characteristics, furnish compositions (including species, and particle/fiber sizes), resin delivery systems, and the mechanical properties of the boards. Further, the survey helped identifying collaborators that would provide samples for further testing.

3.2 Methods

To develop the questionnaire, a series of questions was compiled with the help of the technical industry advisors, as well as members of the wood composites group at UBC and OSU. The technical industry advisors for this project were Dan Sand, R&D Manager, Wood Adhesives at Georgia-Pacific LLC, Robert Breyer, Group Leader, Structural Adhesives at Georgia-Pacific LLC, Carlos Nuila Vice President, Technology at Momentive Specialty Chemicals, Michael Evans, Senior Staff Scientist at Ashland Inc., and Timothy Chaffee,

Staff Scientist at Ashland Inc. The questionnaire contained 25 questions, including yes/no questions, multiple choice, scaled questions, and open-ended questions. In order to maximize the number of participants and for flexibility, the questionnaire was designed as both, an online survey and a telephone survey. The complete layout and design of the questionnaire is given in Appendix A.

The online version was created using the online survey software "SurveyMonkey". Each participant was provided with an individual link via email to access the survey online. Through this method the investigator was able to see which participant had completed the survey. Another advantage was that it simplified the evaluation of the results.

At the time of the survey, there were, according to various sources (WBC, RISI, WBPI, CPA), 63 MDF and PB plants in Canada and the United States. Prior to and during the course of the survey, it was found that 5 of the 63 plants were closed. Several attempts were made to contact each individual plant by phone and email. The goal of these pre-survey notifications was to identify the individual who is capable of and eligible to answer the questionnaire. Dillman (2000) has commented on the importance of identifying "the most appropriate respondent for a business survey and develop multiple ways of contacting that person" which result in improved response rate, targeted communication to avoid repeating the information, and to confirm the organization's existence.

During the initial contact with the companies, in many instances the first objective was to get passed the "gatekeeper". Often, the person who answers the phone is advised to screen

survey requests (Dillman, 2000). Therefore, explaining the nature of the survey, the parties involved, and assurance of confidentiality resulted in getting connected to the potential respondent. They were then given the choice of a scheduled telephone interview or entering the online survey using an individual link that could be sent via email.

31 plants agreed to participate in the survey; all of the participants requested the online survey as opposed to a hard copy/telephone interview. 31 survey requests were sent to 16 MDF and 15 PB plants across Canada and the United States. After the link to the online survey was sent, follow-ups were initiated via email or telephone on a case-by-case basis. 19 plants completed the survey between June 29th, 2011 and August 12th, 2011, which equals an adjusted response rate of 32.7%.

After the survey was closed, the results were analysed and compiled into two reports. One report for internal use that contained company name, location, and other confidential information, and one report that was shared with the participating plants. For the latter, results were randomized. Each question was randomized individually. Therefore the numbers that were assigned to the answers do not represent a certain company. In order to keep the confidentiality, certain questions were removed. A copy of the randomized report is given in Appendix B.

4 Properties Comparison - Materials and Methods

This chapter describes the materials and the various methods, procedures and associated standards that were used to characterize the board properties of PB and MDF panels from North American manufacturers.

4.1 Materials: PB and MDF Panels

The PB and MDF panels from the various manufacturers who participated in the survey where asked to provide five panels 4-foot by 8-foot each for this study. The PB manufacturers were asked to supply M2 grade panels (ANSI 208.1-2009) and MDF producers were asked to supply 155 grade (ANSI 208.2-2009) MDF.

It proved difficult to engage and encourage manufacturers to provide panel sets for the properties comparison study. Three sets of each, PB and MDF, were donated by interested plants, one set of each, was purchased from a local building supplies store (Home Depot), and one set of each was obtained with the help of a resin company colleague encouraging those plants to participate in the study. The various sets of panels were shipped to UBC from July to September 2012. A total number of 25 PB and 25 MDF panels were tested. Preparation of the samples started in August 2012.

4.1.1 Properties of Interest

The properties of interest are listed in Table 3 include internal bond (IB), vertical density profile (VDP), thickness swell (TS), linear expansion (LE) in both directions, parallel (||) and perpendicular (⊥) to machine direction, face screw withdrawal resistance (fSWR), edge screw withdrawal resistance in both directions (eSWR ||, eSWR ⊥), modulus of rupture in

both directions (MOR ⊥, MOR ||), and modulus of elasticity in both directions (MOE ⊥, MOE ||).

Table 3: Specimen ID and number of samples measured per manufacturer, panels and sub-panel. Specimen IDs correspond with the label numbers in Figure 3b.

Property	Specimen ID	Number of samples per		
		Manufacturer	Panel	Sub-panel
IB & VDP	1	40	8	4
Thickness Swelling (TS)	2	40	8	1
MOE/MOR ||	3	40	8	1
MOE/MOR ⊥	4	40	8	1
fSWR	5	40	8	1
eSWR ||	6	40	8	1
eSWR ⊥	7	40	8	1
Linear Expansion ||	8	40	8	1
Linear Expansion ⊥	9	40	8	1

4.1.2 Cutting Patterns for the Samples

Each panel was cut into eight 61 by 61 cm (2 by 2 ft) sub-panels using a sliding table saw and labeled according to Figure 5a. In order to avoid any location bias, the subpanels were randomly assigned to one of eight different cutting patterns (Figure 5b). Each cutting pattern contained all necessary specimens according to ASTM D1037 – 06a to benchmark the properties in question.

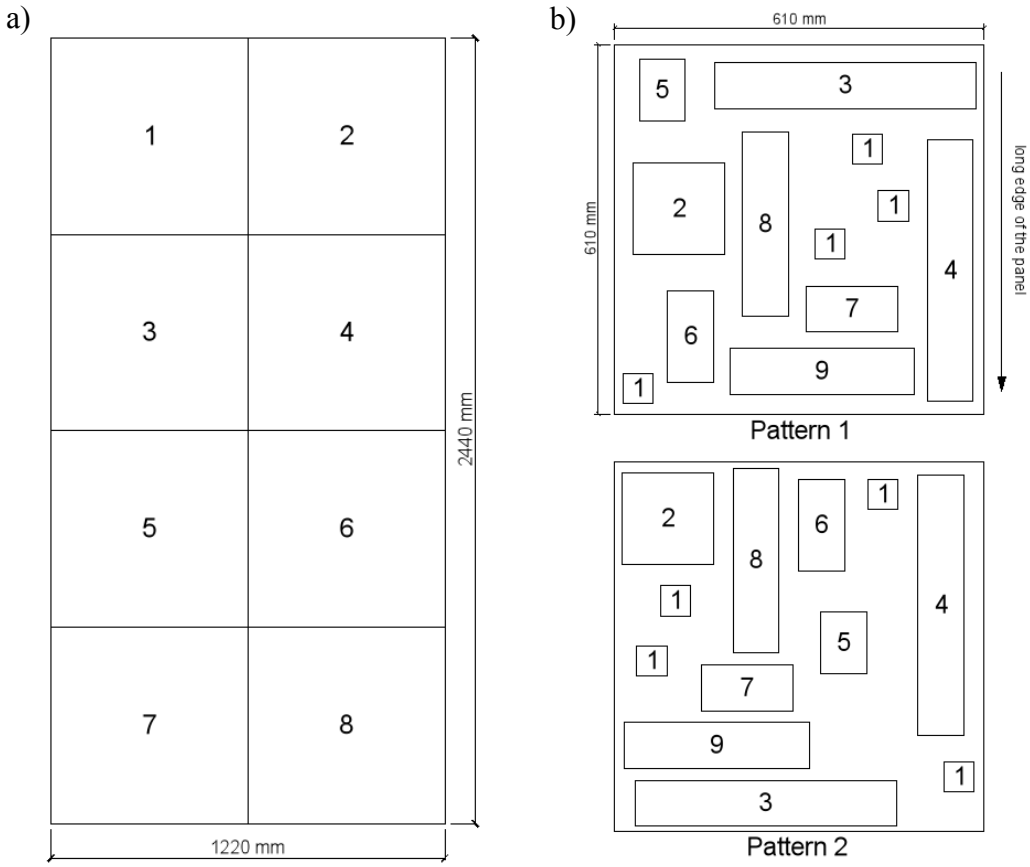


Figure 5: The *(a)* labeling sequence for the sub-panels and *(b)* two of eight cutting patterns. The label numbers in Figure 3b correspond with the specimen IDs in Table 3. All eight cutting patterns are given in Appendix C.

Before cutting, each specimen was labeled with a unique ID that contains information about the mill, panel replicate (1 to 5), sub-panel (1 to 8), and machine direction of the mat (parallel or perpendicular). The machine direction is the panel orientation that corresponds with the direction that the mat moves through the production line. For batch presses, the machine direction usually corresponds to the long edge of the panel, whereas for continuous presses, the machine direction corresponds to the short edge of the panel. When the machine direction was unknown, it was assumed that the machine direction corresponds to the long edge of the panel. A 3-digit stamp was used to label the specimens. The machine direction was indicated by the orientation of the stamp (parallel or perpendicular to the long edge of

the specimen). To ensure the label was clearly visible and not being compromised by the sawdust from the cutting process, the label was applied using a jig prior to cutting. In order to keep the collected information confidential, manufacturers were indicated by a randomly assigned letter. One manufacturer (Manufacturer B) was discarded due to different panel thickness. Therefore samples from this manufacturer do not appear in the study. The specimens were cut, using a Routech Record 121 CNC (Computer Numerical Control) router. The 4' x 10' flat table machine allows loading one side and machining on the other end of the table simultaneously. This resulted in a high throughput and one person was able to cut all 4800 samples in approximately 40 hours. A similar study at UBC by Semple et al. (2005b, 2005c) with half the sample size took 2 people more than 6 weeks. The machine has a vacuum aluminum table with a square grid pattern that in combination with a closed cell gasket and spoil boards allows nested based machining. The eight random cutting patterns were designed using the CAD (Computer Aided Design) software SolidWorks. In order to reduce the number of spoil boards, the eight cutting patterns were based on 4 different patterns that were then rotated 90° or 180°, resulting in eight different cutting patterns (see Appendix C). This not only reduced the number of required spoil boards, but also the programming time for the Computer Aided Manufacturing (CAM) software. Figure 6 shows the sequence from the CAD model to the cut samples: the CAD drawing if Figure 6a, the spoil board mounted in the CRC router, Figure 6b, the samples being labeled with a stamp before being cut Figure 6c, and after cutting, Figure 6d.

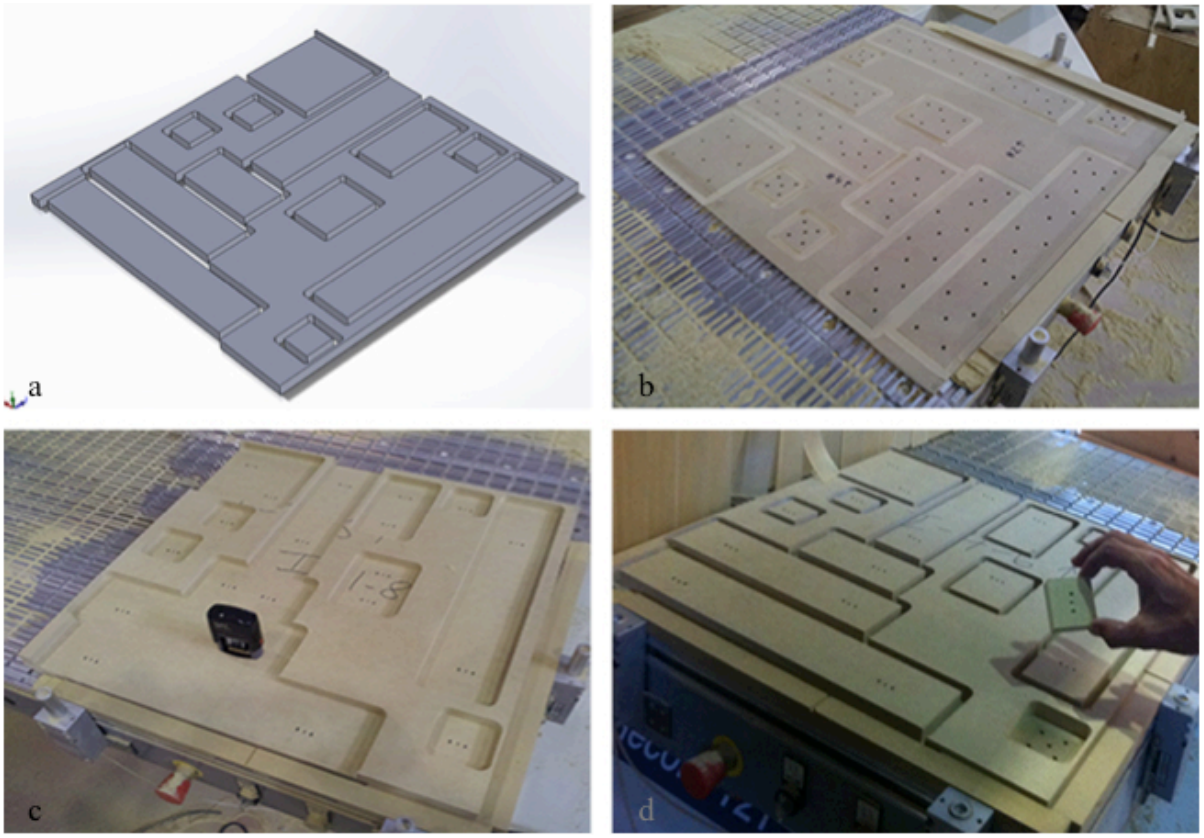


Figure 6: Cutting samples from the sub-panels: *(a)* creating the cutting pattern in Solids Works, *(b)* photograph of the spoiler board on the vacuum table of the CNC Router, *(c)* jig laid out on the surface of a sub-panel lying underneath the jig and being stamped with the sample code, and *(d)* removing samples after they have been cut out of the sub-panel.

4.2 Factors and Levels

The experimental design to analyze the collected data consisted of a completely randomized design (CRD) with one factor and fixed effects with subsampling.

The manufacturers (A to K) are the treatment (here a fixed effect) and the boards of each manufacturer are the experimental units (n = 5); in this case nested within manufacturers. The specimens that were cut from each sub-panel represent the subsampling units (observation units, m = 8). This experiment is a balanced case of subsampling. This means

that "an equal number of experimental units (n) are applied to each treatment and a constant number of observations (m) are made on each experimental unit" (Kutner et al., 1999). The model for this study can be expressed with:

$$y_{ijk} = \mu_{..} + \tau_i + \varepsilon_{j(i)} + \eta_{ijk} \qquad (4)$$

where:

$\mu_{..}$ = is an overall constant
τ_i = the treatment effect
$\varepsilon_{j(i)}$ = is the experimental error associated with the particular panel. The experimental error is nested within the treatment, since the *j*th panel for treatment *i* was not with any other treatment.
η_{ijk} = is the error associated with the *k*th subsample or observation on the jth experimental unit for the ith treatment (random effect).

To analyze the data at a 5 percent significance level, the statistical analysis software package SAS was used with the PROC MIXED under the assumptions of independence of the observations, normal distribution of the residuals, and equality of variances.

4.3 Methods

The following section describes the methods and techniques used to measure the board properties.

4.3.1 Conditioning

Prior to testing, all specimens were conditioned for a minimum of two weeks. They were stacked between stickers in a conditioning room at 20 ± 1°C and 65 ± 5% relative humidity (RH) (Figure 7). Near the end of the two-week conditioning phase, samples were weighed daily to ensure that they have reached equilibrium moisture content.

Figure 7: Thickness Swell samples stacked between stickers on a rack in the conditioning room.

4.3.2 Specific Gravity, Density, and Moisture Content

The specific gravity (SG) of the samples was determined in accordance with test Method A, volume by measurement, ASTM 2395-07a. For this purpose the thickness swell samples were used, since the samples met the requirements of a minimum surface area of 58 cm². The basis for SG was the ovendry weight and the conditioned specimen volume (65 ± 5% RH, 20 ± 3°C).

The Vertical Density Profile was measured using an X-ray density profiler (Quintex Measurement Systems; Model QDP-01X). The IB samples were used prior to IB testing to measure the density through the thickness of the panel at intervals of 0.06mm. This model is capable of scanning 6 samples per batch, resulting in 67 batches (400 samples). Depending on the exact thickness of the sample, this resulted in approximately 274 density readings per sample. The profiler was setup to output the readings as a PDF file (Portable Document

Format), which included a VDP graph (Figure 8), average calculated density (based on sample measurements taken prior to testing), average measured density (based on measured VDP), maximum and minimum measured density, and density for a pre-defined zone (e.g. core density).

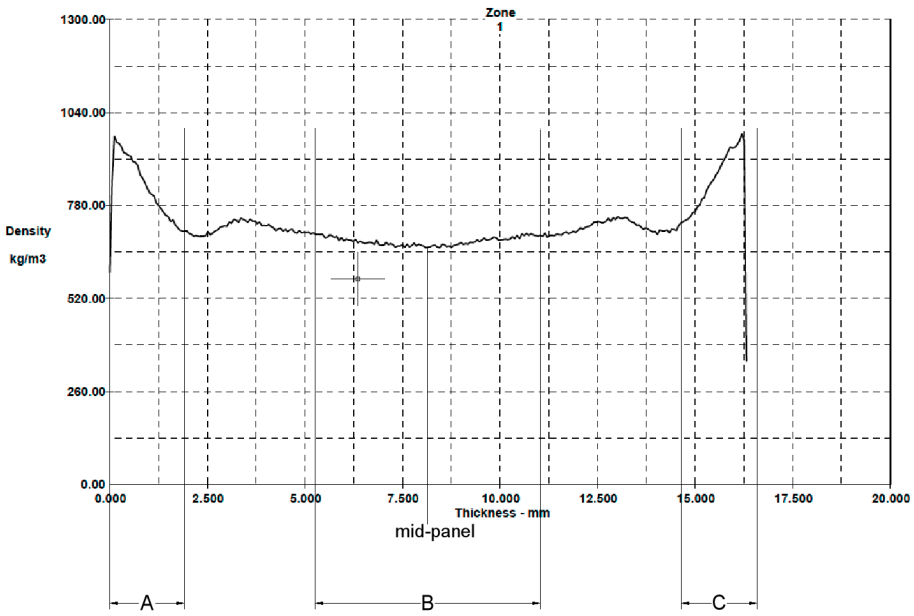


Figure 8: Vertical Density Profile graph taken from a PDF file for one of the MDF samples and the zones that the script used to extract/calculate the desired values. Zone A for the peak density, zone B for the average core density, zone C for the peak density, and the mid-panel density, a single value at 8mm panel thickness.

The machine was also setup to write all data into a data file (approx. 2100 lines per batch) that was used for detailed post-testing analysis, using a customizable Perl script (Appendix D) that was written to analyze the data file. The script was programmed to extract the peak face densities (PFD) for both surfaces, average calculated density, average measured density, mid-panel density (at 8.1mm), and calculate the average core density (CD) for a defined zone and its standard deviation. Figure 8 shows an example VDP graph and the adjustable zones that the script used to extract and calculate the data.

The moisture content was measured in accordance with method B, ASTM D 4442-07. After completing the thickness swell tests, the samples were dried at 103 ± 2°C, until reaching oven-dry equilibrium, and weighed. The moisture content was then calculated using Equation 5:

$$MC = \frac{A-B}{B} \times 100\ (\%) \qquad (5)$$

where:

A = original mass, g, and

B = oven-dry mass, g.

4.3.3 Thickness Swelling

Thickness swelling tests were performed in accordance with Method A of the ASTM D1037-06a, a 2-plus-22-h submersion.

After conditioning the 152 by 152 mm samples, weight and dimensions were measured. To determine the thickness, each sample was measured at four points, 25 mm in from the edge, midway along each side. These four values were used to calculate the average thickness for each sample. The specimens were then horizontally submerged under 1 inch of water, using a custom-made swell tank (Figure 9). The water temperature was constant at 20 ± 1°C. After two hours, the samples were removed from the tank, drained, and weight and thicknesses were measured. The samples were then submerged for an additional 22 hours and then measured in the same fashion.

