WHEAT STRAW AS RAW MATERIAL FOR MANUFACTURE OF MEDIUM DENSITY FIBERBOARD (MDF)

Sören Halvarsson,[a, b*] Håkan Edlund,[a] and Magnus Norgren[a]

Wheat straw was used to produce medium-density fiberboard (MDF). The chemical and physical characteristics of fractionated size-reduced wheat straw were investigated. The pH, pH-buffering capacity, ash, and silicon content increased as wheat straw particle size decreased. Ash of the finest straw, <0.2 mm, had high ash (15%) and silicon (18%) contents. The outer and inner parts of size-reduced straw were analyzed using scanning electron microscopy (SEM). The SEM micrographs revealed a complex ultrastructure containing a notable portion of thin-walled cells approximately 1 µm thick. Pressurized defibration of size-reduced wheat straw produced lignocellulosic fibers nearly 1.0 mm long combined with approximately 24% of small particles and dust. The high water uptake of straw-based MDF was significantly reduced using melamine-modified urea-formaldehyde (UF) resin and removing wheat straw particles and dust by screening. UF resin was added at levels of 12.5%, 13.1%, and 14%. In terms of water resistance, 12-mm-thick straw MDF displayed thickness swelling below 10%, acceptable according to the EN 622-5 MDF standards. It was concluded that manufacturing wheat straw MDF entails straw size reduction (hammer-milling), removing small particles and dust, and adding melamine-modified UF resin to attain necessary MDF quality standards.

Keywords: Wheat straw; Medium-density fiberboard; Hammer-milling; Fiber length; Melamine urea-formaldehyde resin; MUF; Thickness swelling; Ash content; Silicon content; pH; pH buffering; EDX; SEM

*Contact information: a: Department of Natural Sciences, Engineering, and Mathematics, Fibre Science and Communication Network (FSCN), Mid Sweden University, SE-851 70 Sundsvall, Sweden; b: Metso, Mechanical Fiber Unit, Department of Research, Technology, and Development (RTD) SE-851 50 Sundsvall, Sweden; *Corresponding author: soren.halvarsson@box060.com*

INTRODUCTION

The conventional method for producing medium-density fiberboard (MDF) and high-density fiberboard (HDF) uses wood-based raw materials, particularly softwood, hardwood, and mixtures of different wood species. However, expected wood shortages, forestry regulations, and the presumed lower cost of non-wood materials have prompted MDF and panel-board producers worldwide to explore alternative sources of lignocellulosic fibers. Interest in producing MDF panels from agricultural waste is not new: among the first installations of an Asplund Defibrator to produce fiber and fiberboard in the United States was at Celotex Corporation in Marrero in 1937; insulation board was produced and the raw material was bagasse (Lowgren 1986). Agricultural wastes and annual plants have become alternative raw materials for manufacturing fiber composite products. Today, the most frequently considered non-wood materials are

bamboo, jute, hemp, bagasse, and kenaf (Youngqvist et al. 1996; Reddy and Yang 2005), as well as cereal straws such as rice and wheat straw (Han et al. 2001; Reddy and Yang 2005; Hervillard et al. 2007; Ye et al. 2007). The most reported investigations of straw MDF consider the use of wheat straw as raw material. Some fiberboard applications based on rice straw exist and in most cases combined with other lignocellulosic materials, or produced from rice straw pulp, have also been reported (Mobarak et al. 1975; Hiziroglu et al. 2008; Halvarsson et al. 2010).

Non-wood plant materials and polymeric diphenyl-methane diisocyanate (MDI) resins have been successfully used to produce straw particle-board (PB) (Grigoriou 2000; Chunta 2001; Mo et al. 2003; Xing et al. 2006). The benefits of MDI over formaldehyde resins are low resin consumption, good panel properties, and absence of formaldehyde. However, the use of isocyanate adhesives in the board industry has been kept down by high resin costs and by the annoying adhesion of MDI to metal surfaces (necessitating the use of press release agents to facilitate pressing). The more commonly used and less expensive urea-formaldehyde (UF) resins have, on several occasions, resulted in acceptable mechanical board properties but still the thickness swelling and water resistance of UF straw particle boards (PB) and fiberboards have higher TS than wood-based board products (Markessini et al. 1997; Han et al. 2001; Mo et al. 2003). The poor to moderate thickness swelling properties of such straw boards are explained by insufficient wetting of straw material by UF resin. It is speculated that hydrophobic chemical components occurring naturally on external straw surfaces reduce wetting from water-based adhesives (Liu et al. 2004). However, increased melamine content in modified UF resin improves the water-repelling properties and improved fiber board properties are observed (Hervillard et al. 2007). Chemical modifications of straw and straw fibers by acetylation improve the TS. Very low thickness swelling of produced straw MDF less than 2% thickness swelling have been reported (Gomez-Bueso et al. 2000). The main chemical components of the external straw surface are wax, pectin, and silica (Wisniewska et al. 2003). Eventually, pressurized refining of wheat straw under appropriate processing conditions disintegrates the straw material and generates fiber bundles and fiber of sufficient quality (Sauter 1996). Separating most of the above-mentioned components from the produced fiber materials improves the wetting by water-based resins.