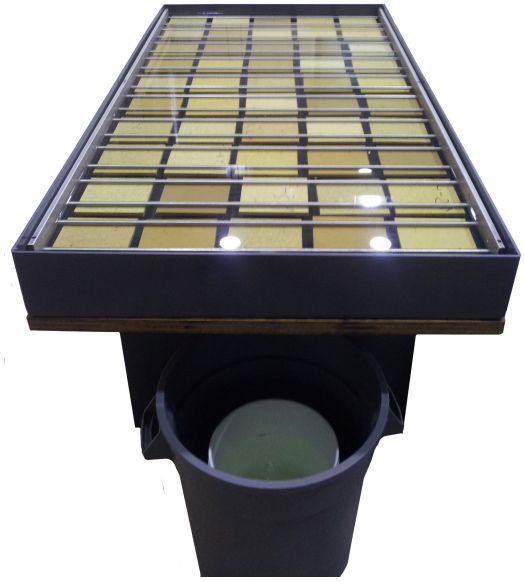


Figure 9: Thickness swelling test using a custom made tank

4.3.4 Internal Bond

The internal bond is the tensile strength perpendicular to the surface. In the WCP industry it is a commonly used measure of the resin performance in wood composites. For the test, two specimen blocks are glued to the top and bottom surfaces of the specimen, using hot-melt adhesive. The specimen is then attached to a loading fixture of the test machine (Figure 10) and tension is applied perpendicular to the specimen surface until specimen failure. The internal bond strength is calculated by dividing the maximum load at failure by the cross-sectional area of the test specimen (equation 6 – ASTM D1037 – 06a).

$$IB = \frac{P_{max}}{ab} \qquad (6)$$

where:

a = width of the specimen measured in dry condition, in. (mm),
b = length of the specimen measured in dry condition, in. (mm),
P_{max} = maximum load, lbf (N), and
IB = internal bond strength, psi (MPa).

Two hundred PB and 200 MDF samples (50mm x 50mm) were tested, using an Instron Series 3300 load frame. For each sample, the IB was calculated by using the maximum load, measured by the load frame and the dimensions, measured prior to the VDP testing.

Figure 10: Photograph of apparatus to determine the IB strength; *(top-right)* prepared IB samples prior to and after testing

4.3.5 Modulus of Rupture and Modulus of Elasticity

Samples for the static bending tests measured 76 x 432 mm. The testing was done on a Sintech 30/D load frame using the TestWorks testing control system. The span for the center point loading test was 381mm and the supports and loading points were rounded. Prior to testing, the width and the thickness of the samples were measured in order to calculate the MOR and MOE. The samples were loaded at the center of span and the load was applied to the sample midpoint at a rate of 7.7 mm/min. Equal numbers of samples were tested face-up and face-down. The MOR and MOE were calculated in accordance with the following equations:

$$R_b = \frac{3P_{max}\,L}{2bd^2} \quad (7)$$

$$E = \frac{L^3}{4bd^3}\frac{\Delta P}{\Delta y} \quad (8)$$

where:

b	= width of specimen measured in dry condition, in. (mm),
d	= thickness (depth) of specimen measured in dry condition, in. (mm),
E	= apparent modulus of elasticity, psi (kPa),
L	= length of span, in. (mm),
$\Delta P / \Delta y$	= slope of the straight line portion of the load-deflection curve lbf/in. (N/mm),
P_{max}	= maximum load, lbf (N),
R_b	= modulus of rupture, psi (kPa).

4.3.6 Screw Withdrawal Resistance

For all SWR tests a 1" Number 10 sheet-metal screw, Pan Head Cross Recessed Drive, Type AB, 18-8 stainless steel, was used. The root diameter of the screw was 3.51 mm with a pitch of 16 threads per inch. More information can be found in Appendix E.

The samples for the fSWR, measuring 76 by 102 mm, were pre-drilled prior to inserting the screw. The resulting pilot hole had a diameter of 3.2 mm (0.9 off the root diameter of the screw). This screw was threaded 17 mm into the sample at the right angle to the face of the panel.

The samples for both eSWR tests (parallel and perpendicular), measuring 76 by 152 mm, were pre-drilled at mid-thickness at the right angle to the surface of the edge, using the same drill bit. This screw was threaded 17 mm into the pilot hole.

The specimens were installed in the testing assembly, screw head facing up, and loaded at a rate of 1.5mm/min and the maximum load required to withdraw the screw from the panel was recorded.

4.3.7 Linear Expansion

Testing the linear expansion reveals information about the dimensional stability of the panel with change in moisture content. Every subpanel had one specimen with the long side parallel and one specimen with the long side perpendicular to the long edge of the panel, each measuring 76 x 305 mm.

For the test the specimens were stacked in racks and conditioned to equilibrium at a relative humidity of 50% and a temperature of 20°C. After reaching the equilibrium the length of the samples was measured and recorded, utilizing a custom-made gauge (Figure 11). A detailed drawing of the gauge can be found in the Appendix F. The samples were then condition to equilibrium at a relative humidity of 90% and temperature of 20°C and the length was measured again. It should be mentioned that the samples were measured the same way after each conditioning period, the label facing up towards the operator for the perpendicular samples and label facing up towards the right of the operator for the parallel samples.

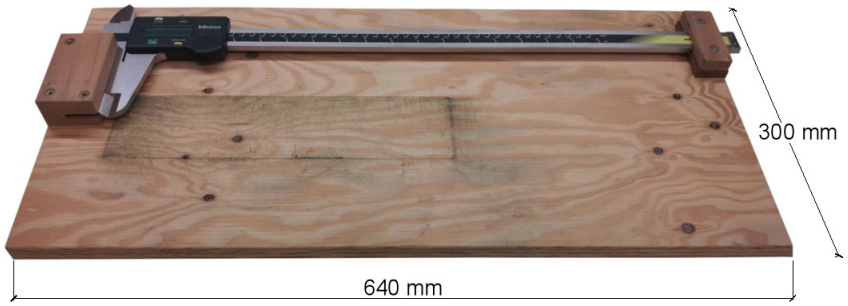


Figure 11: Custom-made gauge to measure the linear expansion

4.4 Results and Discussion

In this section the results from the statistical analysis will be presented, compared, and discussed. Where applicable, the physical and mechanical properties are compared to the appropriate voluntary ANSI standard, namely ANSI A208.1 for PB and ANSI A208.2 for MDF. For PB in particular, the older ANSI A208.1-1999 and the most recent ANSI A208.1-2009 are both presented with the purpose of comparing the findings in this study with older studies that used the standard from 1999. The major change between the two standards is that the new ANSI specified values (ANSI A208.1-2009) for IB, MOR, MOE, and SWR represent a lower specification limit. In order to meet or exceed the 2009 standard, the 5th percentile values have to be equal to or greater than the values specified in the ANSI standard. In comparison, the values for the above mentioned properties in the 1999 standard were based on a 5-panel mean, where no single panel mean shall be 20% lower than the specified value. All multiple means comparisons can be found in Appendix G.

4.4.1 Particleboard

Following, results for the evaluated PB samples are presented and discussed. Table 4 contains all means and coefficients of variation of the physical and mechanical properties for PB.

Table 4: Means and coefficient of variation (CV) of physical and mechanical properties for boards from PB manufacturers

Property		Manufacturer				
		A	C	D	E	F
MC	Mean (%)	12.0	11.4	10.9	10.9	11.8
	CV (%)	2.4	12.8	3.1	3.2	2.8
SG	Mean	639.8	626.9	709.9	596.0	603.6
	CV (%)	2.5	4.4	1.8	2.1	2.8
Density Core	Mean (kg/m^3)	574.7	559.5	670.3	538.9	566.9
	CV (%)	3.1	5.9	2.2	3.3	3.2
Density S1	Mean (kg/m^3)	983.9	937.2	1026.0	1030.2	919.7
	CV (%)	2.6	5.3	1.8	2.7	2.0
Density S2	Mean (kg/m^3)	962.2	795.0	1018.8	1020.1	917.4
	CV (%)	1.9	4.5	2.1	3.0	2.4
IB	Mean (MPa)	0.50	0.32	0.53	0.50	0.52
	CV (%)	9.3	23.9	14.4	11.4	14.6
TS	Mean (%)	19.4	25.5	4.8	12.4	7.9
	CV (%)	8.7	14.2	8.0	10.7	18.4
WA	Mean (%)	47.7	44.3	12.0	34.1	21.0
	CV (%)	11.3	14.7	7.7	11.4	16.9
LE ‖	Mean (%)	0.54	0.79	0.65	0.34	0.48
	CV (%)	9.1	8.7	7.7	11.4	8.7
LE ⊥	Mean (%)	0.70	0.87	0.65	0.32	0.54
	CV (%)	6.9	10.8	9.8	15.7	9.3
eSWR	Mean (N)	769.9	596.7	777.2	746.7	638.8
	CV (%)	8.6	17.8	10.4	6.3	9.3
fSWR	Mean (N)	1037.3	776.2	1181.9	1085.3	884.0
	CV (%)	10.5	14.4	7.3	7.6	12.3
MOR ‖	Mean (MPa)	11.7	9.4	12.6	13.9	11.0
	CV (%)	9.3	19.1	7.7	8.7	12.1
MOR ⊥	Mean (MPa)	10.6	9.5	12.4	14.0	10.6
	CV (%)	8.2	22.4	9.3	7.7	11.0
MOE ‖	Mean (GPa)	2.5	2.1	2.8	2.8	2.1
	CV (%)	6.6	11.2	5.7	9.9	9.6
MOE ⊥	Mean (GPa)	2.2	2.0	2.7	3.1	2.1
	CV (%)	7.7	15.6	5.7	7.0	9.5

4.4.1.1 Moisture Content, Specific Gravity, Vertical Density Profile, and Internal Bond

The specific gravity and moisture content are shown in Figure 12a and b for each manufacturer. The mean specific gravities of the five particleboard sets tested (Figure 12a) ranged from 710 kg/m^3 for manufacturer D (CV = 1.8%) to 596 kg/m^3 for manufacturer E (CV = 2.1%). There was no significant difference (alpha = 0.05) between manufacturers A and C, with a mean of 640 kg/m^3 (CV = 2.5%) and 627 kg/m^3 (CV = 4.4%), and between manufacturers E and F (604 kg/m^3, CV = 2.8%).

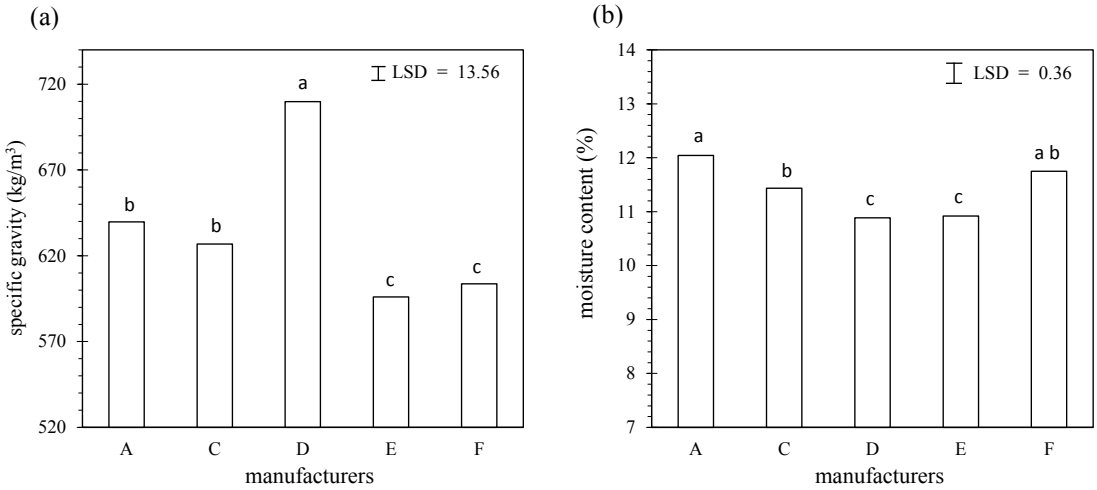
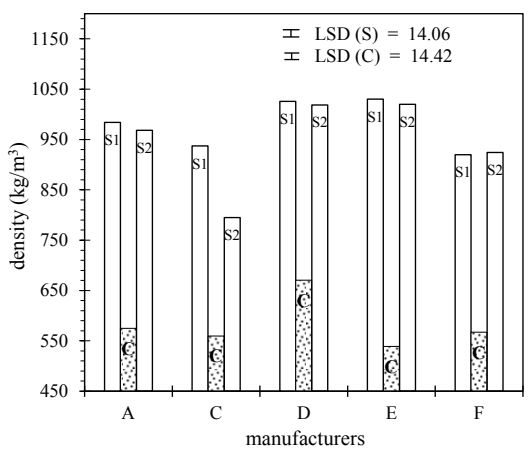


Figure 12: The *(a)* specific gravity and *(b)* moisture content of M2 grade particleboard by manufacturer. Each mean value represents 40 samples tested. Means with the same lower case letter above the column are not significantly different at $\alpha = 0.05$.

The manufacturer with the highest moisture content was manufacturer A (Figure 12b) with an average MC of 12% (CV = 2.4%). The lowest MC of 10.9% (CV = 3.1%) was measured for manufacturer D. No significant differences were observed between manufacturers A and F, C and F, and D and E.

The comparison of VDP means is visualized in Figure 13a. Peak face densities (PFD) ranged from 1030 kg/m^3 (CV = 2.7%) for surface one (S1) of manufacturer E to 795 kg/m^3 (CV = 4.5%) for surface two (S2) of manufacturer C. The highest core density (CD), averaged over a 6 mm zone around the middle of the board, was observed for manufacturer D (670 kg/m^3, CV = 2.2%). Manufacturer E had the lowest core density of 539 kg/m^3 (CV = 3.3%).

(a)



(b)

Means with the same letter in the t-Grouping are not significantly different at $\alpha = 0.05$			
t Grouping	Mean Density	N	Manuf. & Surface
a	1030	40	E-S1
a	1026	40	D-S1
a	1020	40	E-S2
a	1019	40	D-S2
b	984	40	A-S1
c	968	40	A-S2
d	937	40	C-S1
d e	924	40	F-S2
e	920	40	F-S1
f	795	40	C-S2

(c)

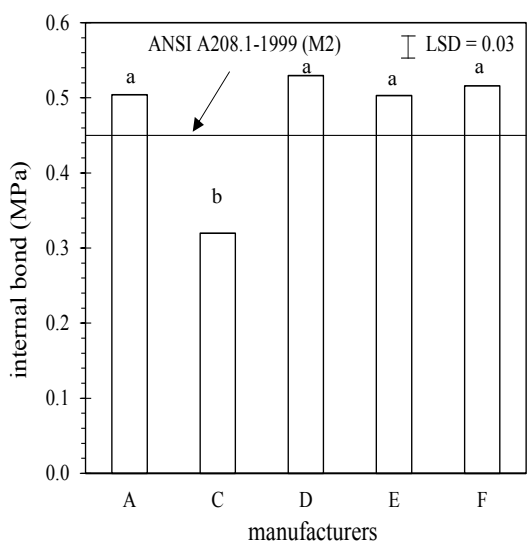


Figure 13: The *(a)* VDP, expressed as the means of peak density surface 1 (S1), core density averaged over a 6mm zone (C), and peak density for surface 2 (S2) for the five tested particleboard sets and *(b)* the significance grouping for the peak density. The means are sorted from highest to lowest. Note: The lowercase letters in the t-Grouping do not correspond with the letters for the manufacturers. The *(c)* means for IB strength for the five PB manufacturers, each mean representing 40 replicates. The horizontal line indicates the minimum IB value, required to meet the voluntary ANSI A208.1-1999. Means with the same lower case letter above the column are not significantly different at $\alpha = 0.05$.

For both, PFD and CD analyses, the assumption for equal variances was not met (H_0 was rejected), but multiple means comparison using Fisher's LSD and the robust Games-Howell test gave the same results. Manufacturers A and F, and C and F did not show significant differences between means of the core density. Figure 13b shows the significant differences for the PFDs. The means of IB strength (Figure 13c) show no significant differences between means, except for manufacturer C, with the lowest IB of 0.32 MPa (CV = 23.9%).

Manufacturer D had the highest IB strength of 0.53 MPa (CV = 14.4%). All manufacturers, except manufacturer C, met the voluntary ANSI A208.1-1999 and ANSI A208.1-2009 for M2 grade particleboard. A visual comparison of the two standards is shown in Figure 14.

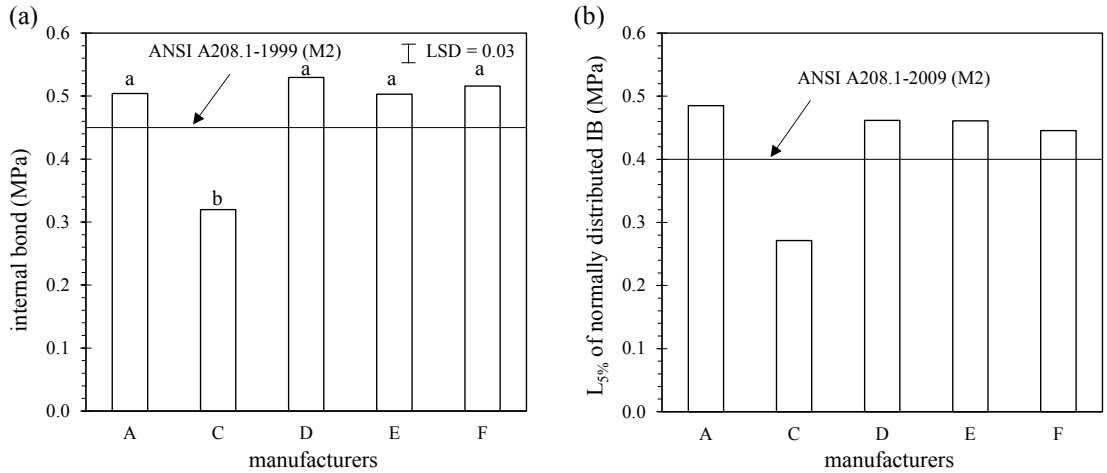


Figure 14: Comparison of the ANSI A208.1-1999 and ANSI A208.1-2009 standards for M2 grade PB. The *(a)* IB means with the horizontal line representing the minimum value as specified in the 1999 standard, as shown in Figure 13c, and the *(b)* lower 5th percentile of the normally distributed IB strength. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$.

The known correlation between density/specific gravity and IB (Lehmann, 1970) can be observed within the presented results. Manufacturer D, with the highest SG, as well as the highest core density, also had the highest IB. However, manufacturer C, with a significantly

lower mean IB than all other manufacturers did not have the lowest SG nor the lowest core density. Other unknown causes include resin type and content, moisture content, and furnish properties like wood species and particle size. According to the survey, manufacturer C (with the lowest IB) exclusively uses UF resin, with unspecified resin content. Manufacturer D, with the highest IB, did not specify resin content but listed MUF/UF (face/core) and occasionally NAUF/MUF (face/core) as the combinations used for the PB production. In work by Oh (1999), two sets of PB samples were made. One set was made with UF resin and the other with MUF resin; in all other respects the two sets of board were identical. Oh did not find any significant difference in IB strength between UF and MUF bonded PB, and therefore it is unlikely that the difference in our study can be attributed to resin type but may be related to resin content, as this was not disclosed by either manufacturer in the survey. Manufacturer C uses spruce and pine with core particle sizes of 8-35 Mesh for the furnish and Manufacturer D uses southern yellow pine with core particle sizes of 7-100 Mesh and fines (pan). Different wood species used in the furnish is a known factor that affects the IB of wood composites (Kelly, 1977). Further, the composition of the furnish in regards to particle size distribution can have a significant impact on the IB. For example, Sackey et. al (2008) used a customized furnish mix that increased the IB by up to 40%.

Despite a relatively low variation in SG and core density within manufacturers, with CVs between 2% and 6%, the IB results show a larger variation within manufacturers, with CVs between 9% (Manufacturer A) to the disproportionately high CV of 24% for manufacturer C. The CV for IB of the five boards of manufacturer C ranged from 18.3% (Panel 5) to 35.7% (Panel 4), and the remaining three panels with a CV around 22%. Reasons for this high

variation are unknown, but resin distribution and variations in the furnish are possible factors. Semple et al. (2005b) found similar results, especially in regards to IB variation within manufacturers.

It should also be pointed out that most manufacturers, except for Manufacturer C, had the expected U-shaped VDP. The mean PFDs for both surfaces (S1 and S2) of panels from manufacturer C had a significant difference of 142 kg/m^3.