The ultrastructure of wheat straw is somewhat more complicated than that of wood. A relatively large number of cell types and elements are observed, including reinforcing fibers, parenchyma cells, vessel elements, and epidermal cells. In addition, there are special cells in the plant to deposit silica (Sangster et al. 2001). The observed higher ash and sand contents of straw materials than of more traditional wood-based raw materials (Jenkins et al. 1996; Rowell 2001) suggest greater wear of processing equipment. The origin of the high silica content of straw materials is explained by phytoliths (microfossils of opal silica) formation (Jones and Milne 1963; Jones et al. 1963; Ball et al. 1999). Silica deposits in plants are known as phytoliths, and have dimensions in the 10–100 μm range. Moreover, the actual habitat, weathering, and harvesting conditions can introduce external crystalline quartz or sand into the straw material. The fear of increased tool wear and rapid wear of machines and equipment in straw MDF processing has been disputed (Sauter 1996).

Wheat grows for just one season and develops shorter fibers and thinner cell walls than do perennial wood organisms. Therefore, the potential to generate longer, high-quality fiber during defibration is lower for straw materials. Small particles and dust are easily created in the straw-refining process. Moreover, the straw MDF process must also include wetting, heating, and pH reduction pretreatment before defibration to loosen up the straw structure. This investigation attempts to characterize size-reduced wheat straw, and identify some of its important properties that substantially influence the MDF process and the properties of the panels produced.

EXPERIMENTAL

Materials

The wheat straw material (*Triticum aestivium*) was harvested in the Uppsala region of Sweden. The wheat straw was cut to a length of approximately 30 to 40 cm and bailed in 250 kg units. Together with the wheat straw, a small amount of leaf and wheat seed was observed in the wheat straw bales. The bales were stored under dry, cold conditions before hammer-milling. A commercial melamine-modified UF resin was used, Prefere 11G321 (Dynea, Gent, Belgium). The resin, characterized by low formaldehyde emission and water resistance, comprised approximately 10% melamine. Ammonium chloride was added (1.0%) as a hardener and hexamine (0.2%) as a retarder (Labservice, Sundsvall, Sweden). The resin mixture was diluted to 50% before addition to the defibrator blowline. The target levels of UF resin were set to 12%, 13%, and 14% based on oven-dried (OD) wheat straw. The solid content of the anionic wax emulsion, Boardwax B100 (Emutech, City, Sweden), was 56%; the emulsion was diluted to a solid content of 30% before addition to the defibrator system. The target wax emulsion content was set to 1.0% based on OD wheat straw.

Methods

Size reduction of wheat straw

The wheat straw was size-reduced using two connected hammer mills. The first hammer mill was a swinghammer shredder, size 15 × 8 and equipped with 25-mm screens (Jeffrey Rader, Stockholm, Sweden); the second was a H-30.C hammer mill (Kamas Industri, Karlstad, Sweden) equipped with 10-mm oval screening holes. The rotation speed of the first hammer mill was set to 1000 rpm and of the second to 1500 rpm. A production rate of 60 kg/h was chosen and the length of the size-reduced wheat straw was in the 10–15 mm range. Two fans and a cyclone were connected to the hammer-milling system. Finally, the hammer-milled wheat straw was fractionated using a 0.7-mm screen. Approximately 15% of the wheat straw was rejected during screening.

Fractionation of size-reduced wheat straw

Size-reduced (unscreened) wheat straw was fractionated in a screening equipment (Allgaier-Werke, Uhingen, Germany) using 1.0-, 0.6-, and 0.2-mm screens.

Ash analysis of fractionated hammer-milled wheat straw

The wheat straw fractions were further milled in a 600 W, ZM-1 grinder (Retsch, Haan, Germany) equipped with a 0.5-mm screen to obtain powder samples of uniform consistency. The ash content of each wheat straw fraction was investigated. The ground straw materials were heated in an oven at 575°C for 2 + 4 h (2 h to reach the target temperature) according to the TAPPI T-244CM-99 method for determining ash in biomass.

The pH and pH-buffering capacity

The pH and pH-buffering capacity measurements were made using a modified version of the analysis method introduced by Johns and Niazi (Johns and Niazi 1980). The pH-buffering capacity was only determined using acid titration (0.025 N H_2SO_4), due to the high initial pH values of the wheat straw materials.

Energy dispersive X-Ray (EDX) analysis

The ash samples of the different straw factions were investigated using EDX analysis. The ash samples were coated with carbon before analysis, which used a LEO 1450 EP scanning electron microscope equipped with an EDX device. The silicon (Si) content of the ash of each fraction (i.e., fractions A–D) was determined.

Fiber length and small particles and dust

The fiber length and size of the defibrated, dried fibers were measured by means of image analysis using a laser-based PQM™ 1000 pulp quality monitoring system (Metso Paper, Sundsvall, Sweden).

Pilot plant manufacturing of straw MDF

Wheat straw MDF was produced in a complete pilot-plant MDF process line, including hammer-milling the wheat straw, pretreatment, pressurized refining, blowline resin addition, tube flash drying, fiber mat forming, pre-pressing, and pressing, situated at Metso Technology Center in Sundsvall, Sweden. Steam and water were used to increase the temperature and moisture content (MC) during pretreatment. The water pretreatment and steam heating resulted in a temperature of 80 to 90°C and MC of 90 to 100% for the pretreated wheat straw. The acid water/steam-pretreated wheat straw material was refined in a pressurized single-disk laboratory refiner with a plate diameter of 508 mm (20") and equipped with a horizontal preheater. Refining was carried out at a rotation speed of 1500 rpm and at a preheater pressure of 0.6 MPa. Refined fiber was vented from the refining house into the blowline. The fiber was resinated in the blowline and dried in a connected continuous flash dryer. The retention time in the defibrator system was 2 min. The average moisture content of the refined, resinated, and dried fiber was below 10%.

Fiber mats were formed manually in a 500 × 600 mm^2 forming box, followed by cold prepressing at 1.5 MPa for 60 s. The prepressing operation increased the homogeneity and density of the formed fiber mats, which resulted in easier handling and subsequent pressing of the fiber material. Pressing was performed in a laboratory hot press. The target panel thickness was set to 12 mm and target density to 800 kg/m^3.

Table 1. Experimental Average Values and Standard Deviations of Defibrator Processing Parameters and Fiber Quality Parameters of Defibrated Wheat Straw. (Standard deviations are presented in parenthesis.)

Process parameters	Unit	Average value (Standard Deviation)
Production	kg/h	62 (5.5)
Preheating pressure	kPa	595 (10)
Preheating temperature	°C	155 (1.7)
Preheating time	s	120 (6.0)
Housing pressure	kPa	590 (8.0)
Rotational speed	rpm	1500 (2.0)
Disc clearance	mm	0.55 (0.01)
Energy Consumption	kWh/ton	285 (78)
Dryer inlet temperature	°C	125 (11)
Dryer outlet temperature	°C	75 (2.0)
Fiber Quality Parameters		
Fiber length	mm	0.99 (0.03)
Fiber width	µm	27 (0.52)
Shive weight	%	23 (1.7)
Dust <0.45 mm	%	24 (0.64)

The press sequence was optimized for wheat straw, including a cooling sequence at the end of the press cycle. An initial pressure of 4.0 MPa and a press factor of approximately 12 s/mm were chosen. A total of 15 fiber mats were hot platen pressed at 190°C. However, panel density varied due to efforts to optimize the pressing profile to obtain an acceptable vertical density profile. The final wheat straw MDF panel dimensions were 500 × 600 × 12 mm^3.

Evaluating MDF properties

The finished straw MDF was conditioned for 1 week at 20°C and 65% relative humidity. The MDF was evaluated according to the requirements of the EN 622-5 European MDF standard (EN 622-5 2006).

RESULTS AND DISCUSSION

Some of the physical and chemical properties of hammer-milled wheat straw were characterized to investigate material component variation in different material fractions. The analysis determined the ash and silicon contents of the screened wheat straw fractions. The pH and pH-buffering capacity of the different straw fractions were also investigated. The morphology of the hammer-milled wheat straw was studied using SEM. Wheat straw MDF was produced, using a melamine-modified UF resin. The straw MDF panel properties were investigated as a function of density.

Fractions of Screened Wheat Straw

The dry screening of size-reduced wheat straw was performed in a screening apparatus (Allgaier-Werke) equipped with three screens. Four fractions of the size-reduced wheat straw were of interest. The screen-opening diameter and yield for each fraction are summarized in Table 2.