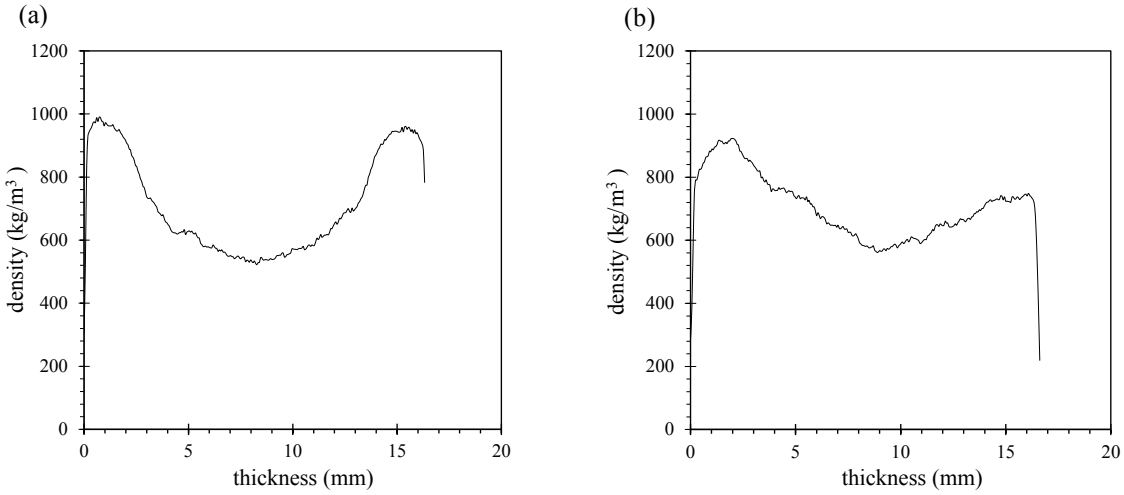


Figure 15: Comparison of typical VDP plots from *(a)* manufacturer A and *(b)* manufacturer C. The significant difference between PFDs is very pronounced for manufacturer C.

Even though manufacturer A also showed significantly different PFDs (Δ=15.7 kg/m^3, LSD = 14 kg/m^3), the VDP plots were far more consistent than the ones of manufacturer C (Figure 15). Possible causes for an inconsistent VDP include differences between the furnish parameters, resin distribution, or resin pre-cure (Wong et al., 1999), as well as unequal sanding of the faces.

4.4.1.2 Thickness Swell and Water Absorption

The TS after 2 and 24 hours is reported as the percentage of the conditioned sample thickness (Figure 16a). It ranged from 4.8% (CV = 8%) for Manufacturer D to 25.5% for Manufacturer C (CV = 14.2%). The Games-Howell multiple pairwise comparison test showed significant differences between all means. The CVs were between 8% (Manufacturer D) and 18.4% (Manufacturer F).

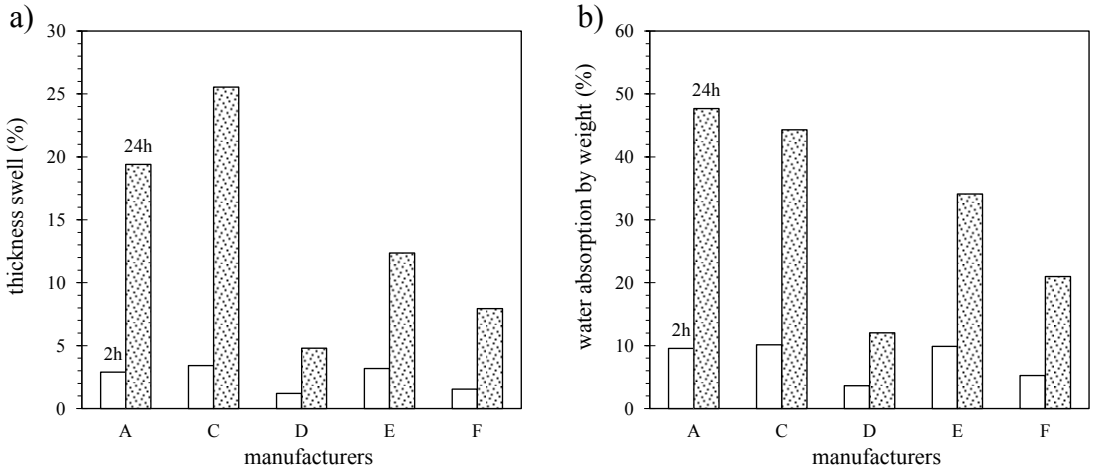


Figure 16: The *(a)* thickness swelling after 2 and 24 hours for all particleboard manufacturers and *(b)* water absorption after 2 and 24 hours

The means of water absorption, presented in Figure 16b, are based on the initial sample weight after conditioning. Manufacturer D had the lowest WA of 12% (CV = 7.7%) and Manufacturer A had the highest (WA = 47.7%, CV = 11.3%). Means of Manufacturers A and C were not significantly different according to the Games-Howell test.

Generally it can be observed that higher TS correlated to higher WA. Manufacturers A and C do not show this direct correlation. Despite no significant difference in means for WA, a inverse correlation between TS and WA can be observed after 24 hours. Lower MC as an explanation for the higher water absorption of Manufacturer A can be ruled out, since it had

the highest MC. In his review of thickness swelling in particleboard, Halligan and Schniewind (1974) summarize that TS is influenced by process parameters such as wood species, particle geometry, blending efficiency, resin level, board density, densification, and pressing conditions. Medved et al. (2011) concluded that the condition of the core furnish of three layer particleboard in regards to resin content has higher impact on TS than changing resin contents in the surface layer. Table 5 compares the known properties of the two manufacturers in question.

Table 5: Comparison of Manufacturers A and C

Property	Manufacturer	
	A	C
CD (kg/m^3)	575	560
SG	640	627
Wood species	Douglas Fir, Hemlock	Spruce, Pine
Resin type/ Resin content	UF/n.a.	UF/n.a.
TS - 24h (%)	19.4	25.5
WA - 24h (%)	47.7	44.3

The different wood species used by the two manufacturers is a possible explanation for the reversed correlation of TS and WA. Particle size, compressibility, sorption properties, and anatomical and chemical composition of the wood species have an impact on TS and WA. The disproportionately low PFD for surface 2 of Manufacturer C might also be responsible for the higher TS.

The significantly better performance in TS and WA of Manufacturer D is most likely related to resin type and resin content of the core furnish. Oh (1999) found significantly lower percentages for TS and WA for boards manufactured with MUF resin than boards made with UF resin. The combination of the low percentage in TS and WA and the significantly higher core density (Figure 13a) suggests a high resin content. A high core density achieved through higher densification of the furnish can be ruled out, since this would have resulted in a higher TS.

4.4.1.3 Linear Expansion

Mean LE values were between 0.32% (CV = 15.7%) for Manufacturer E, perpendicular to machine direction, and 0.87% (CV = 10.8%) for Manufacturer C, perpendicular to machine direction. Machine direction had no significant effect on panels from Manufacturers D and E (Figure 17).

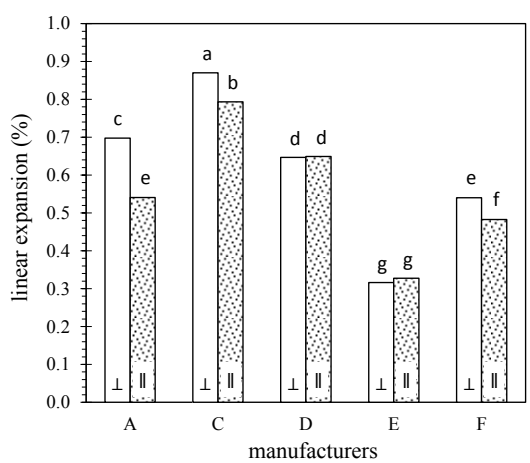


Figure 17: Mean LE values. Each pair of columns represents one manufacturer and the two sample orientations tested ($n_{\perp} = 40$, $n_{\parallel} = 40$, for each manufacturer). Means with the same lower case letter above the column are not significantly different at $\alpha = 0.05$ (a = highest mean, g = lowest mean).

The CVs ranged from 6.9% for the samples of Manufacturer A (perpendicular to machine direction) to 15.7% for the above-mentioned samples of Manufacturer E.

The results were not compared to the ANSI standard. In contrast to ASTM 1037, the ANSI standard maximum values are for a RH range from 50% to 80%, whereas the here presented values represent a RH change from 50% to 90%. Cassens et al. (1994) used a RH range from 39% to 68% to collect the LE data and pointed out that this smaller range is more representative for the end-use of M2 grade particleboard. They found the LE results to be highly variable with a combined CV of 35%. The LE for all seven evaluated commercial PB manufacturers ranged from 0.14 to 0.34% at a change in RH from 39 to 68%. Linear expansion was between 0.7 and 1.8% with an overall CV of 28% for an RH range of 39 to 98%.

In the past, several studies show that particle geometry and particle orientation distribution are important factors affecting the LE of particleboard (Kelly, 1977; Rofii et al., 2013; Xu & Suchsland, 1997). A more oriented particle distribution results in a larger difference of LE between the two tested directions of the same board (|| and ⊥ to machine direction). This suggests that Manufacturers A, C and F, with a significant effect of machine direction on that property mean, have a more oriented particle distribution than Manufacturers D and E. Miyamoto et al. (2002a) found that PB made with Hinoki particles (Japanese cypress) showed an increase in LE with decreasing particle size. Further, Suzuki and Miyamoto (1998) concluded in their study evaluating the effect of resin content (RC) on LE, that an increase of RC (PF resin) from 6% to 12% increased the LE. They did not find any clear reasons for this phenomenon but list differences of the layer structure and hygroscopicity of

PF resins cured in the boards as candidates for further investigation. Although the resin type for Manufacturer D is unknown (MUF/UF or NAUF/MUF), Suzuki and Miyamoto's findings offer an explanation for the higher LE and the previously stated hypothesis of higher resin content for this manufacturer.

4.4.1.4 Screw Withdrawal Resistance

4.4.1.4.1 Face Screw Withdrawal Resistance

The fSWR showed a trend similar to the previously presented results for IB, SG, VDP, and TS. The fSWR was highest for Manufacturer D (1182 N, CV = 7.3%) and lowest for Manufacturer C (776 N, CV = 14.4%). Fisher's LSD test, as illustrated in Figure 18a, revealed no significant difference in means for Manufacturers A and E. The CV range was between 7.3% (Manufacturer D) and 14.4% (Manufacturer A).

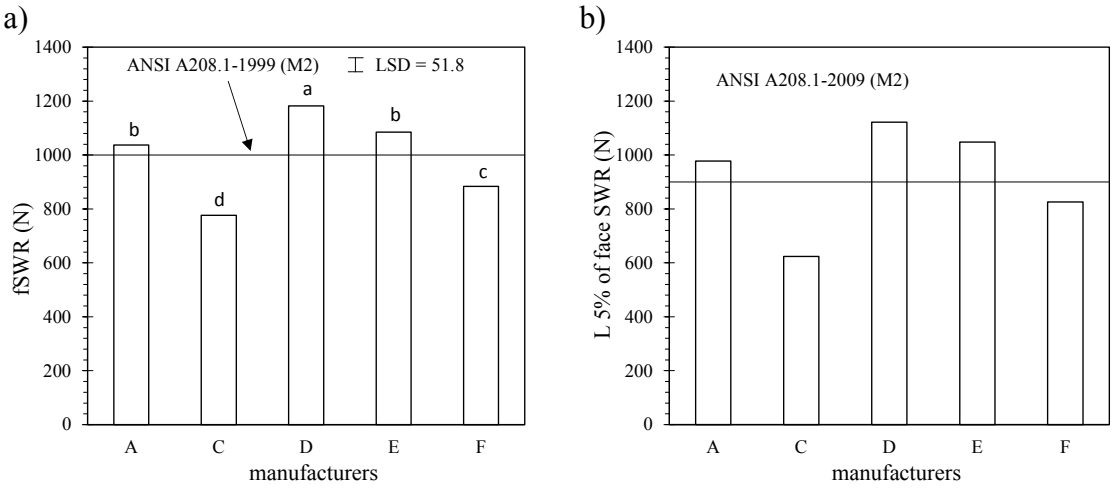


Figure 18: The *(a)* mean fSWR values. Each column represents one manufacturer (n = 40). Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$ (a = group with highest mean, d = group with lowest mean). The *(b)* lower 5th percentile of the fSWR values distribution in accordance with ANSI A208.1-2009.

Manufacturers A, D, and E met or exceeded both, the ANSI A208.1-1999 (Figure 18a) and ANSI A208.1-2009 (Figure 18b) standards. Manufacturers C and F did not meet either standard.

Values reported by Cassens et al. (1994) were roughly 60% higher for the maximum value (1880N) and 67% higher for the lowest value (1300N). The CV range was almost identical with 6.5% to 15%. A possible explanation for the overall higher values from Cassens et al., is the different preparation of the samples. They glued three 3/8" thick pieces (3" by 6") together into one specimen to reach the recommended minimum thickness of 1" (ASTM D 1037).

Departures from the ASTM recommended minimum thickness are tolerated if "other considerations make it desirable to test with the thickness as manufactured" (ASTM, 2010). The preparation of the samples for this study, as reported in Section 4.3.6, was similar to the study of Semple et al. (2005b), who found comparable fSWR means of 880 N to 1170N (CV = 7% to 11%).

4.4.1.4.2 Edge Screw Withdrawal Resistance

Machine direction had no significant effect on the eSWR, and therefore the values were pooled across machine direction and re-analyzed with the appropriate ANOVA. The Games-Howell multiple comparison procedure did not show any significant differences between Manufacturers A, D, and E, and Manufacturers C and F. The mean eSWRs of the first group were in a close range from a low of 747 N (Manufacturer E, CV = 6.3%) to a high of 777 N (Manufacturer D, CV = 10.4%). The values of the second group with overall lower eSWRs

ranged from 597 N (CV = 17.8%) for Manufacturer C to 639 N (CV = 9.3%) for Manufacturer F. All manufacturers failed to meet the voluntary ANSI A208.1 (1999) and A208.1 (2009) standards for M2 grade PB (Figure 19).

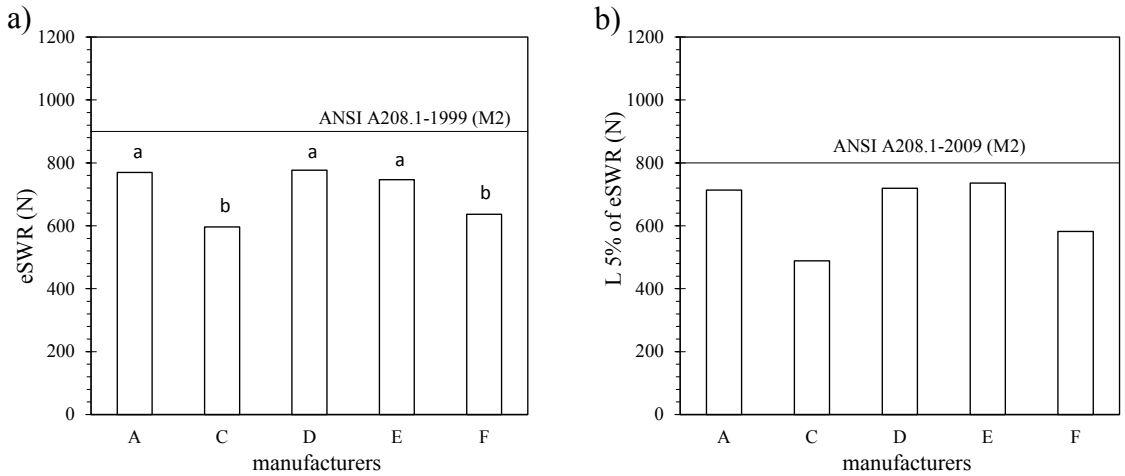


Figure 19: The eSWR for the evaluated PB manufacturers. The *(a)* mean values (n=40) compared to the ANSI standard from 1999. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed eSWR, presented in accordance with the new ANSI standard from 2009.

Values for eSWR were approximately 25 to 35% lower than fSWR. This is somewhat in accordance with Semple et al. (2005b) who reported a difference of 25%, but smaller than Cassens et al. (1994), who found eSWR to be 65% lower than fSWR. This is most likely related to the two different screw sizes that were used for the test (1" No. 10 woodscrew for fSWR and 1" No. 6 woodscrew for eSWR). Both also reported a higher CV range for eSWR than for fSWR. Semple et al. explain the higher variability of eSWR with the lower core density and greater structural heterogeneity due to the presence of coarser particles in the core layer. For this study CV range for eSWR was slightly bigger (6.3% - 17.8%).

Similar to fSWR, Semple and Smith (2005) found little or no correlations between CD and eSWR for the 20 evaluated commercially produced particleboard panels from two press

lines. For this study, correlations were low for eSWR and SG ($r^2 = 0.24$), CD ($r^2 = 0.21$), and IB ($r^2 = 0.5$).

4.4.1.5 Modulus of Rupture and Modulus of Elasticity

For MOR machine direction only had a significant effect on Manufacturer A. Figure 20a shows the mean MORs, sorted by machine direction and manufacturer. Manufacturer E had the highest MOR of 14 MPa (averaged across machine direction). The lowest MOR of 9.5 MPa was found for Manufacturer C, who also had the highest CV of 22%. The CVs for the other manufacturers were between 8% and 12% (Table 4). None of the tested PB manufacturers reached the recommended ANSI A208.1-1999 value of 14.5 MPa. However, as shown in Figure 20b, Manufacturer E complied with the newer ANSI A208.1-2009 standard that supersedes the older standard from 1999.

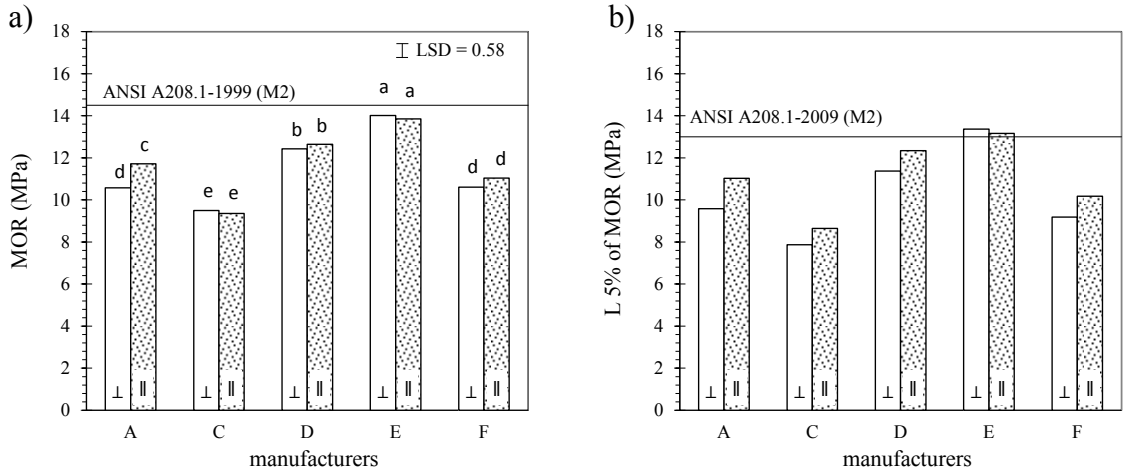


Figure 20: The MOR for the evaluated PB manufacturers for both machine directions. The *(a)* mean values (n=40) for MOR of each manufacturer. The horizontal line represents the ANSI standard from 1999. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed MOR, presented in accordance with the new ANSI standard from 2009.

The results for MOE were similar in regards to the ranking of the manufacturers. Manufacturer E had a significantly higher MOE for samples tested perpendicular to the machine direction (MOE $\perp = 3.1$ MPa). The lowest MOE was found for Manufacturer C, perpendicular to machine direction (MOE $\perp = 2.0$ MPa). The effect of machine direction on MOE was more pronounced than for MOR. Only Manufacturers D and F did not show a significant difference between machine directions (Figure 21).

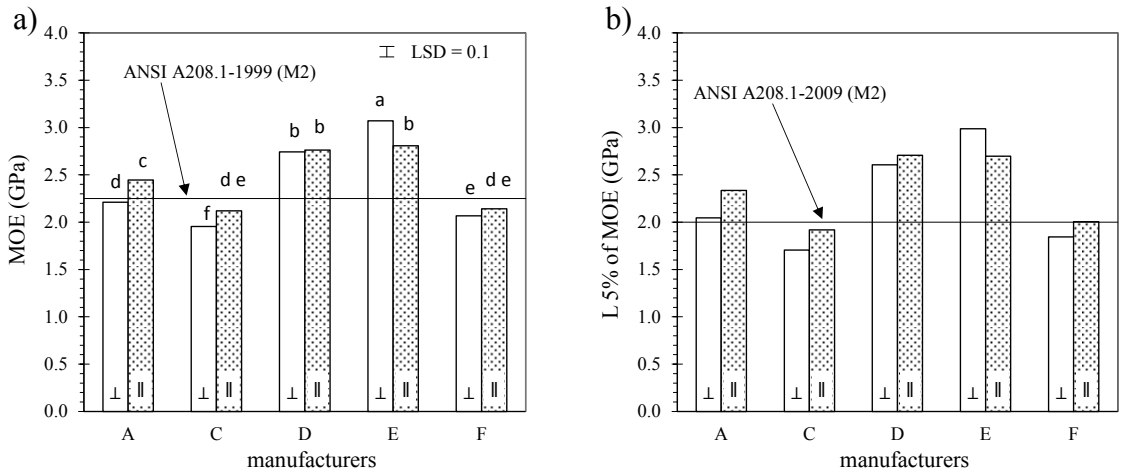


Figure 21: Comparison of the two ANSI standards. The *(a)* mean MOE values for both machine directions for each manufacturer. The horizontal line represents the ANSI standard from 1999. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed MOE, presented in accordance with the new ANSI standard from 2009.