Table 2. Fractions and Yields of Size-Reduced Wheat Straw; Percent Weight Left on the Specific Test Screen

Fraction	Screen-opening diameter, mm	Wheat straw yield, %
Fraction A	# >1.0 mm	76.8
Fraction B	# >0.6 mm	10.0
Fraction C	# >0.2 mm	10.0
Fraction D (PAN)	<0.2 mm	3.2

Size-reduced wheat straw was screened to remove the smallest particles. Straw thickness rather than length is the significant property for separation. The size-reduced straw material, approximately 10 to 15 mm in length, passed through screen openings of 1.0 mm or smaller. Approximately 77% of the material remained on the first screen, followed by 10% each on 0.6- and 0.2-mm screens. Finally, the small particles, straw fragments, and dust were captured as Fraction D (PAN); the PAN or straw particles <0.2 mm comprised approximately 3% of the material.

In general, small particles, fragments, and dust are troublesome in MDF manufacture and degrade the mechanical properties of the MDF. More resin is then needed to maintain the required panel properties. Silica, sand, and inorganic compounds are also undesired components, as they cause increased equipment and tool wear. Effective screening of the straw material and removal of sand, straw fragments, and dust is an appropriate way to improve the straw MDF properties.

Ash content of wheat straw fractions

The ash content of wheat straw fractions was 6.5 to 14.7%, the maximum ash content being observed in Fraction D (see Table 3). The original hammer-milled wheat straw sample had an ash content of 7.2%. Agricultural wastes and wheat straw have much higher ash contents than do wood-based materials. Wood (Douglas fir) was reported to have an ash content of 0.45% (Jenkins et al. 1996). In general, the ash contents of straw materials are in the 4 to 19% range, silica and potassium oxide being the dominant components. The recommended silica content (sand content) in ash of wood-based MDF is 0.05%.

Deposits of microfossils or phytoliths in plants may explain the high ash and silicon content of wheat straw. Accelerated tool wear when producing PB and MDF panels from agricultural waste was predicted to be troublesome for MDF manufacturers. However, this claim has been disputed, and investigation indicates moderate or even lower tool wear associated with wheat straw than wood-based panels (Sauter 1996).

Table 3. Ash Content and Silicon Content in Ash of Hammer-milled Straw and Straw Fractions. (Standard deviations are presented in parenthesis.)

Wheat Straw Material and Fractions	Ash Content (%)	Silicon Content in ash (%)
Size-Reduced Wheat Straw	7.2 (0.33)	12 ± 2
Fraction A - # > 1.0 mm	6.8 (0.11)	13 ± 2
Fraction B - # > 0.6 mm	8.0 (0.17)	14 ± 2
Fraction C - # > 0.2 mm	9.7 (0.07)	17 ± 2
Fraction D - # < 0.2 mm	14.7 (0.49)	18 ± 2

Elemental analysis of ash from wheat straw fractions

The outer part, or epidermis, of the straw surface contains wax and micro-sized silica particles—phytoliths, which are unique to each plant species (Ball et al. 1999; Sangster et al. 2001). The chemical composition of wheat straw surface layers was analyzed using Fourier transform infrared spectroscopy (FTIR), and a high level of silicon was observed in the surface layer (Yao et al. 2003). In the present investigation, ash originating from the screened fractions of wheat straw was subjected to elemental analysis using EDX methodology. The silicon weight fraction of the ash samples increased with reduced particle sizes (see Table 3). The silicon content of ash from the original size-reduced wheat straw sample was nearly 12%. The silicon content of ash samples of Fractions C and D displayed the highest values and exceeded 17%. The strengthening and protective parts of the wheat straw are situated on the outer part of the straw (Liu et al. 2004). Hammer-milling and intensively processing the straw degrade and crush tissues and cells at the straw surface. Consequently, most of the silicon found in straw is expected to be situated on the external surface parts of the internodes. Small particles, straw fragments and dust are easily removed from the straw and are found in the fine particle fractions. The silicon content of wheat straw fractions increased as the particle size declined. The highest silicon content was found in Fraction D and was approximately 18%.

The pH and buffering capacity of wheat straw fractions

The fractionated wheat straw materials were analyzed with respect to pH and buffering capacity. The curing reaction of UF resin is initiated and accelerated by adding acid generating chemicals (hardener). The normal pH of refined wood-based fiber is below 6 and samples display pH values in the 3.5–5.5 range. The curing rate of UF resin when pressing wood-based fiber material is generally not a problem in conventional MDF manufacture (Xing et al. 2006). Unlike wood materials, wheat straw and cereal wastes have higher pH values and pH-buffering capacity levels, pH-levels above 7 not being uncommon. In Fig. 1, the pH and acid pH-buffering capacity of the different wheat straw fractions are plotted.