The range of CVs was lower than for MOR (Manufacturer $C_{\perp} = 15.6\%$, Manufacturer $D_{\perp/\parallel} = 5.7\%$). Manufacturers A, D, and E were equal to, or exceeded both ANSI standards. Manufacturer E with the highest mean values for MOE showed a higher value for samples tested perpendicular to the machine direction. Since the samples from this supplier were obtained through a local lumber supplier, the orientation of the panel's long edge with respect to the machine direction is unknown. It is likely that the assumption that the machine direction is parallel to the long edge of the panel is incorrect for this manufacturer.

It is known that density and related properties like SG and VDP (Halligan & Schniewind, 1974; Kelly, 1977; Miyamoto et al. 2002b), as well as particle orientation (Arabi et al. 2011) and resin content (W. Lehmann, 1970) affect the bending properties of wood composites. Results for MOE from this study correspond well with those of Semple et al. (2005b) and Cassens et al. (1994). MOR values were about 20% lower.

Particularly interesting is that Manufacturer E with the lowest SG (Table 4 and Figure 12) had the highest bending strength. This is most likely due to the highest PFD values (Figure 13a). Miyamoto et al. (2002b) found that the press closing time strongly affected the bending properties of PB. Faster press closing times led to a more pronounced U-shaped VDP with higher PFDs, which in return led to higher bending properties. Often, achieving higher bending properties through a faster press closing time is at the expense of lower IB and SWR (Semple et al. 2005b, Dai and Wang, 2004), but results for these properties for Manufacturer E were among the highest (Figure 13a, Figure 18, and Figure 19). Results from this study suggest more complex interactions of properties and process variables.

4.4.2 Medium Density Fiberboard

In this section, the results for the evaluated MDF samples are presented and discussed. Table 6 contains all means and coefficients of variation of the physical and mechanical properties for MDF.

Table 6: Means and coefficient of variation (CV) of physical and mechanical properties for boards from MDF manufacturers

Property		Manufacturer				
		G	H	I	J	K
MC	Mean (%)	10.0	8.9	10.3	10.4	10.7
	CV (%)	1.9	6.4	11.5	6.0	13.7
SG	Mean	700.9	677.3	664.0	691.9	713.9
	CV (%)	0.8	0.8	0.9	1.1	2.2
Density Core	Mean (kg/m^3)	691.8	693.5	671.5	669.4	715.8
	CV (%)	1.4	1.2	1.7	2.7	2.3
Density S1	Mean (kg/m^3)	1124.5	1096.7	985.2	975.9	1031.8
	CV (%)	2.1	2.2	2.9	3.6	2.5
Density S2	Mean (kg/m^3)	1126.3	1052.7	974.2	949.8	1038.0
	CV (%)	2.1	1.5	2.7	4.4	3.0
IB	Mean (MPa)	0.83	0.75	0.59	0.50	0.87
	CV (%)	10.5	18.6	15.6	19.5	15.5
TS	Mean (%)	6.0	5.3	6.6	10.8	7.5
	CV (%)	4.9	5.3	4.5	6.2	6.5
WA	Mean (%)	17.2	10.2	13.8	19.3	17.6
	CV (%)	5.7	7.1	10.0	7.9	12.9
LE ‖	Mean (%)	0.27	0.19	0.23	0.23	0.16
	CV (%)	11.6	12.5	18.5	11.2	18.2
LE ⊥	Mean (%)	0.27	0.19	0.24	0.22	0.18
	CV (%)	8.0	11.5	16.1	17.14	10.6
eSWR	Mean (N)	1331.5	1406.5	1033.9	1053.2	1455.7
	CV (%)	3.4	5.7	5.7	9.6	7.3
fSWR	Mean (N)	1539.5	1315.7	1200.9	1307.6	1523.0
	CV (%)	4.1	5.4	7.4	7.4	6.5
MOR ‖	Mean (MPa)	31.3	27.9	20.2	26.6	31.1
	CV (%)	5.1	6.3	8.9	11.1	9.3
MOR ⊥	Mean (MPa)	31.6	27.3	22.3	29.1	29.9
	CV (%)	6.0	9.0	6.3	13.1	9.0
MOE ‖	Mean (GPa)	3.5	3.5	2.7	3.3	3.4
	CV (%)	3.9	4.9	8.3	10.7	6.5
MOE ⊥	Mean (GPa)	3.5	3.5	2.7	3.5	3.2
	CV (%)	4.8	4.9	7.8	10.5	6.5

4.4.2.1 Moisture Content, Specific Gravity, Vertical Density Profile, and Internal Bond

The MC for the MDF samples, Figure 22a, was between 8.9% (Manufacturer H) and 10.7% (Manufacturer K) with a relatively large CV range of 1.9% (Manufacturer G) to 13.7% (Manufacturer K). The statistical analysis revealed that the assumption of equal variances was not met. Therefore the Games-Howell multiple comparison procedure was employed to reveal differences among means and no LSD is shown in the graph of Figure 22a. Similar to the tested PB, some MDF samples did not show a significant difference between means. Manufacturers G, I, J, and K showed similar mean values, whereas Manufacturer H had a significantly lower MC compared to all other manufacturers.

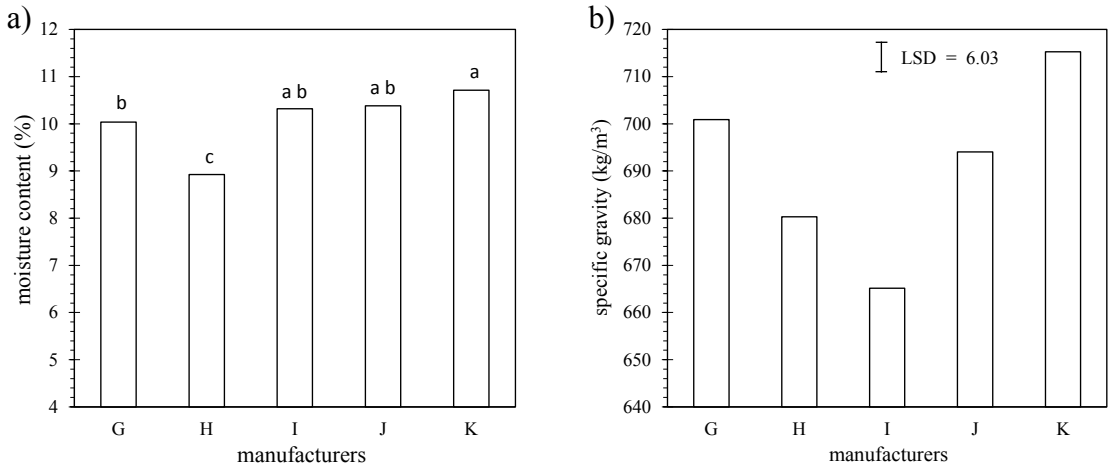
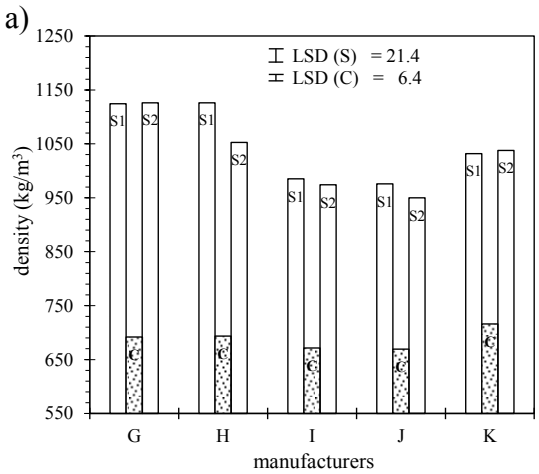


Figure 22: The *(a)* moisture content and *(b)* specific gravity of MDF by manufacturer. Each mean value represents 40 samples tested. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$

For SG, all manufacturers had significantly different mean values that ranged from 664 for Manufacturer I to 713.9 for Manufacturer K. Coefficients of variation were within a tight range of 0.8% to 2.2% (Table 6). Core densities, as shown in Figure 23a, were between 669.4 kg/m^3 (Manufacturer J) and 715.8 kg/m^3 (Manufacturer K). Fisher's LSD procedure found no significant differences between Manufacturers G and H, and Manufacturers I and J.

Peak face densities ranged from 1126.3 kg/m^3 (Manufacturer G - S2) to 949.8 kg/m^3 for S2 of Manufacturer J (Figure 23b). The CVs for the VDP were in a close range of 1.2% to 4.4% (Table 6).

a)

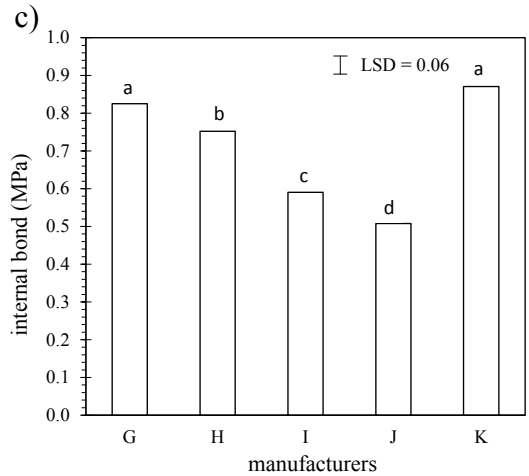


b)

Means with the same letter in the t-Grouping are not significantly different at $\alpha = 0.05$

t Grouping	Mean Density	N	Manuf. & Surface
a	1126	40	G-S2
a	1125	40	G-S1
b	1097	40	H-S1
c	1053	40	H-S2
c	1038	40	K-S2
c	1032	40	K-S1
d	985	40	I-S1
d	976	40	J-S1
d	974	40	I-S2
e	950	40	J-S2

c)



d)

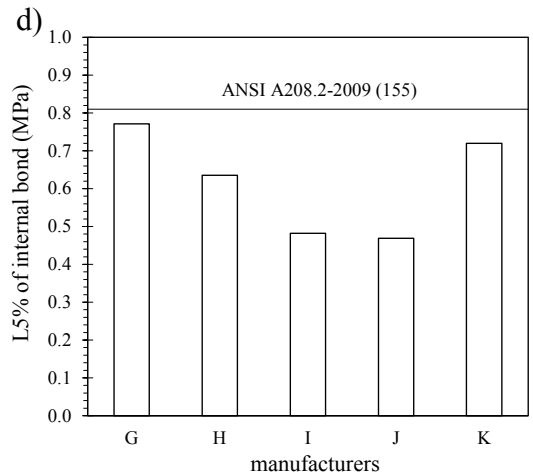


Figure 23: The *(a)* VDP, expressed as the means of peak density surface 1 (S1), core density averaged over a 6mm zone (C), and peak density for surface 2 (S2) for the five tested MDF sets and *(b)* the significance grouping for the peak density. The means are sorted from highest to lowest. Note: The letters in the t-Grouping do not correspond with the letters for the manufacturers. The *(c)* means for IB strength for the five MDF manufacturers, each mean representing 40 replicates. The horizontal line *(d)* indicates the minimum IB value, required to meet the voluntary ANSI A208.2-2009.

Except for Manufacturers G and K, all manufacturers showed significantly different IB strengths (Figure 23c), ranging from 0.5 MPa (Manufacturer J) to 0.87 MPa (Manufacturer K). Similar to the tested PB samples, the CVs for IB were high, between 10.5% (Manufacturer G) and 19.5% (Manufacturer J).

The known correlations between density and IB for PB apply to MDF as well. Manufacturer K, with the highest SG, also had the highest IB. Manufacturer J with the lowest IB did not show the lowest SG but had the lowest CD. Visually comparing IB and CD Figure 23a and c show an overall good relation between the two properties. Nevertheless, none of the tested MDF panels complied with the voluntary ANSI A208.2-2009 standard for 155 grade MDF (Figure 23d). A closer look at the VDP reveals significant differences in PFD between the two faces (S1 and S2) for Manufacturers H and J. Figure 24 compares the plotted VDPs of one sample for each manufacturer.

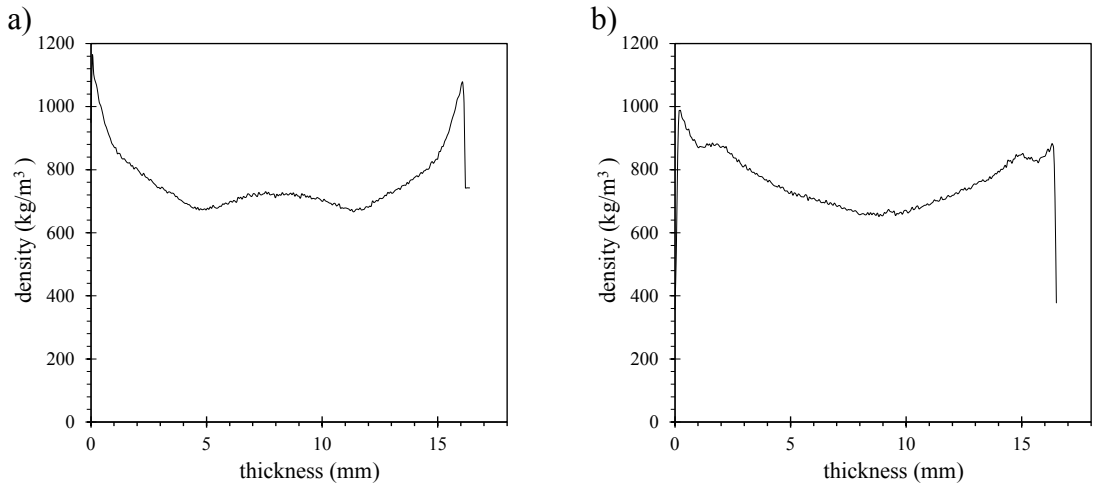
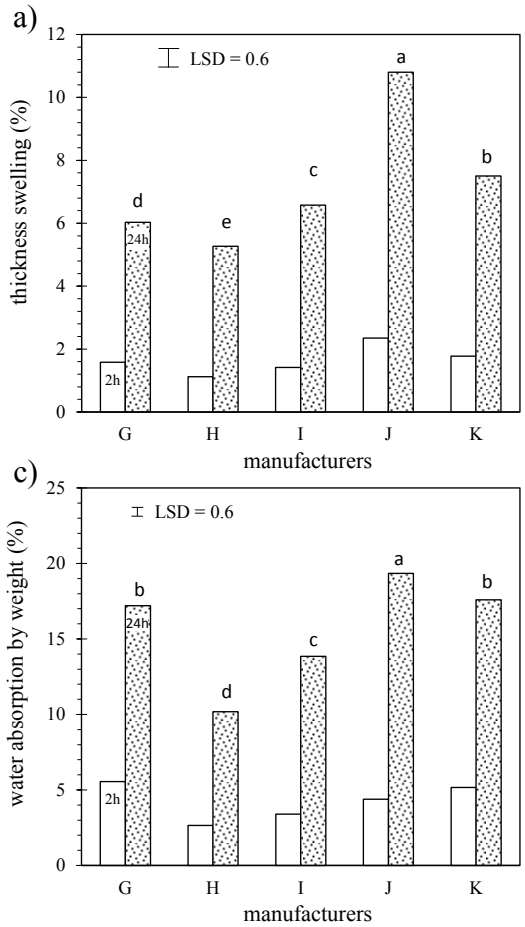


Figure 24: Comparison of typical VDP plots from *(a)* manufacturer H and *(b)* manufacturer J. Manufacturer H has a more symmetrical VDP.

PFDs of the two faces, yet significantly different, are more pronounced for Manufacturer H (Figure 24a) than for Manufacturer J. Overall, the shape of Manufacturer H's VDP is more symmetrical. Similar to PB, possible reasons for the inconsistent VDPs include differences between furnish parameters, excessive sanding, springback of the mat while the press opens (Wang et al. 2004), resin distribution, or resin pre-cure (Xing et al. 2004).

4.4.2.2 Thickness Swell and Water Absorption

Thickness swelling, as shown in Figure 25a, is based on the conditioned sample thickness and represents the swelling in percent after 2 and 24 hours. It ranged from 5.3% for Manufacturer H to 10.8% for Manufacturer J. Coefficients of variance were between a low of 4.5% (Manufacturer I) to a high of 6.5% (Manufacturer K). All means were significantly different. Figure 25b shows the upper 95th percentile of the normally distributed TS in accordance with ANSI A208.2-2009 (155). All manufacturers, except Manufacturer J were well below the recommended maximum value for TS.



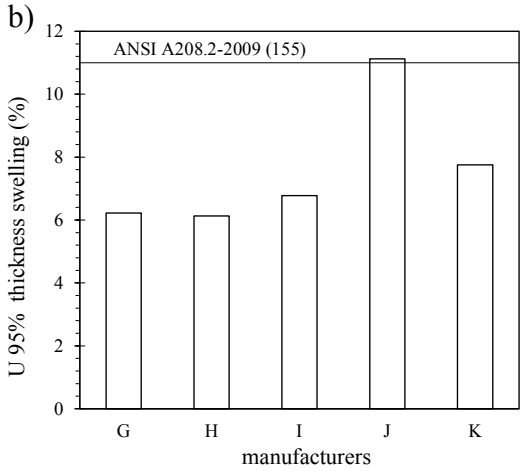


Figure 25: The *(a)* mean values for TS after 2 and 24 hours, the *(b)* upper 95th percentile of the normally distributed TS values with the horizontal line representing the ANSI recommended value, and the *(c)* WA after 2 and 24 hours. Means with the lower case letter are not significantly different at α= 0.05.

Water absorption, based on initial conditioned sample weight, is shown in Figure 25c. All manufacturers, except Manufacturer G and K, were significantly different. Manufacturer J had the highest WA (19.3%) and Manufacturer H the lowest (10.2%). The variation of panels from the same manufacturer was up to 100% higher than for TS, with CVs ranging from 5.7% (Manufacturer G) to 12.9% (Manufacturer K).

To better understand and compare the results, Table 7 presents an overview of the known parameters for the boards of each manufacturer.

Table 7: Comparison of known parameters of the five evaluated MDF manufacturers

Property	Manufacturer				
	G	H	I	J	K
CD (kg/m^3)	691.8	693.5	671.5	669.4	715.8
SG	700.9	677.3	664.0	691.9	713.9
Wood species	Spruce (10%) Pine (80%) Fir (10%)	Spruce, Pine, Fir, Oak, Maple, Birch, Aspen, Cedar	Pine, Spruce, Fir, Maple, Birch, Oak, Poplar	n.a.	Lodgepole Pine, Douglas Fir, Larch
Resin type/ Resin content	pMDI/n.a.	UF/12.3% (od)	UMF/n.a.	n.a.	MUF/UF (face/core) 9 - 11% (od)
TS - 24h (%)	6.0	5.3	6.6	10.8	7.5
WA - 24h (%)	17.2	10.2	13.8	19.3	17.6

As expected, Manufacturer G, using pMDI resin, showed low TS. It is known that pMDI resins perform better in regards to dimensional stability (Pilato, 2010; Pizzi & Mittal, 2003). However, Manufacturer H, using UF resin, had the lowest TS. Papadopoulos (2006) investigated and compared the performance of PB bonded with pMDI and UF resins. He found that boards made with UF resin content above 10%, had roughly the same TS as pMDI-bonded boards with a resin content of just above 3%. Papadopoulos concluded that in order to achieve similar board properties using UF and pMDI resins, the latter could be used at a considerably lower dosage.

A clear trend can be observed, when comparing TS and WA of Manufacturers H to K. Higher TS corresponded with higher WA.

4.4.2.3 Linear Expansion

Machine direction only had a significant effect on Manufacturer K. Linear expansion parallel to machine direction for this manufacturer was the lowest at 0.16%. Manufacturer G had the highest mean LE of 0.27%. Coefficients of variance ranged from 8% (Manufacturer $G_{\perp}$) to 18.5% (Manufacturer $I_{\parallel}$). A comparison of all means can be found in Figure 26.