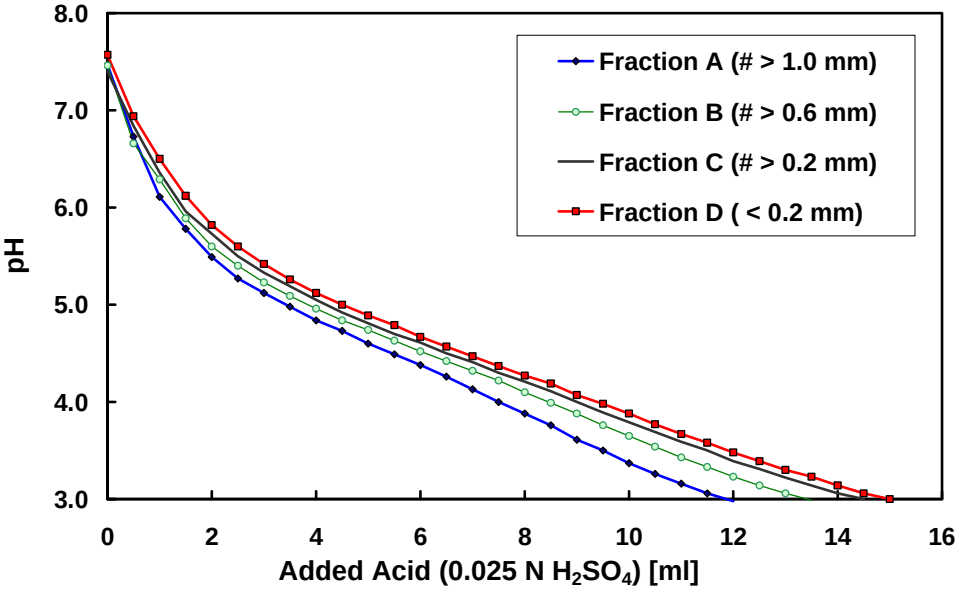


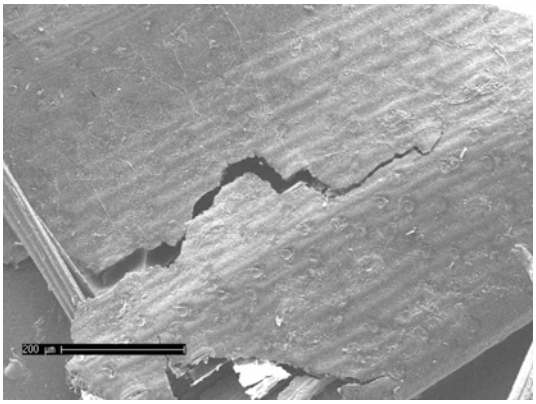
Fig. 1. The pH and buffering capacity of four wheat straw fractions

The initial pH of all fractions was approximately 7.5 and declined after adding acid according to a somewhat modified version of a method originally developed by Johns and Niazi (1980). Figure 1 shows the pH variation of the four wheat straw fractions as a function of added acid. Fraction A (wheat straw particles left on 1.0-mm screen openings) needed the least added acid, only 12 mL, to reduce the pH to 3.0. Fraction D (the fine wheat straw particles below 0.2 mm in size) displayed the highest buffering capacity, and 15 mL of acid solution had to be added to reach the pH = 3.0 level. Silicon and other chemical components are concentrated in the fine particle fraction and most likely contribute to the increased buffering capacity. Even if the reduction of the pH-buffering is comparably small, the separation of a fine (dust) fraction from the straw has two main effects. Firstly, the total resin consumption will be reduced, and secondly, the level of inorganic components (silicon and potassium) is decreased in the finished MDF. However, addition of acid into the wheat straw process is more effective and an alternative way to adapt the pH-level of the refined straw fibers to attain the optimal curing conditions of the selected adhesive system. Considering the optimum conditions for the UF resin curing reaction, it is important to remove inorganic compounds from the straw and to maintain curing reactions at a level closer to the conditions in the fiberboard production of wood-based materials.

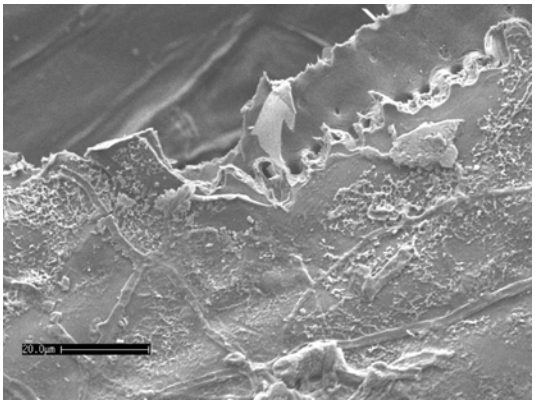
Morphological Analysis of Wheat Straw

Morphological analyses of straw materials have established different types of non-fibrous thin-walled cells (i.e., parenchyma and epidermal cells) from those found in wood materials (Zhai and Lee 1989; Liu et al. 2005). Besides the surface silicon (amorphous silica), complex wax structures have been speculated on leaves and stems. FTIR analysis, scanning electron microscopy (SEM), and atomic force spectroscopy (AFM) of bare straw surfaces have been reported (Wisniewska et al. 2002). Similar results have been reported for rice straw (Shen et al. 1999).