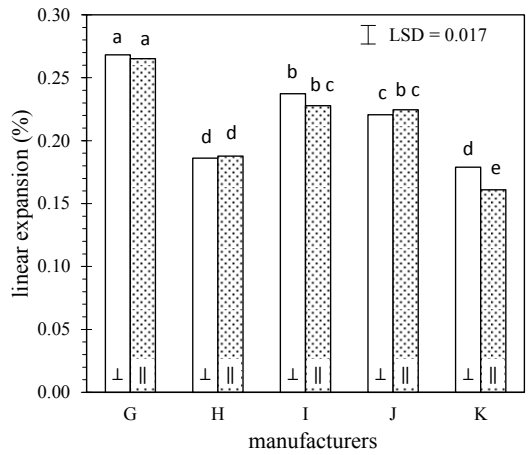


Figure 26: Mean LE values. Each pair of columns represents one manufacturer and the two sample orientations tested ($n_{\perp} = 40$, $n_{\parallel} = 40$). Means with the same lower case letter above the column are not significantly different at $\alpha = 0.05$ (a = highest mean, e = lowest mean).

Similar to the test procedures for PB, the results here are based on a RH change from 50% to 90%. Therefore results were not compared to the ANSI standard. Interestingly, Manufacturer G, using pMDI, had the highest LE. Xu and Suchsland (1991) explain LE in MDF, similar to solid wood, by swelling in the cell walls. In this study, no correlation was found between density and LE, which agrees with Xu and Suchsland (1997) but contradicts with Ayrilmis (2007), who found a significant relationship between density and LE and TS for MDF and High Density Fiberboards (HDF). The 11mm thick boards were manufactured (dry process)

using industrial sized equipment with a mix of beech and pine fibres, UF resin (RC = 10%, based on oven-dry fibre weight), and target densities of 720, 760, and 800 kg/m^3 for the MDF panels. Linear expansion and contraction, and TS and thickness shrinkage increased with increasing density. Similar to the results presented in our study, values for TS were higher than LE values. Complex correlations between input, output and process parameters, some of which are unknown for this study, make it difficult to compare the analysed manufacturers and draw final conclusions.

4.4.2.4 Screw Withdrawal Resistance

4.4.2.4.1 Face Screw Withdrawal Resistance

The highest mean value for fSWR was 1540 N for Manufacturer G and CVs ranged between 4 and 7% (Table 6). Manufacturer I with the lowest mean fSWR of 1201 N was the only manufacturer that did not comply with the voluntary ANSI standard (Figure 27b). As illustrated in Figure 27a, mean values for Manufacturers G and K, and for Manufacturers H and J were not significantly different.

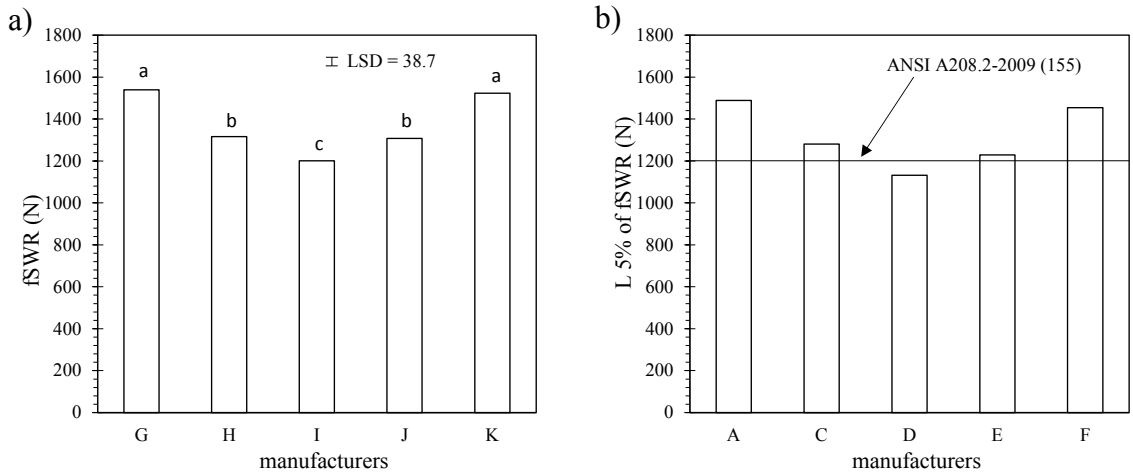


Figure 27: The *(a)* mean fSWR values. Each column represents one manufacturer (n = 40). Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$ (a = highest mean, c = lowest mean). The *(b)* lower 5th percentile of the fSWR values distribution in accordance with ANSI A208.2-2009.

A correlation similar to that of PB between PFD and fSWR was not found, but there was a trend that showed an increased fSWR with increasing SG. A possible explanation is that the surface layers of MDF are thinner than those of PB, due to the higher compaction ratio (Xu and Winistorfer, 1995). Comparing the results of IB and fSWR, a similar trend can be observed. Higher IB lead to higher fSWR. It should also be mentioned that Manufacturer G, using pMDI (Table 7), had the highest fSWR. The combination of a mechanical and chemical bond of pMDI-bonded panels makes it possible to manufacture high strength boards at a significantly lower resin content (Papadopoulos, 2006). Manufacturer K that showed similarly high values for fSWR, uses a combination of MUF/UF at resin contents between 9 – 11%. The high fSWR can likely be attributed to the significantly higher SG (Figure 22b).

4.4.2.4.2 Edge Screw Withdrawal Resistance

Similar to the evaluated PB panels, machine direction had no significant effect on eSWR. Measured values for each sample were averaged across machine direction and re-analyzed. Figure 28a and b show the means and ANSI standard comparisons.

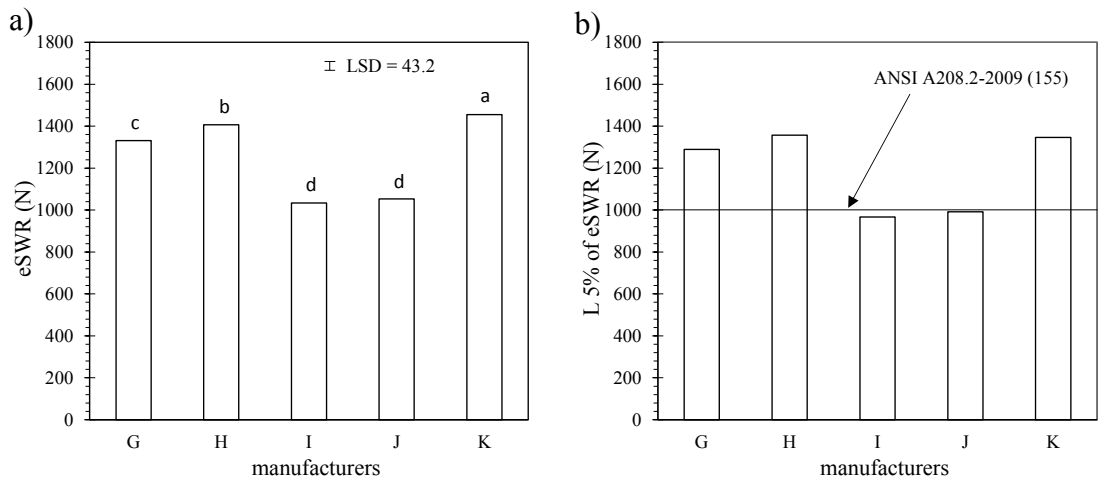


Figure 28: The eSWR for the evaluated MDF manufacturers. The *(a)* mean values (n=40). Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed eSWR, presented in accordance with the new ANSI standard from 2009.

Except for Manufacturers I and J, all manufacturers had significantly different mean values for eSWR. Manufacturer K had the highest value of 1455.7 N (CV = 7.3%) and Manufacturer I the lowest with 1033.9 N (CV = 5.7). Manufacturers I and J did not meet the recommended ANSI value of 1001 N for the lower 5th percentile of a normally distributed eSWR. When comparing eSWR and CD (Figure 22b) a clear trend can be observed. Higher CD corresponds to higher eSWR. Interestingly, Manufacturer H has higher eSWR than fSWR. Possible reasons include densification of the core furnish, the asymmetrical VDP (Figure 23a and Figure 24a) that might have negatively influenced the fSWR, and furnish composition.

4.4.2.5 Modulus of Rupture and Modulus of Elasticity

The results for the mean comparison of MOR (Figure 29a) were more complex than for the previously discussed MDF properties. Mean values ranged from a maximum of 31.6 MPa (Manufacturer $G_{\perp}$) to a minimum of 20.2 MPa (Manufacturer $I_{||}$).

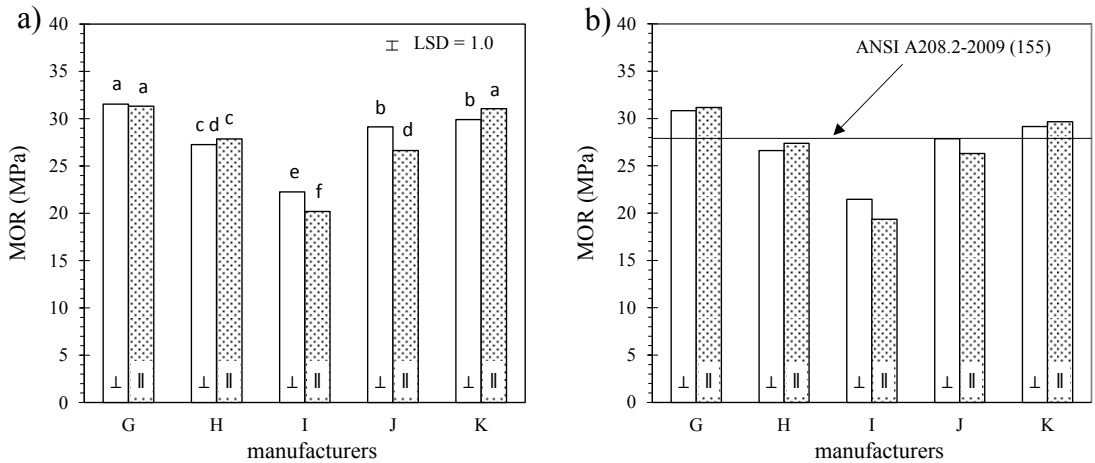


Figure 29: The MOR for the evaluated MDF manufacturers for both machine directions. The *(a)* mean values (n=40) for MOR of each manufacturer. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed MOR, presented in accordance with the new ANSI standard from 2009.

Only Manufacturer G and K exceeded the ANSI standard, whereas the remaining three manufacturers did not meet the voluntary standard. Manufacturer J had the highest CVs for both machine directions (⊥ = 13.1%, || = 11.1%) and Manufacturer G the lowest (⊥ = 4.8%, || = 3.5%). The relatively high CVs for Manufacturer J explain the larger difference between the mean values (Figure 29a) and the values for the lower 5th percentile (Figure 29b).

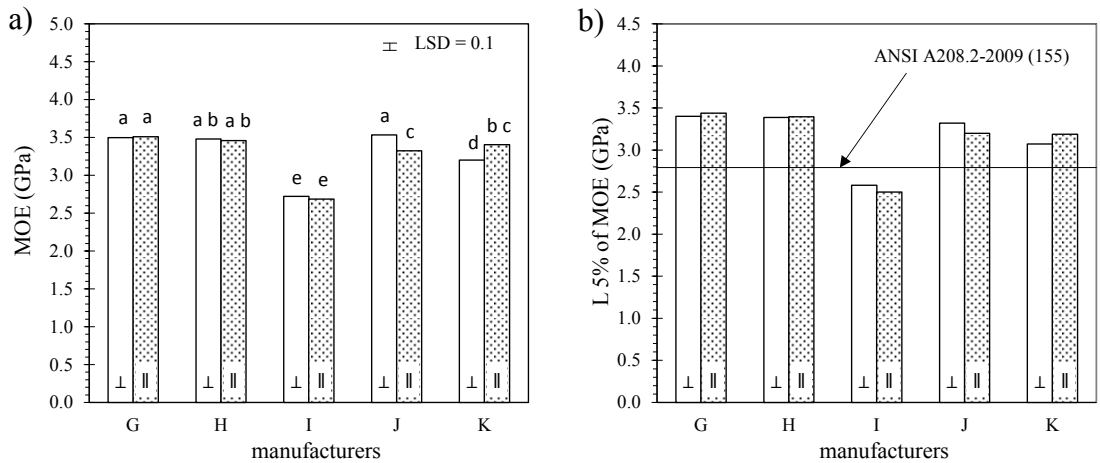


Figure 30: The *(a)* mean MOE values for both machine directions for each manufacturer. Means with the same lower case letter above the columns are not significantly different at $\alpha = 0.05$. The *(b)* lower 5th percentile of the normally distributed MOE, presented in accordance with the new ANSI standard from 2009.

Means for MOE showed a similar trend as MOR, but had fewer differences in regards to machine direction. It had no significant impact on Manufacturers G, H, and I. Further, means for Manufacturers $G_{\perp, \parallel}$, $H_{\perp, \parallel}$, and $J_{\perp}$ were not significantly different. Figure 30a and Table 6 show the detailed comparison of the means for each manufacturer and machine direction. Mean values ranged from 2.7 GPa (Manufacturer I) to 3.5 GPa (Manufacturers G and H). Coefficients of variance showed very similar results. The highest CVs were found for Manufacturer J for both machine directions ($\perp$ = 10.5%, $\parallel$ = 10.7%) and the lowest for Manufacturer G ($\perp$ = 4.8%, $\parallel$ = 3.9%). In contrast to MOR, only Manufacturer I did not comply with the ANSI standard (Figure 30b).

Manufacturer G had the highest MOR and MOE values, similar to other mechanical properties. As discussed earlier for other properties, it is likely that this can be partly attributed to the use of pMDI. Lee et al. (2012) studied the effects of different mole ratios of UMF resin on MDF properties and compared them to boards bonded with UF. They

concluded that UMF bonded panels had similar mechanical properties. Comparing the different resin systems in this study, it is known that Manufacturer H used UF at 12.3% (od), Manufacturer I UMF at unknown resin content and Manufacturer K MUF/UF (face/core) at 9 - 11% (od). It was observed that Manufacturer I had the lowest bending strength properties, but complex interactions between unknown parameters such as resin content, press schedule, and exact furnish composition make it difficult to determine the definite factors that are responsible for the here presented results.

5 Conclusions

The evaluation of M2 grade particleboard samples from five North American manufacturers showed significant variations in physical and mechanical properties. Four out of five manufacturers exceeded the voluntary ANSI a208.1-2009 standard for IB and three out of five complied with the standard for fSWR. All PB manufacturers failed to meet the recommended value for eSWR, neither ANSI a208.1-1999 nor ANSI a208.1-2009. For MOR, no sample set reached the ANSI a208.1-1999 but one manufacturer met the recommended value of the newer revised ANSI a208.1-2009 standard. Results for MOE showed three out of five manufacturers complying with both standards. Panels from one manufacturer showed consistently lower strength properties, as well as a higher dimensional instability. The same manufacturer also had the highest CVs for all evaluated physical and mechanical properties and significantly asymmetrical VDPs.

Variations between properties of MDF manufacturers were similar. None of the five tested sample sets reached the recommended ANSI a208.2-2009 value for IB. Mean values for TS were all significantly different and one manufacturer did not comply with the standard. Similar to the test procedures for PB, LE was evaluated for a RH change from 50% to 90%. Therefore results were not compared to the ANSI standard. Three manufacturers exceeded the recommended values for fSWR, one was equal to, and one failed to meet the requirements. For eSWR, three manufacturers exceeded the standard, and the remaining two were below the standard. Two manufacturers met the standard for MOR and only one manufacturer failed to meet it for MOE. A trend was observed for the manufacturer that used pMDI resin. As expected, this manufacturer showed consistently some of the highest mean

values for MOR, MOE, fSWR, IB, as well as good performance for the TS test. Surprisingly, LE values were significantly higher than all other manufacturers.

Results from the industry survey showed a shift in resin systems from UF to pMDI, MUF/UF and NAUF resins to comply with the more stringent formaldehyde emissions regulations such as CARB.

It became clear that the use of a CNC router significantly reduced the processing time to cut the samples. Depending on the number of samples, project investigators should consider employing this technique to minimize the time spent on labor intensive tasks such as sample preparation.

In conclusion, it can be said that even though some manufacturers did not meet the appropriate voluntary ANSI standards, it is clear that these manufacturers are still competitive in the wood composites market and are able to sell their products. Especially the results from property tests such as MOR or eSWR in this study suggest that the recommended ANSI values may be set too high. Further, some test procedures (e.g. linear expansion) described by the ASTM put the tested boards far beyond their intended use and increase the testing time and cost significantly. Revising the values and testing procedures, or creating sub-categories for PB and MDF grades for specific target groups could offer a solution to a more transparent and competitive wood composites market.

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Appendices

Appendix A: Online Questionnaire

The online questionnaire for the industry survey was created using the online survey software “SurveyMonkey” (www.surveymonkey.com). Each participant was provided with an individual link via email to access the survey online. Through this method the investigator was able to see which participant had completed the survey. Another advantage was that it simplified the evaluation of the results. Below is shown the survey as it could be seen on the website.

Confidentiality: You can be assured of complete confidentiality. The identity of all participants shall remain confidential. This means that your responses will be confidential. We will make every effort to ensure that information is not reported in a manner that will identify the participants.
The online survey is hosted by http://www.surveymonkey.net/ which is located in the United States. The survey is configured in a way that will not capture the IP address of your computer. The security and privacy policy for the web survey company can be found at the following link: http://www.surveymonkey.net/privacypolicy.aspx
All survey records will be stored on password-protected computers at the University of British Columbia, Faculty of Forestry. Greg Smith and Jörn Dettmer are the only individuals who will have access to these files.

1. Where is your manufacturing plant situated?

2. What types of panel products do you produce at your mill and which thicknesses are the most common ones?

3. What are principle applications for your products?

4. What is your plants total production per annum?

5. What are expected product trends in the future?

6. Who are your main customers?

7. Where do you get the furnish or do you produce it in-house? If so, how?

8. What wood species are being used in the furnish?

9. Depending on the panel product, what are the particle/fibre sizes of the furnish?

particle/fibre size (please include product type):	
Outer layers (where applicable):	
Core layer (where applicable):	

10. What is the moisture content of the furnish and how do you store it?

11. What is the age of the furnish/What is the maximum storage time?

12. Resin costs - Please check one option:

- Resin costs are a major (>50%) part of raw material costs
- Resin costs are a moderate part (10% - 50%) of raw material costs
- Resin costs are a minor part (<10%) of raw material costs

13. What types of resin do you use and which one is most commonly used?

14. How much resin do you use per year for each of your panel products?

15. What resination system do you use?

16. Are you considering other resination systems?

- No
- Yes. Please explain

17. Do you verify the efficiency of the resination (particle/fibre coverage)?

- No
- Yes. Please explain what method you are using.

18. Have you used imaging technologies to analyze the resination?

- No
- Yes. Please explain what imaging technology is employed.

19. Do you think the resination process can be improved?

- No
- Yes. Please explain.

20. Is the cleaning process of the resinator of concern?

- ○ No
- ○ Yes. Please explain

21. Do you do in-house testing for panel properties?

- ○ No
- ○ Yes. Please name the properties you test in-house.

22. How frequently do you test the panel properties?

- ○ N/A
- ○ We test...

23. Based on your experience, which board properties are most correlated to the resin content?

- ☐ Face screw holding
- ☐ Edge screw holding
- ☐ Internal bond
- ☐ Thickness swell
- ☐ Modulus of Rupture
- ☐ Modulus of Elasticity

24. Please rate how important the following items are to your company:

	not important	of interest	important	very important
Knowledge of the relationship between internal bond and edge or face screw holding ability?	○	○	○	○
Knowledge of how the resin is distributed to the furnish?	○	○	○	○
Measurement of the resin content and the distribution in the resonated furnish?	○	○	○	○
Measurement of the resin content and the distribution in the finished board?	○	○	○	○

25. What parameters can be controlled during the resination process?

- ☐ Resin flow rate
- ☐ Additive flow rate
- ☐ Resin solid content percentage
- ☐ Moisture Content
- ☐ Steam pressure (for blowlines)

Other (please specify)

Appendix B: Survey Report

The following survey report presents the results from the industry survey that was performed between June and August 2011.

Survey report: Resin efficiency for Particleboard and MDF

Jörn Dettmer & Gregory D. Smith
Department of Wood Science
University of British Columbia

1. Introduction

1.1. About the project

This survey is part of a research project that is investigating the resin efficiency for non-structural panels. The project is funded by the Wood Based Composites Center (WBC). This consortium is a National Science Foundation Industry/University Cooperative Research Center. The project is in collaboration with the Oregon State University, Corvalis, OR.

The goal of the proposed research is to identify variables controlling resin consumption in non-structural panels (PB and MDF), investigate their effects on panel quality and to investigate methods for improving resin efficiency in these products.
1) Perform a survey of products, processing sequences (blender and former types), and post treatments in use in North American PB and MDF plants.
2) Measure the critical benchmark properties for each board type across different plants and manufacturers for typically production run panels. The properties in question include internal bond strength (IB), in-plane elastic modulus (E), in-plane strength characteristics in tension or bending, resistance to nail and screw withdrawal, dimensional stability, regulated emissions, and machinability
3) Collaborate with interested manufacturers on plant specific methods for marking resins and extraction of furnish samples for the resin micro-distribution to be investigated using various imaging techniques. The micro-distribution of resin will be examined in unconsolidated, resinated furnish mates and in board samples.
4) Correlate the resin content and distribution characteristics in furnish and panels to the properties characterized in step 2).
5) Make recommendation on the most effective ways of increasing resin efficiency in panel products manufacturing.

1.2. About the survey

According to various sources, there are 63 MDF and Particleboard plants that are operated in Canada and the United States. As of today, 5 of the 63 plants are closed.
Several attempts were made to contact each individual plant (telephone and email). 31 plants agreed to participate in the survey, all of the participants requested the online survey oppose to do a telephone interview. To create the questionnaire, the online survey software "SurveyMonkey" was used.
31 survey requests were sent to 16 MDF and 15 PB plants across Canada and the United States. 19 plants completed the survey between June 29th, 2011 and August 12th, 2011.

2. Results

The results in this report were randomized. Each question was randomized individually. Therefore the numbers that are assigned to the answers do not represent a certain company. An online software (RANDOM.ORG) was used for the randomization. RANDOM.ORG is a true random number service that generates randomness via atmospheric noise (for more information visit https://www.random.org/faq/). The data for each question was submitted individually through a secure ssh encrypted connection. In order to keep the confidentiality, certain questions were removed.
The following are the questions as they appeared in the questionnaire that was sent out and the respective answers.

1. Where is your manufacturing plant situated?
Removed due to confidentiality

2. What types of panel products do you produce at your mill and which thicknesses are the most common ones?

1. Particleboard, NAUF Particleboard 3/4" and 1-1/8"
2. 8' wide Decking. 5/8" and 3/4" most common.
3. Particleboard-- 5/8 11/16 3/4 1 Door core--1 1/8 and 1 1/2
4. MDF, 17MM
5. Medium Density Fiberboard 2.5mm to 3/4" (42pcf to 57pcf) 6mm - most common thickness
6. Door skins. 0.115"
7. We produce thin MDF 3mm thick is the most common thickness
8. Particleboard 3/8 - 1 1/8
9. TMDF, mostly around 3mm thick.
10. MDF...5/8 through 3/4"
11. Medium-lower density fiberboard. 5/8" 3/4"
12. Interior and exterior MDF boards 1/8"-3/8" thick

13. MDF, range from 6mm to 1.5" Most common size is 5/8 and 3/4" Lamination of our product.
14. MDF Door skins ~.120"
15. MDF, HDF 6.00mm up to 31.75mm, Average 17mm
16. PB - 5/8"
17. All panel products are rated for exterior exposure with a nominal thickness of 7/16". Building materials (soffit, trim, shutters, utility siding panels, and garage door panels and inserts)
18. Particle Board: 1/2" to 1 3/16" but 5/8 and 3/4 are most common
19. MDF & HDF: 3.0 mm - 25.4 mm Highest volume range is 5.6 mm - 7.8 mm.

3. What are principle applications for your products?

1. door skins, drawer bottoms, backers
2. raised panel doors, moulding, cabinetry
3. Furniture and interior doors
4. Manufactured home floors.
5. Lamination, Fixtures, Shelving, Stepping, misc OEM
6. Door skins, substrate for various laminating processes, furniture (drawer bottoms, cabinet backs, etc).
7. Moulding and sheet stock
8. Moulding, cabinets, furniture, millwork
9. Interior doors
10. Interior, exterior, and garage doors
11. No response
12. Furniture (house and office)
13. Flooring, Flat-Pack & Case Goods Furniture, Misc. Industrial Applications
14. Office Furniture and Counter Tops
15. RTA Furniture and Counter Tops
16. Furniture, Cabinets, Flooring, Moulding, Shelving
17. Interior applications - Furniture, Cabinets, Countertops, Flooring, Mouldings, Hardwood Plywood (veneers), Wall panels
18. Resins, wax
19. Interior molded doors

4. What is your plants total production per annum?

1. Running at 7% capacity with a ceiling of 24 MM surface feet.
2. 160MM sq ft 3/4" basis
3. 50K - 150K MSF
4. 51.6 million MSF (5/8" basis)

5. No response
6. 5-10 million skins
7. $26M
8. 84,000,000 sq ft 3/4" basis
9. Approx. 250,000 m3.
10. With the current market conditions, we are only running about 95 million feet per year.
11. 125,000,000 to 180,000,000 sq. ft on 3/4 basis
12. 100M sqft
13. 240 million sq ft, 3mm thickness basis
14. 400 000 m^3 (on full production basis)
15. 25 millon sq. ft. on 3/4 base
16. about 150 MMSF, 1/8" basis
17. 135000 m^3 per year
18. Up to 43,000,000'
19. 2010 - 72,000 MSF (3/4" basis)

5. What are expected product trends in the future?

1. No response
2. NAF, NAUF, Moisture resistant, Fire retardant
3. Lower density, "flaked core"
4. With particleboard, the customers still want the lowest cost board that fills their needs
5. Anticipate joint efforts with customers to produce effective, but lower specification panels due to marketplace cost pressures. Also expect to see more diverse product requirements in the next 3-5 years.
6. Minor - no change
7. Low formaldehyde emitting
8. No major changes
9. We will produce floor decking and only decking in the future. Housing is expected to remain slow for 2-3 years
10. Smooth skins of various patterns
11. No response
12. Unknown
13. increased variety of laminated materials
14. Green - Non Formaldehyde
15. Garage door panels
16. light panels for furniture (i.e. honey comb cored composite), NAF products

17. Expecting to make more thin board than thick board in the future (<12mm)

18. Most applications follow housing starts.

19. More exterior grade product- both garage and exterior doors

6. Who are your main customers?

1. No response
2. Colledgewood (doorskins), TP (ply veneer), MJB, Holland
3. Ashley Furniture, Alexandria Moulding, Sauder Woodworking
4. Laminators, Fixtures, OEMs
5. Stevens Ind, Funder, Dixyply, VTI
6. Kitchen companies
7. Internal Customers
8. Distributors, Cabinet manufacturers, Flooring manufacturers
9. Manufactured home builders
10. JELD-WEN
11. Sauder, VTI, RSI
12. Kronotex USA, Shaw Inc., Faus Group, Inc., Ashley Furniture, Standard Furniture, Sauder Woodworking.
13. building material distribution centers, internal customers, and licensees
14. Mostly North American customers - furniture producers, cabinet producers, flooring producers, moulding producers, hardwood plywood (veneers) producers, distributors
15. furniture manufacturers
16. Company making the furniture (Quebec, Ontario and North of USA)
17. No response
18. Interior door plants, Amarr garage doors
19. Moulders and distributors

7. Where do you get the furnish or do you produce it in-house? If so, how?

1. In house. Refiners
2. All our furnish comes from planner residuals,
3. Our fiber is 100% in house and 100% green chips.
4. From sawmill residuals
5. Sawmills
6. Chipped veneer cants - Columbia Forest Products and Weyerhaueser
7. Local mills
8. Regional window and door manufacturers.
9. Purchased from saw mills
10. We purchase all furnish.
11. Northwest
12. Surrounding saw mills

13. Sawmill Shavings, Saw Dust, Ply-Trim, Recycled Wood
14. Local saw/lumber mills and other local suppliers.
15. Shavings and sawdust is purchased from local planer mills and sawmills
16. Surrounding sawmills
17. Waste from a lumber mill
18. From saw mill around the plant
19. mostly public land in chip form - some off of private land

8. What wood species are being used in the furnish?

1. Douglas Fir, White Fir, Cedar, Pine
2. Spruce, pine
3. Black spruce Jack pine Birch Douglas Fir
4. 100% hardwood chips (mostly maple, birch and beech - on occasion poplar)
5. Pine
6. Pine
7. Multiple species, including a mix of hardwood and softwood species. The mix is controlled.
8. Mostly Southern Yellow Pine, but some mixed hardwoods
9. Pine and Fir
10. Doug fir and redwood
11. Oak pine and popular
12. Spruce, Pine, Fir, Oak, Maple, Birch, Aspen, Cedar
13. pine, spruce, fir, maple, birch, oak, poplar
14. Douglas Fir
15. Southern yellow pine
16. Spruce (approx 10%) Pine (approx 80%) Fur (approx 10%)
17. Southern yellow pine
18. 100% green Douglas Fir
19. Yellow Poplar

9. Depending on the panel product, what are the particle/fibre sizes of the furnish?

1. No Response
2. Outer layers (where applicable): - Fines, 80 mesh

   Core layer (where applicable): - core, 8-35 mesh
3. Particle/fibre size (please include product type): - n/a - do not measure

   Outer layers (where applicable): N/A - single former head
   Core layer (where applicable): N/A - single former head
4. Particle/fibre size (please include product type): - 1/4" all products

5. 5/16 to 1/16

6. Particle/fibre size (please include product type): - MDF/HDF : 0.60 to 0.80 mm avg. length

7. No Response

8. Outer layers (where applicable): - 7 Mesh-1.2%, 12 Mesh-12.1%, 14 Mesh-9.1%, 20 Mesh-29.6%, 35 Mesh-21.5%, 100 Mesh-23.3%, Pan-3.2%

   Core layer (where applicable): - 7 Mesh-16.7%, 12 Mesh-22.9%, 14 Mesh-8.9%, 20 Mesh-19.9%, 35 Mesh-14.0%, 100 Mesh-15.5%, Pan-2.1%
9. Particle/fibre size (please include product type): - less than 0.5" by less than 0.006"

10. 3-7% Shives (Shive is greater than 0.008")

11. Small, fine fibers up to about 1/2" in length in all products (homogeneous)

12. Particle/fibre size (please include product type): - Sieve size 20 is dominate, with few smaller and fewer larger

    Outer layers (where applicable): - all homogenious on one press, other is fines face course back
    Core layer (where applicable): - all homogenious on one press, other is fines face course back
13. Particle/fibre size (please include product type): - PB : Surface layers (2x) and Core layer Outer layers (where applicable): - Fines : average 0.5 mm

    Core layer (where applicable): - Chips : average 1.8 mm
14. No Response

15. Particle/fibre size (please include product type): - individual fibers to dust Outer layers (where applicable): - individual fibers to dust Core layer (where applicable): - individual fibers to dust

16. Particle/fibre size (please include product type): - In order of finest to coarsest fiber grind: Deep Routing Grade; MDF; Furniture Grade HDF; Flooring HDF. We have data on the particle size, but it is influenced by multiple factors.

17. Particle/fibre size (please include product type): - Chips, sawdust, shavings

18. No Response

19. Particle/fibre size (please include product type): - 20% above 16 mesh, 80% under

    Outer layers (where applicable): - 12% above 16 mesh, 88% under
    Core layer (where applicable): - 27% above 16 mesh, 83% under

10. What is the moisture content of the furnish and how do you store it?

1. 12 - 15%. Stored inside buildings.
2. The fiber moisture content ranges from 9.0 % - 11.0 % dependent on product requirements and is not stored.
3. 30 to 50%, stored unheated inside and outside
4. 50% to 100%, stored in a wood yard
5. Sawdust: 50% Shavings: 12%
6. 70% TO 8% In a dry shed and on a pad
7. Green - 100% Silos
8. We have dry furnish (~3-5% moisture) and wet furnish (~15-30% moisture).
9. 5% moisture Temperature-controlled warehouse
10. Shavings: 12% Saw dust: 45% PlyTrim: 9% Recycled Wood: 9%
11. 45-55%
12. 40-55%, Stored in barns and outside in elements
13. In coming is 30-40% stored under roof
14. Varies depending on season between 35% and 55% wet basis - stored outside
15. 10%. Doffing roll bins.
16. NA
17. 15%- silo
18. 45 - 55%, stored inside
19. Shavings approx 20%MC Sawdust approx 50%MC Stored inside building (excess stored outside)

11. What is the age of the furnish/What is the maximum storage time?

1. NA.
2. <30 minutes.
3. 0-13 months. Maximum approximately 13 months.
4. 1 day to 3 weeks.
5. Prefer all furnish to be fresh. Shavings last longer with lower MC, sawdust cannot be stored as long. Storage time depends on many factors - inside or outside, ambient temperature, weather conditions.
6. 4 to 6 weeks, maximum 3 months.
7. Up to 6 months.
8. 8-12 minutes.
9. A few weeks with maximum of three months.
10. Age is typically 1 to 2 weeks old. Can store the higher moisture material up to about two months. Dry material can be stored indefinitely.
11. Up to one week old not sure on storage but ~ one month before degradation.
12. 30 days.
13. Fresh furnish, maximum 1 year.
14. Within 1 month and 3 months.
15. It is used anywhere from right off the truck to several weeks.

16. 30-60 days max.
17. 2 weeks can be storied up to 2 years.
18. Unknown. 1 week.
19. Typically 7 to 10 days old.

12. Resin costs - Please check one option:

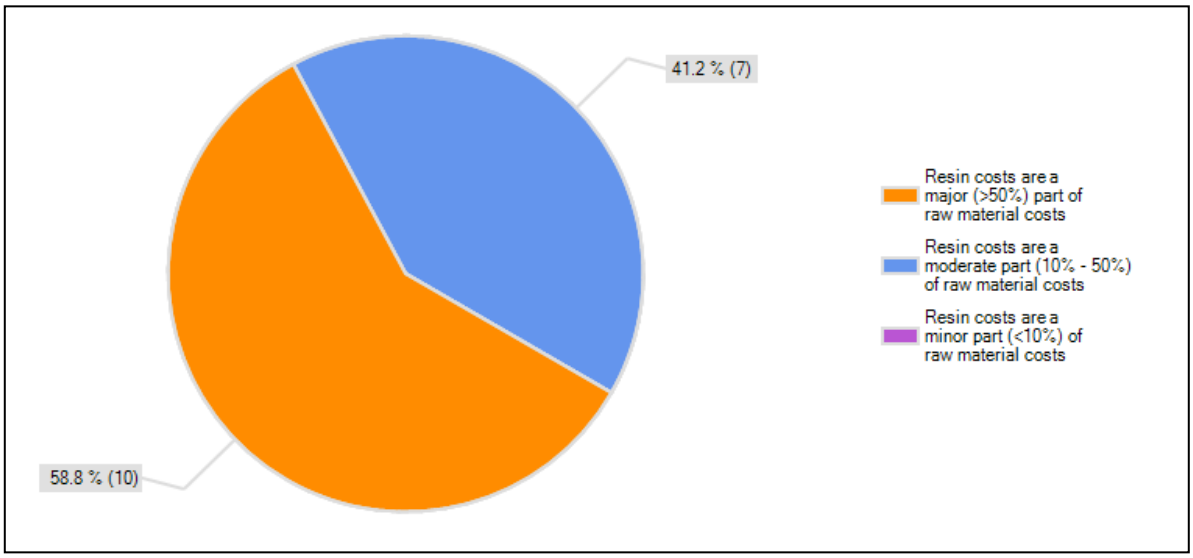


Figure 31: Resin costs. Note: 2 Participants skipped the question.

13. What types of resin do you use and which one is most commonly used?

1. Particleboard - MUF face and UF core (most common) NAUF - MUF
2. UF, Melamyn, MUF, Phenolic, and MDI. MDI is most common.
3. MUF in surface layers UF in core layers
4. Melamine/Urea Formaldehyde
5. pMDI with catalyst
6. MDI and UF. MDI is the most commonly used 2009-2011 UF most commonly used 1996-2008
7. Phenolic Resin
8. Urea-Formaldehyde (main), Melamine-Urea-Formaldehyde, Phenolic-Formaldehyde
9. UF, fortified UF proprietary
10. Face: Melamine-Urea Formaldehyde Core: Urea Formaldehyde
11. melamine
12. UF
13. Urea Formaldehyde
14. Urea-Formaldehyde & Melamine-Urea-Formaldehyde thermosetting resins.
15. UMF
16. MDI
17. Exclusively UF resin.
18. MUF UF MF

19. pMDI

14. How much resin do you use per year for each of your panel products?

1. No response
2. 8.5% of the core wood weight
3. No response
4. PB: roughly 40,000,000 pounds at 65% solids
5. No response
6. No response
7. 70,000,000 lbs annually for all products
8. MDI 2-4% on oven dried fiber UF 8-14% on oven dried fiber
9. 12,000 ODT total
10. 2010 usage = 900,000 lbs
11. 1.5 million pounds
12. No response
13. About 15 million pounds for the mill.
14. 18,000,000 to 20,000,000 lbs/yr
15. Too many kind of panel products, we have an average of 55 kg/m³
16. No response
17. 400000 gal.
18. about 345 lbs solids per MSF
19. approx 2,000,000 lbs, or 916,363 kgs

15. What resination system do you use?

1. Drais KTTP 350
2. Both blowline and after drier resination
3. Blowline nozzles
4. Blender,
5. Blowline blending resin injection before the dryers
6. Blowline blending (steam atomized application in the blowline)
7. Atomizing nozzles, with mechanical blending.
8. Custom dry resination system
9. Littleford blenders
10. Attrition mill blending
11. Nozzles in Littleford blenders
12. Injection into blowline
13. Littleford Core Blender GT Zesor Face Blender "In-House" Addition
14. Steam injection nozzles in blow line
15. Blender
16. Multiple injection in turbo blender
17. Heated air atomized spray system with two stage blending
18. Resin guns in a chute preceding an attrition mill blender

19. Custom system.

16. Are you considering other resination systems?

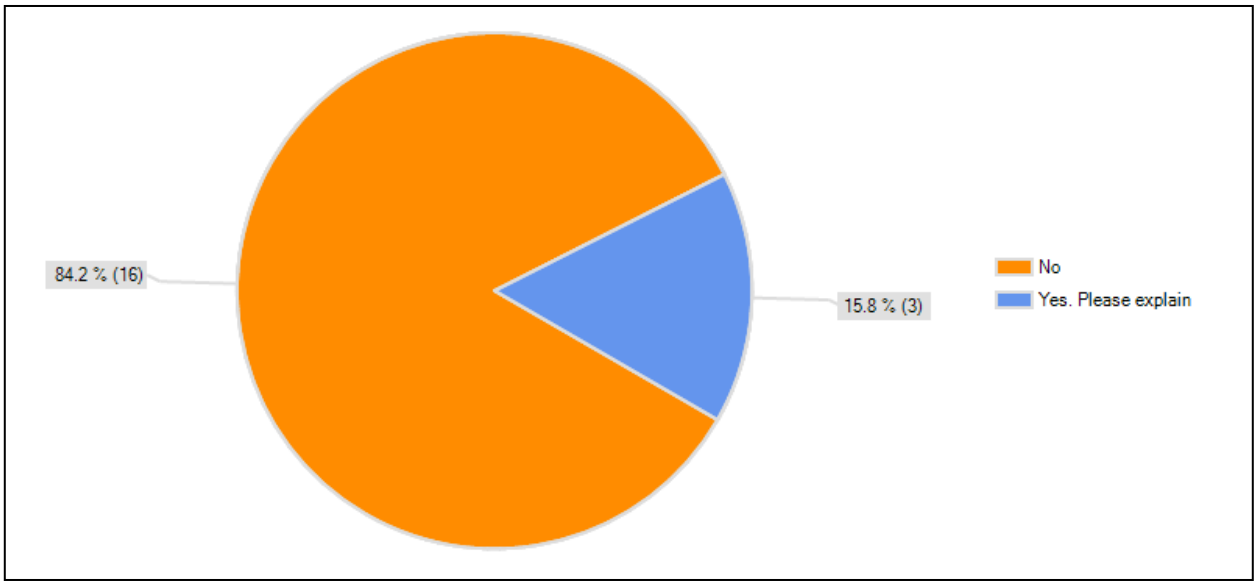


Figure 32: Other resination systems?

Participant: Yes. Always considering different resin systems as new technologies become available.
Participant: Yes. Please explain - Shrink nozzle system.
Participant: Yes. Proprietary info - cannot disclose.