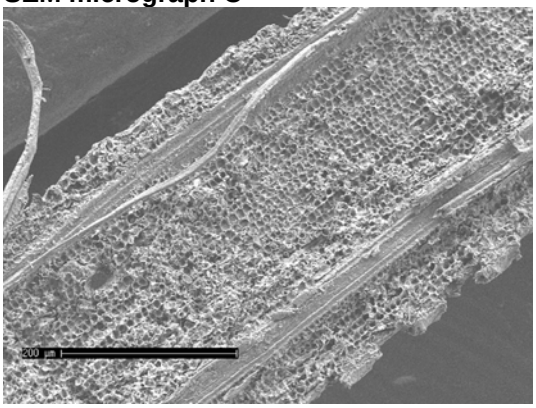
SEM micrograph A



SEM micrograph B



SEM micrograph C



SEM micrograph D

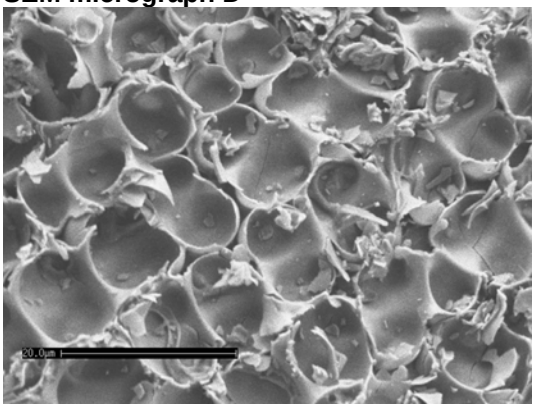


Fig. 2. Scanning electron microscopy (SEM) micrographs of size-reduced wheat straw from fraction B. *Micrograph A* - Size-reduced wheat straw external surface (epidermis); the bar in micrograph A represents 200 µm. *Micrograph B* – Magnified external surface of a wheat straw fragment; the bar in micrograph B represents 20 µm. *Micrograph C* - The surface of the internal (core) part of a wheat straw fragment; the bar in micrograph C represents 200 µm. *Micrograph D* - Magnified core surface of a wheat straw fragment; the bar in the micrograph D represents 20 µm.

Figure 2 shows the external and internal surfaces of wheat straw particles sampled from Fraction B. Magnified micrographs display the complex surfaces structures. One physiological function of surface wax on straw is to effectively repel water. Obviously, wetting straw or straw particles with water-based adhesives is a challenge. Insufficient wetting with water-based adhesives results in poorer bonding between straw particles, and weaken the mechanical properties of the produced fiber composite (Mantanis and Berns 2001; Liu et al. 2004). Analyzing the external surface of wheat straw particles using SEM revealed a complex ultrastructure and surface patterns. The magnified micrograph B of the external surface (epidermis) showed complex patterns on the surface probably representing wax and inorganic substances. In the case of straw particleboards the board properties are strongly dependant on a proper wetting of water-based adhesives of straw particles. These complex patterns may consist of wax or hydrophobic

components, probably combined with silicon and make wetting more difficult. Thermo-mechanical refining at high pressures 500–600 kPa will break down the straw particles into fibers, straw fragments, and dust. Wax and silicon is removed from the hydrophilic straw surfaces and the water based adhesives can be more effective in bonding of the straw MDF.

Effective size reduction (i.e., hammer-milling) will degrade the wheat straw surface (see typical cracks in a straw particle in Fig. 2, SEM micrograph A) and generate small fragments and dust that can be removed from the straw raw material. The inside of the wheat straw consists of a honeycomb-like structure (see Fig. 2, SEM micrographs C and D). The cell walls in this honeycomb-like structure are thin and estimated to be only a few micrometers thick. The pressurized refining of straw for production of fibers containing this type of thin-walled cells generate much more fragments and dust than refining of wood-based raw materials. The resin consumption of straw materials will consequently be higher than wood-based MDF for the same strength-properties.