17. Do you verify the efficiency of the resination (particle/fibre coverage)?

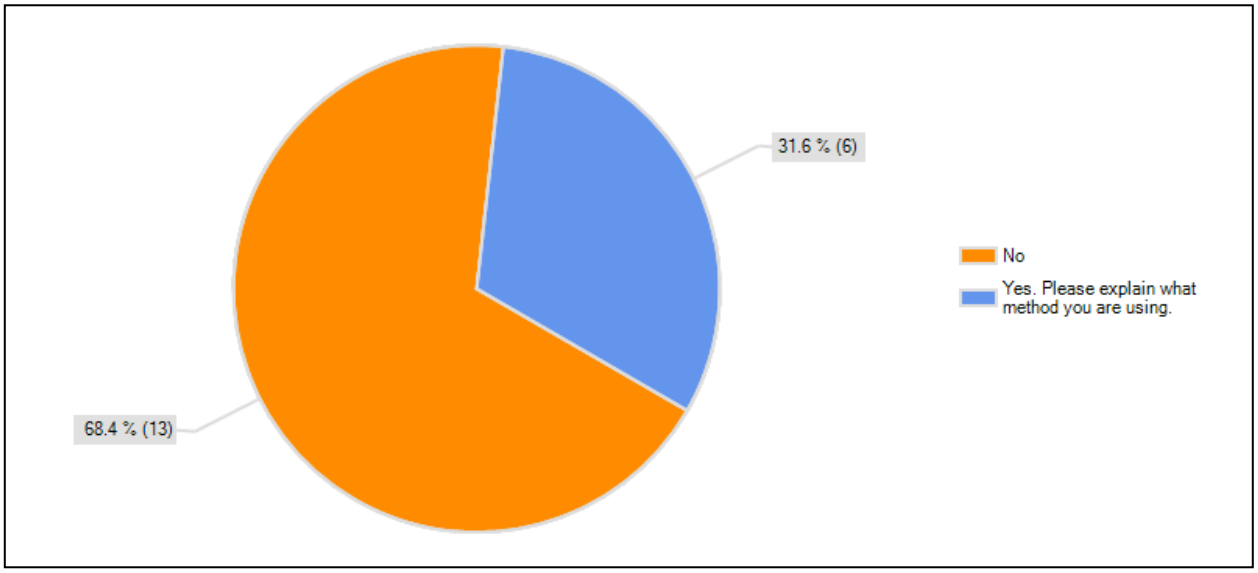


Figure 33: Verification of the resination efficiency.

Participant: Yes. Resin pumped into a static blender and then into Littleford blender through several tubes. Blending time is controlled by the pressure on the outfeed chute
Participant: Yes. We use internal and external testing measures to ensure proper resination.
Participant: Yes. Test are made external institute
Participant: Yes. NIR analysis developed through FP Innovations. Also monitor resin flow to ensure setpoints are being met
Participant: Compare target usage to actual usage
Participant: draw-down comparisons

18. Have you used imaging technologies to analyze the resination?

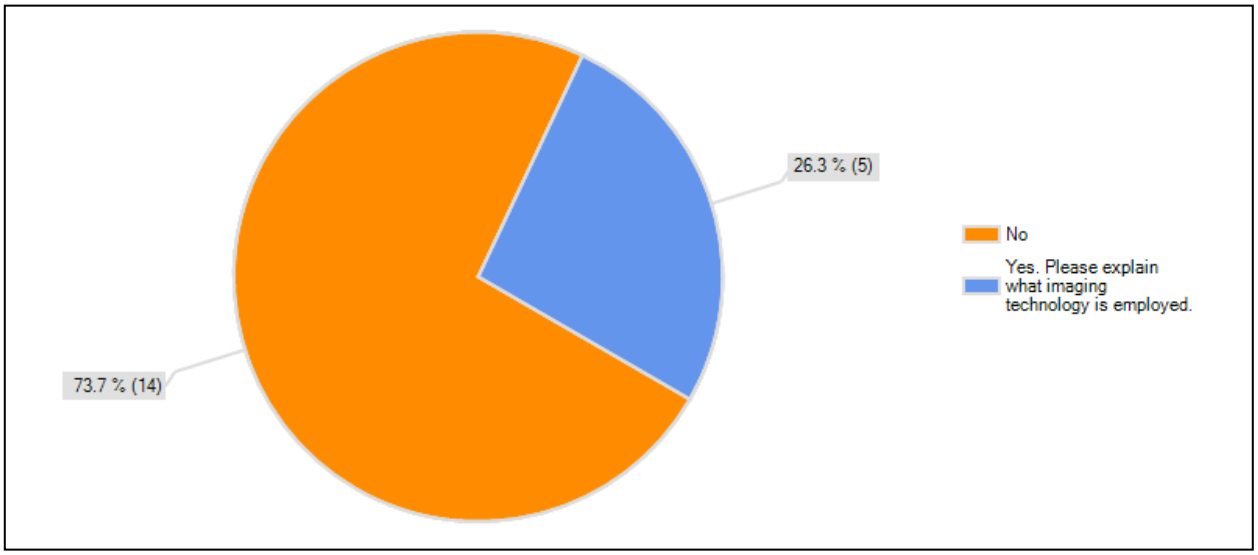


Figure 34: Imaging technologies.

Participant: Yes. High resolution microscope images. Uses dye that interacts with the UF resin to highlight the coverage.
Participant: Yes, dye based testing.
Participant: Yes, have had analysis performed by third party lab.
Participant: Yes, Blue marker technology using x-ray (FP Innovations)
Participant: Yes, our R&D group had a university do some imaging.

19. Do you think the resination process can be improved?

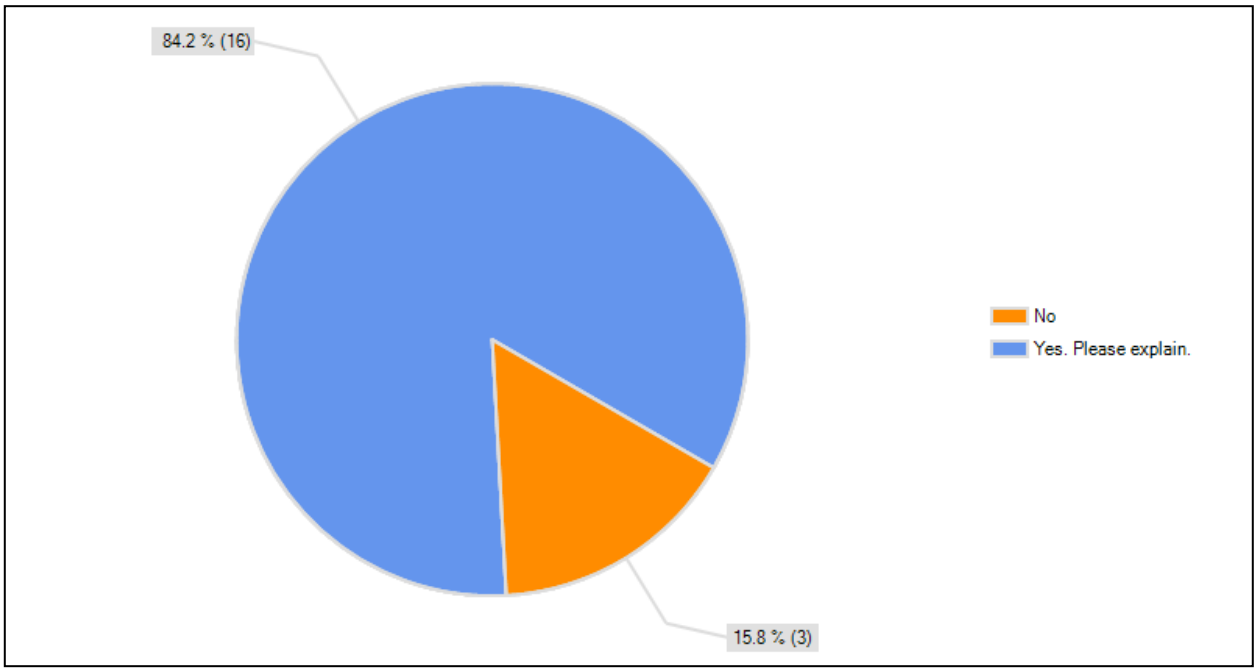


Figure 35: Improvement of resination process.

1. Always room to improve distribution and efficiency
2. Possibly through different application areas in the blowline.
3. No Response
4. Anything can be improved
5. Depends on available technology.
6. It could/should be studied and I don't know that it has been done.
7. It’s not perfect
8. reduce resin pre-cure in dryer system
9. No Response
10. I do not know if my blenders are optimized for efficiency.
11. Resination after drying
12. Finding ways to improve homogeneity
13. In order to improve efficiencies, it must be improved
14. split flows with two blenders and two separate addition rates relating to chip geometry
15. better atomization
16. There is always room from improving the resination process. Better resin distribution provides a more consistent product and allows for resin add-on decreases which is financially beneficial.
17. New system of resination are avalaible on the market
18. No Response
19. Evaluating a different size blowline to improve distribution.

20. Is the cleaning process of the resinator of concern?

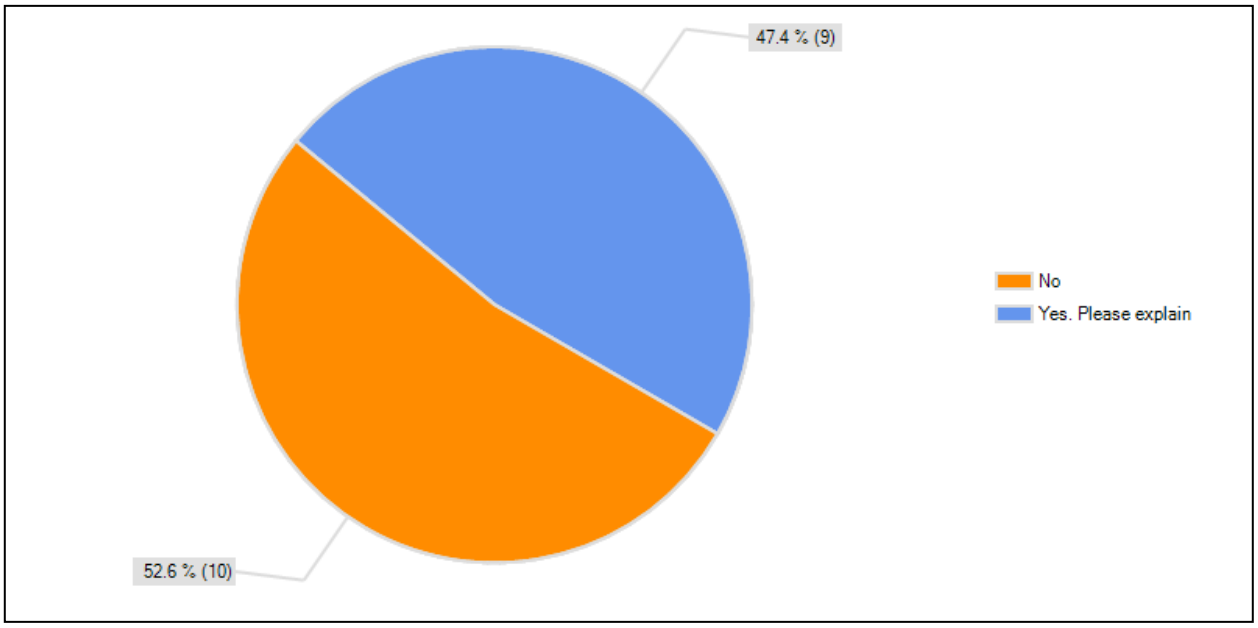


Figure 36: Cleaning of the resinator.

1. Yes sometimes we have build up inside the blenders
2. sometimes we have build up in the air transport system
3. risk of sensitization to MDI
4. Occasional clogging of the nozzles
5. weekly cleaning
6. Resin can build up in the blowline causing restrictions (requiring downtime for cleaning), poor resin distribution and quality problems. MDI tends to build up more in the blowlines that UF.
7. Not of concern
8. Not of concern
9. Not of concern
10. Substantial downtime cleaning blending system
11. Occasionally resin nozzles will become plugged
12. Not of concern
13. Need to keep pipes clean
14. Not of concern
15. Not of concern
16. Not of concern
17. Not of concern
18. Not of concern
19. Not of concern

21. Do you do in-house testing for panel properties?

All participants answered the question with YES

22. How frequently do you test the panel properties?

1. A LOT
2. Hot tests consist of IB, MOR, MOE and VDP and are run on every product change and every two hours of long runs. Finished board tests comprise most of the res of the tests and are run on matching samples of hot tests and are run on two tests per day.
3. Daily
4. Every lot
5. About once every 1.5 to 2 hours.
6. 3 or more times per 8 hr shift of production
7. No Response
8. Every two hours or every product change, or every major process change
9. QC - every 2 hours or every size change QA - minimum one/day, varies depending on QC values and products produced
10. minimum 4 tests per days for mechanical properties and 3 tests per days for formaldehyde emission
11. every 4 hours
12. each shift
13. Frequency varies based on product. Multiple times daily.
14. Multiple times daily depending on the test
15. every 2 hrs for bond, every 8 hrs for full ANSI testing.
16. lots
17. every 4 hours typically
18. Hourly. What I would like to know is how to reduce Linear Expansion and swell when my exterior MDF gets wet. This is a huge issue.
19. During building material runs, we test once per shift

23. Based on your experience, which board properties are most correlated to the resin content?

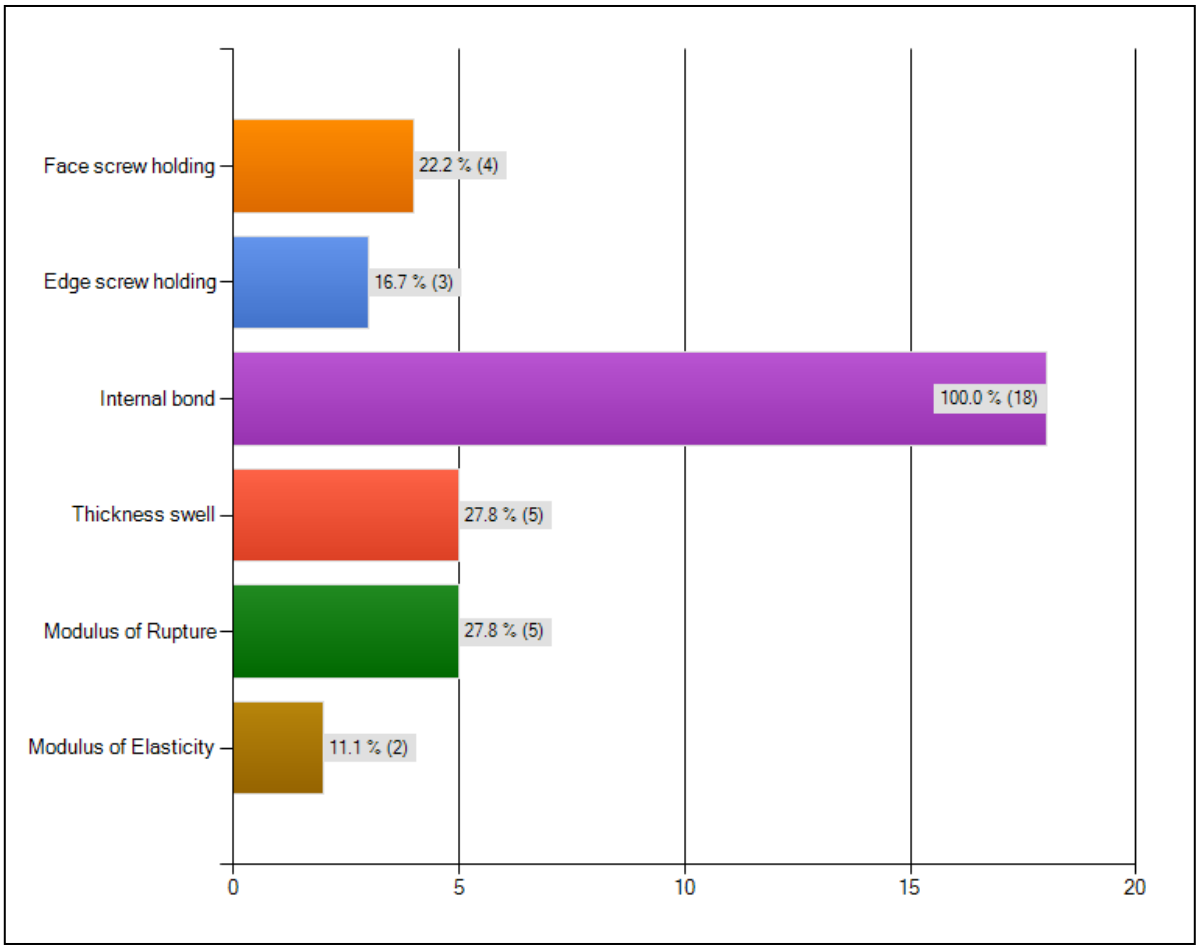


Figure 37: Correlation between board properties and resin content. Note: 1 Participant skipped the question.

24. Please rate how important the following items are to your company

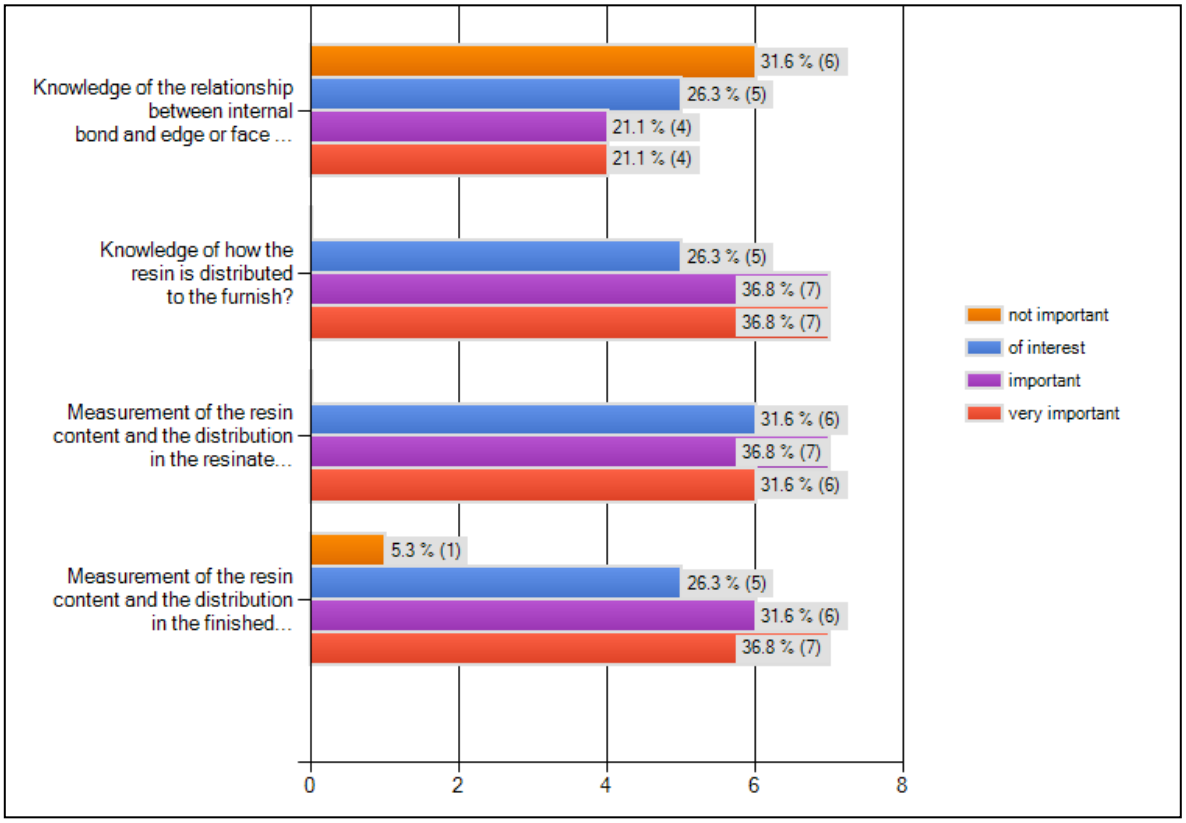


Figure 38: Importance of various properties.