Wheat Straw MDF Fiber Properties

The fiber length distribution of wheat straw fiber samples was analyzed in the PQM 1000 system. The average wheat straw fibers were relatively short and were calculated to be 0.99 mm long (see Table 1). Small particles, straw fragments, and dust smaller than 0.45 mm accounted for approximately 24% of the total amount of MDF fiber pulp. Defibrating softwood produces much longer fibers and smaller amounts of short fibers and dust. The shorter average length of wheat straw fibers will not necessarily adversely affect all MDF panel properties, as the fiber length distribution and strength of the fiber itself influence them. MDFs produced from hardwoods with shorter average fibers (1.2 to 1.5 mm) generally have excellent properties. Several other variables, such as refining conditions, fiber surface properties, pressing conditions, MDF density, type of adhesive, and method of resin application, can play an important role in the finished MDF properties.

Wheat Straw MDF Properties

Three sets of panels were produced with different resin contents and average densities. The target resin contents were set to 12%, 13%, and 14%, and actual values were in rather good agreement with these targets. However, the 12% target resin content deviated +0.5% and was 12.5%, which is rather close to the 13% target resin content of the straw MDF. Average MDF densities were adjusted to attain the same vertical density profiles during hot pressing at approximately 800 kg/m^3 average densities. The goal was to produce straw MDF of high surface density, preferably above 1100 kg/m^3, with a core density in the 700 to 750 kg/m^3 range.

The density variation in the thickness direction is generally referred to as the vertical density profile and is a parameter that profoundly affects the mechanical and physical properties of the finished MDF (Wang et al. 2001). The bending property, i.e., modulus of rupture (MOR), increases as the density increases (Xu and Suchsland 1998). Theoretical considerations indicate that the modulus of elasticity (MOE) benefits from the high-density surface layer and increases linearly with increasing peak density (Xu 1999). High surface density also enhances painting and the overlaying of paper and

laminating on the MDF. Moreover, water resistance or thickness swelling (TS) is also influenced by the vertical density profile. MDF specimens soaked in water for 24 h will swell, and it is generally the compressed fibers in the high-density surface layers that expand from a compressed, flat cross-section to a more natural, round cross-section. The vertical density profile of typical MDF is plotted in Fig. 3.

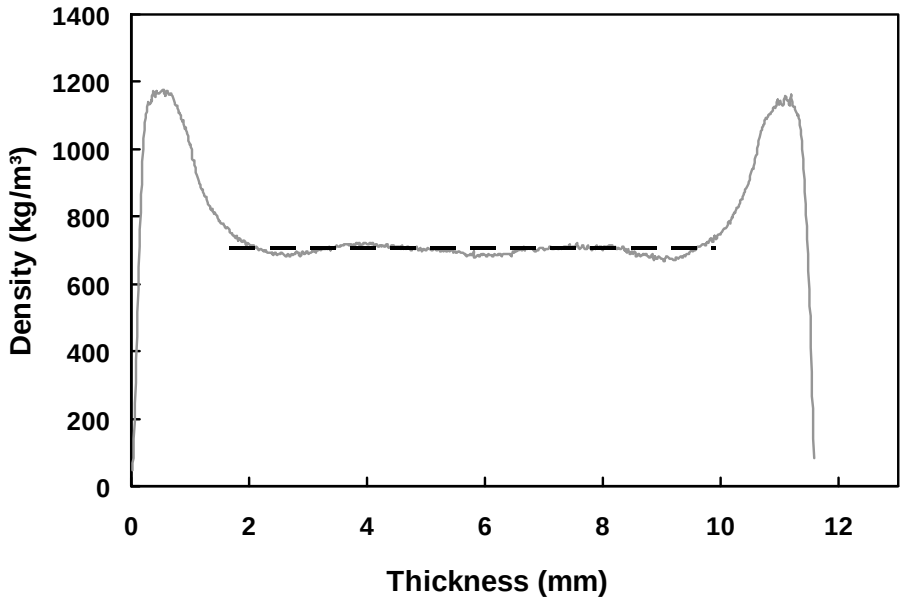


Fig. 3. Vertical density profile of a typical hot-pressed wheat straw MDF panel. The average calculated core density is represented by a horizontal dotted line (- -).

The strength of an MDF panel, i.e., internal bond (IB) strength, is related to the average or, alternately, the core density. Generally, increased average or core density improves the IB strength. MDF fracturing is perhaps more related to the core density than the average density. The failure during an IB test is normally positioned in the core layer at the lowest density, the weakest link in the MDF. The IB of the produced straw MDF was plotted as a function of the core density (see Fig. 4). The average density was unintentionally changed during hot pressing due to the optimization of surface and core density. IB is obviously dependent on the straw MDF density.