25. What parameters can be controlled during the resination process?

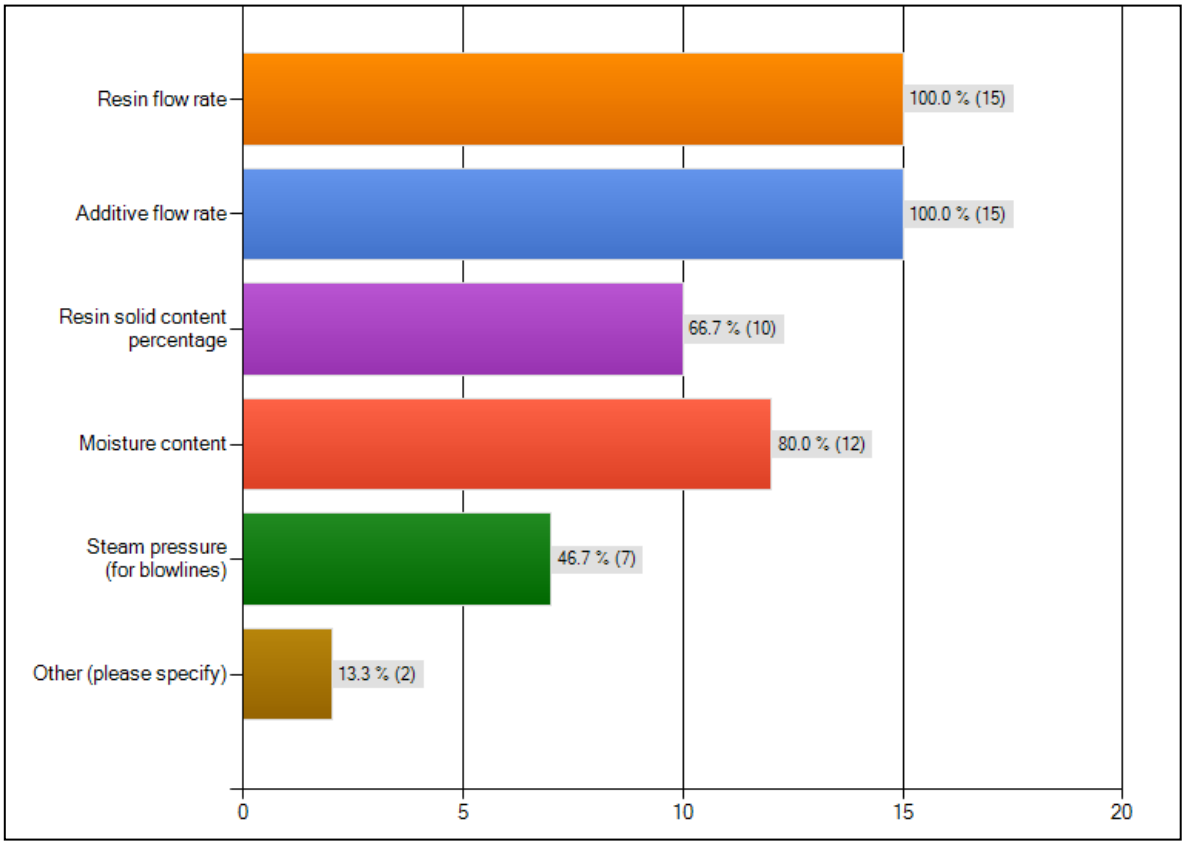
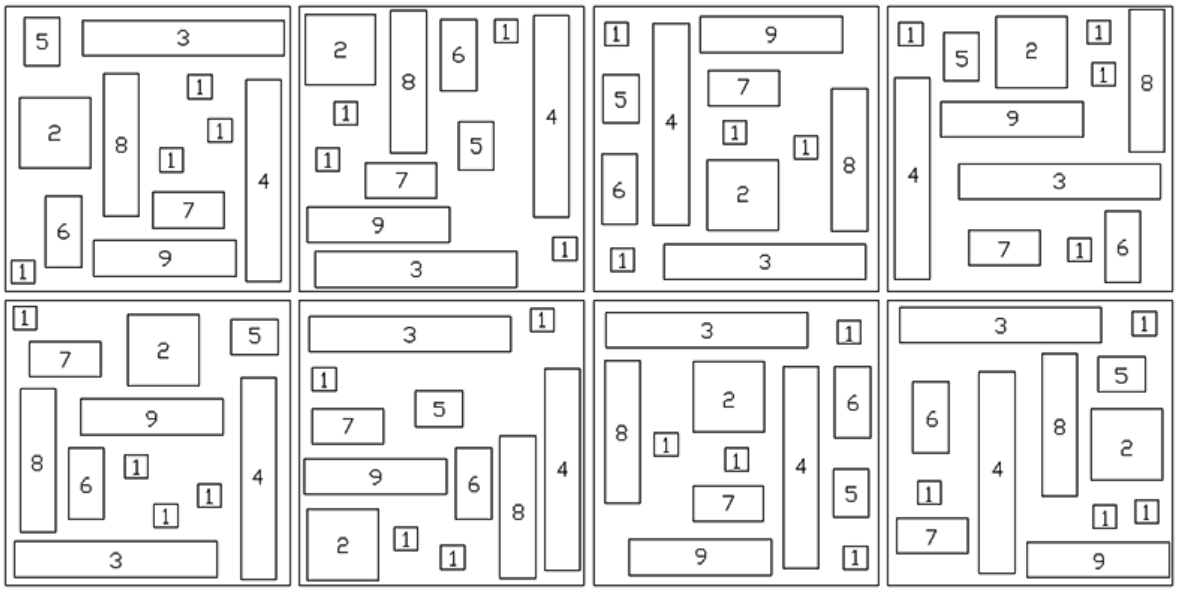


Figure 39: Control parameters for resination process. Note: This question was added while the survey was already in progress. It was not presented to the first 4 participants.

Participant: Other - furnish (fractionated wood flow)
Participant: Other - Resin temperature (important for MDI)

Appendix C: Cutting Patterns

The drawing below shows the schematic layout of the eight different cutting patterns that were used to cut the specimens for the various mechanical and physical tests for the properties comparison of the tested particleboard and MDF from ten North American manufacturers. The table shows the corresponding specimen IDs.



Property	Specimen ID	Number of samples per		
		Manufacturer	Panel	Sub-panel
IB & VDP	1	40	8	4
Thickness Swelling (TS)	2	40	8	1
MOE/MOR ‖	3	40	8	1
MOE/MOR ⊥	4	40	8	1
fSWR	5	40	8	1
eSWR ‖	6	40	8	1
eSWR ⊥	7	40	8	1
Linear Expansion ‖	8	40	8	1
Linear Expansion ⊥	9	40	8	1

Appendix D: Pearl Script for VDP Data Extraction

The following Pearl script was written to analyze the raw data file from the vertical density profiler.The script was programmed to extract the peak face densities (PFD) for both surfaces, average calculated density, average measured density, mid-panel density (at 8.1mm), and calculate the average core density (CD) for a defined zone and its standard deviation.

```
#!/usr/bin/perl
#
# Script to extract maximum at top and bottom, and mean
# density in [6.54,9.54] with standard deviation of mean
# in that range.
#
use strict;
use warnings;
use Scalar::Util qw(looks_like_number);

my ($foo,$bar,$denave,@values,@den,@res,@res2);
my $pattern = "dat";            # File extension
my $pattern2 = "Sample Name:";  # Match for sample name
my $pattern3 = "5.0400";        # Low depth for density average
my $pattern4 = "11.0400";       # Hi depth for density average
my $pattern6 = "10.0000";       # Range for bottom max value
my $pattern7 = "3.0000";        # Range for top max value
my $pattern5 = "Zone, Average";

opendir(CURRENT,".");
my @files = grep(/$pattern/,readdir(CURRENT));
closedir(CURRENT);

foreach my $file (@files){

    open my $info, $file or die "Could not open $file: $!";

    print "\n";
    print "$file\n";
    my $iwrite = 0;my $icount = 0;my $barsum = 0;my $izone = 0;
    my $denmx1 = 0;my $denmx2 = 0;
    while( my $line = <$info>)  {
        chomp($line);$line=~ tr/\015//d;
        ($foo, $bar) = split(',', $line);
        ## Write max values for last sample (already been through loop
once):
        if($line =~ /$pattern2/){
          if($denmx2 > 0){
            print "Maximum Density 1,",$denmx1,"\n";
            print "Maximum Density 2,",$denmx2,"\n";
```

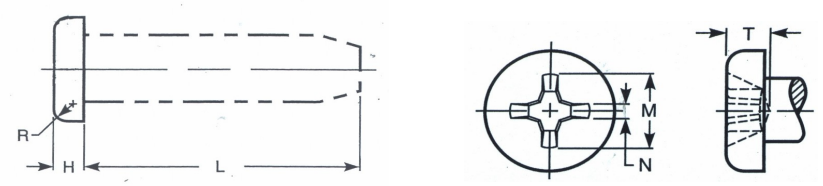
```
            $denmx1 = 0;$denmx2 = 0;
          }
          print "\n";
          ## Write sample name:
          print "$line\n";
        }
        if(looks_like_number($foo)){
          if($foo >= $pattern3 and $foo <= $pattern4){
            $iwrite = 1;
            $barsum = $barsum + $bar;
            $den[$icount] = $bar;
            $icount++;
            if($foo == $pattern4){
              ## Density average:
              $denave = $barsum/$icount;
              ## Compute std dev over depth interval (clumsy):
              my $idx = 0;
              for ( @den ) {$res[$idx] = $den[$idx] - $denave;$idx++;}
              $idx = 0;
              for ( @res ) {$res2[$idx] = $res[$idx]**2;$idx++;}
              my $sum = 0;
              for ( @res2 ) {$sum += $_;}
              my $std = $sum / $icount;
              $std = $std**(0.5);

              print "Density average, $denave\n";
              print "Density stddev, $std\n";
              $barsum = 0;
              $icount = 0;
            }
          }else{
            $iwrite = 0;
          }
          if($foo < $pattern7){
            if($bar > $denmx1){
              $denmx1 = $bar;
            }
          }
          if($foo > $pattern6){
            if($bar > $denmx2){
              $denmx2 = $bar;
            }
          }
        }

        #last if $. == 2;
    }
    ## Write max values for Batch average:
    print "Maximum Density 1,",$denmx1,"\n";
    print "Maximum Density 2,",$denmx2,"\n";
    close $info;
}


#EOF
```

Appendix E: Details on Sheet Metal Screw for SWR

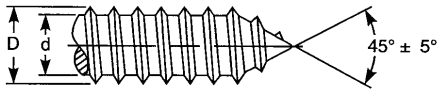
Technical information on the screws that were used for the screw withdrawal resistance tests according to ASTM 1037 - 06A.

FASTENAL

Sheet Metal Screw, Pan Head Cross Recessed Drive, Type AB, 18-8 Stainless Steel
The information below lists the required dimensional, chemical and physical characteristics of the products in this purchase order. If the order received does not meet these requirements, it may result in a supplier corrective action request, which could jeopardize your status as an approved vendor. Unless otherwise specified, all referenced consensus standards must be adhered to in their entirety.



Size	A		H		R	M	T	N	
	Head Diameter		Head Height		Head Radius	Recess Diameter	Recess Depth	Recess Width	Recess Penetration
	Max.	Min.	Max.	Min.	Min.	Ref.	Ref.	Ref.	Min / Max
10	.373	.357	.133	.122	.020	.192	.112	.031	0.098 / 0.124



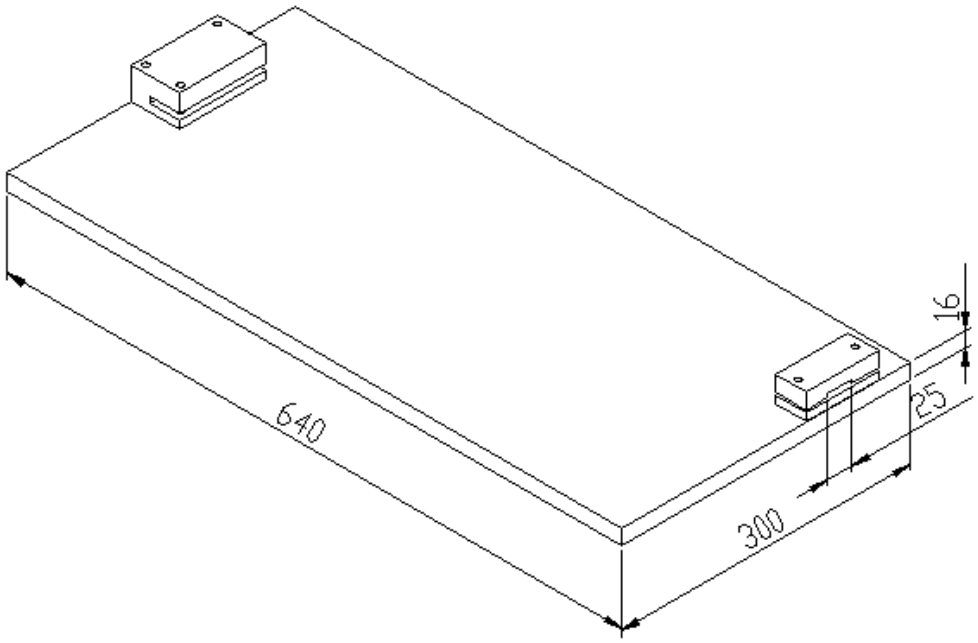
Nominal Size	Threads per Inch	D		d	
		Major Diameter		Minor	
		Max.	Min.	Max.	Min.
10	16	0.189	0.182	0.141	0.135

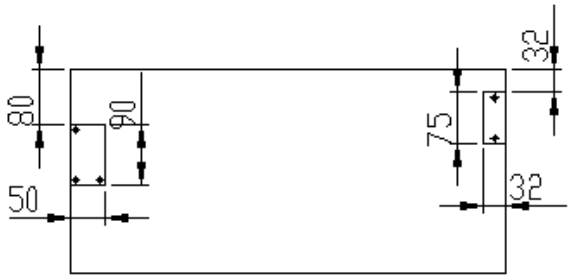
Specification Requirements:

- Dimensions: ASME B18.6.3.
  All sizes are fully threaded
- Drive Style: Cross Recessed, (Type 1)
- Material: 18-8 Stainless Steel.
- Thread requirements: Rolled Thread Screws per ASME B18.6.3, Type AB.
  (ANSI/ASME Designation Type AB)
- Finish: Per ASTM A380.

Appendix F: Schematic Drawing of Linear Expansion Gauge

Schematic drawing of the custom-made jig to measure the linear expansion.





Appendix G: Results for Multiple Means Comparison

In this appendix the multiple means comparison for the statistical analysis are shown for the performed physical and mechanical test.

Moisture Content

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.610019
Critical Value of t	2.08596
Least Significant Difference	0.3643

Means with the same letter are not significantly different.				
t Grouping		Mean	N	manuf
	A	12.0411	40	A
	A			
B	A	11.7484	40	F
B				
B		11.4338	40	C
	C	10.9207	40	E
	C			
	C	10.8858	40	D

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.860513
Critical Value of t	2.08596
Least Significant Difference	0.4327

Means with the same letter are not significantly different.				
t Grouping		Mean	N	manuf
	A	10.7131	40	K
	A			
B	A	10.3820	40	J
B	A			
B	A	10.3208	40	I
B				
B		10.0387	40	G
	C	8.9253	40	H

Specific Gravity

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	845.3806
Critical Value of t	2.08596
Least Significant Difference	13.562

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	709.875	40	D
B	639.745	40	A
B			
B	626.877	40	C
C	603.625	40	F
C			
C	596.012	40	E

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	92.01002
Critical Value of t	2.08596
Least Significant Difference	4.4741

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	713.943	40	K
B	700.873	40	G
C	691.912	40	J
D	677.256	40	H
E	663.959	40	I

Internal Bond

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.004962
Critical Value of t	2.08596
Least Significant Difference	0.0329

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	0.52964	40	D
A			
A	0.51591	40	F
A			
A	0.50419	40	A
A			
A	0.50291	40	E
B	0.31969	40	C

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.018474
Critical Value of t	2.08596
Least Significant Difference	0.0634

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	0.87047	40	K
A			
A	0.82494	40	G
B	0.75223	40	H
C	0.59053	40	I
D	0.50777	40	J

Edge Screw Withdrawal Resistance

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	7593.334
Critical Value of t	2.08596
Least Significant Difference	40.645

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	777.18	40	D-PP
A			
A	769.88	40	A-PP
A			
A	746.68	40	E-PP
B	638.80	40	F-PP
C	596.71	40	C-PP

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	8565.844
Critical Value of t	2.08596
Least Significant Difference	43.169

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	1455.69	40	K
B	1406.50	40	H
C	1331.45	40	G
D	1053.18	40	J
D			
D	1033.93	40	I

Face Screw Withdrawal Resistance

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	12373.02
Critical Value of t	2.08596
Least Significant Difference	51.884

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	1181.93	40	D
B	1085.28	40	E
B			
B	1037.30	40	A
C	883.95	40	F
D	776.23	40	C

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	6893.825
Critical Value of t	2.08596
Least Significant Difference	38.728

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	1539.50	40	G
A			
A	1523.03	40	K
B	1315.70	40	H
B			
B	1307.55	40	J
C	1200.90	40	I

Modulus of Rupture

PB

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	1.66953
Critical Value of t	2.02108
Least Significant Difference	0.5839

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	14.0147	40	E-PP
A			
A	13.8542	40	E-P
B	12.6379	40	D-P
B			
B	12.4290	40	D-PP
C	11.7203	40	A-P
D	11.0345	40	F-P
D			
D	10.6053	40	F-PP
D			
D	10.5717	40	A-PP
E	9.4947	40	C-PP
E			
E	9.3564	40	C-P

MDF

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	4.861309
Critical Value of t	2.02108
Least Significant Difference	0.9964

Means with the same letter are not significantly different.				
t Grouping		Mean	N	manuf
	A	31.5531	40	G-PP
	A			
	A	31.3313	40	G-P
	A			
	A	31.0688	40	K-P
	B	29.9022	40	K-PP
	B			
	B	29.1406	40	J-PP
	C	27.8550	40	H-PP
	C			
D	C	27.2631	40	H-P
D				
D		26.6343	40	J-P
	E	22.2570	40	I-P
	F	20.1947	40	I-PP

Modulus of Elasticity

PB

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	0.044494
Critical Value of t	2.02108
Least Significant Difference	0.0953

Means with the same letter are not significantly different.

t Grouping		Mean	N	manuf
	A	3.07228	40	E-PP
	B	2.80680	40	E-P
	B			
	B	2.76085	40	D-P
	B			
	B	2.74312	40	D-PP
	C	2.44554	40	A-P
	D	2.20991	40	A-PP
	D			
E	D	2.13995	40	F-P
E	D			
E	D	2.11978	40	C-P
E				
E		2.06628	40	F-PP
	F	1.95507	40	C-PP

MDF

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	0.036032
Critical Value of t	2.02108
Least Significant Difference	0.0858

Means with the same letter are not significantly different.

t Grouping		Mean	N	manuf
	A	3.53451	40	J-PP
	A			
	A	3.50964	40	G-P
	A			
	A	3.49681	40	G-PP
	A			
B	A	3.47835	40	H-P
B	A			
B	A	3.45877	40	H-PP
B				
B	C	3.40303	40	K-P
	C			
	C	3.32263	40	J-P
	D	3.20224	40	K-PP
	E	2.72105	40	I-P
	E			
	E	2.68415	40	I-PP

Linear Expansion

PB

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	0.005343
Critical Value of t	2.02108
Least Significant Difference	0.033

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	0.87010	40	C-PP
B	0.79365	40	C-P
C	0.69789	40	A-PP
D	0.64890	40	D-P
D			
D	0.64648	40	D-PP
E	0.54089	40	A-P
E			
E	0.54006	40	F-PP
F	0.48281	40	F-P
G	0.34363	40	E-P
G			
G	0.31622	40	E-PP

MDF

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	0.001376
Critical Value of t	2.02108
Least Significant Difference	0.0168

Means with the same letter are not significantly different.				
t Grouping		Mean	N	manuf
	A	0.268212	40	G-PP
	A			
	A	0.265079	40	G-P
	B	0.237413	40	I-P
	B			
C	B	0.227759	40	I-PP
C	B			
C	B	0.224501	40	J-P
C				
C		0.220591	40	J-PP
	D	0.187672	40	H-PP
	D			
	D	0.186181	40	H-P
	D			
	D	0.178795	40	K-PP
	E	0.160876	40	K-P

Thickness Swelling (after 24h)

PB

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	8.663582
Critical Value of t	2.08596
Least Significant Difference	1.3729

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	25.5410	40	C
B	19.4113	40	A
C	12.3551	40	E
D	7.9372	40	F
E	4.7952	40	D

MDF

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.099515
Critical Value of t	2.08596
Least Significant Difference	0.1471

Means with the same letter are not significantly different.			
t Grouping	Mean	N	manuf
A	10.79878	40	J
B	7.49810	40	K
C	6.57522	40	I
D	6.03148	40	G
E	5.26268	40	H