The increased IB strength property can be identified for different UF resin contents when compared at the same density. However, the IB measurement of MDF samples can be misleading if the vertical density profiles are unknown. Unfortunately, straw MDF containing the least level of UF resin (12.5%) displayed a narrow distribution of measured core densities. Regressions of IB on core density were investigated for the three resin content levels. Statistical analysis displays the estimates of error (R^2) between the observed and predicted IB. MDF samples at a resin content of 12.5% displayed a R^2 value of 0.53. The MDF samples of (RC=13.1%) and (RC=14%) improved the statistical significance to R^2=0.71 and R^2=0.81, respectively (see Fig. 4). Increased core density and elevated level of melamine modified UF resin improved the IB of the straw MDF. Generally, increased density and resin content improves most of the typical fiberboard properties (Suzuki and Kato 1989).

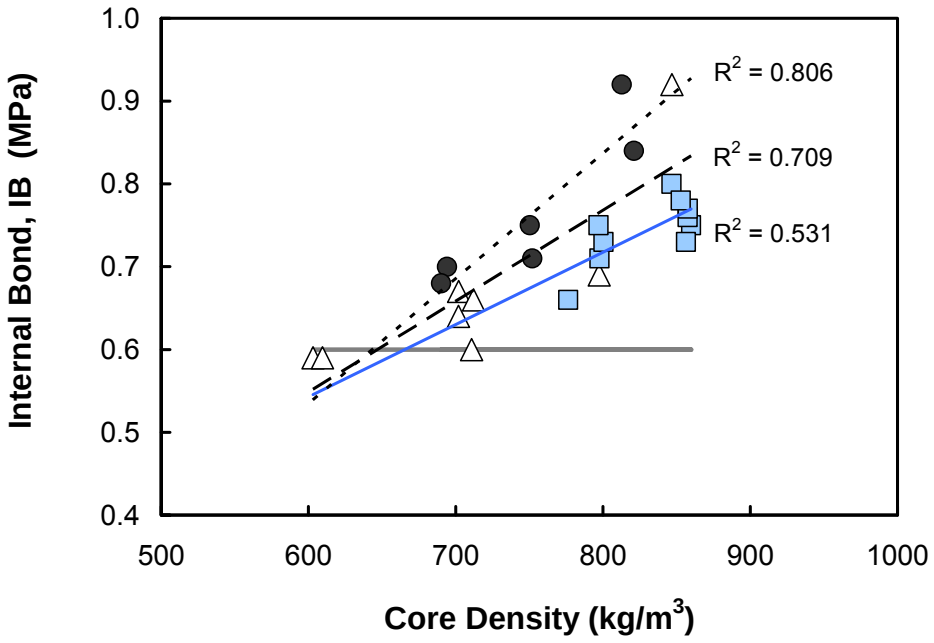


Fig. 4. Internal bond (IB) of wheat straw MDF vs. core density at different resin contents (RC), i.e., RC=12.5% (■), RC=13.1% (Δ), and RC=14% (●). The horizontal line represents the requirements of the EN 622-5 MDF standard. Estimate of error (R^2) is shown for each level of RC.

The average values of IB, MOR, MOE, TS, average density, and density range of manufactured straw MDFs for three resin contents are presented in Table 4. From Table 4 the minimum requirements of MDF standard in dry conditions (EN 622-5 2006) are fulfilled for almost all straw MDF. The average IB of straw MDFs at 12.5% resin content is less than the straw MDFs at 13.1% due to the lower MDF density of the RC=13.1% samples. The analysis bending properties MOR and MOE of the wheat straw MDFs indicated excellent bending properties, and the produced MDF met the requirements of the EN 622-5 MDF standards (see Table 4). The vertical density profiles of the straw MDF shifted during pressing, which may explain the MOR and MOE scattering. The best bending properties were observed for straw MDF at a resin loading of 14%.

The most annoying property of straw MDF made with UF resin is its poor water resistance or thickness swelling. This phenomenon is presumably due to the higher hemicellulose and lower lignin contents of straw versus wood-based MDF. However, the hemicellulose content of some hard-wood species is in the same level as observed in straw materials. Differences between softwood and hardwood shrinking/swelling have been reported (Schroeder 1972). The chemical composition of straw hemicellulose is also different compared with wood-based materials and more sensitive to hydrolysis. This is also an indication of the poorer water resistance in straw-based materials. The lignin polymer in wheat straw is of different structure compared to wood-based lignin. Wheat straw lignin is composed of *p*-hydroxyphenyl–guiacyl–syringyl lignin units and differs from wood-based lignin components. Only guiacyl and syringyl lignin units are found in wood-based lignin (Buranov and Mazza 2008).

Table 4. Fiberboard Properties of Straw MDF of Approximately 12 mm Thickness for Different Melamine Modified UF-resin Contents (RC), Dry Basis. The requirements in the EN standard (EN 6-225, 2006) of wood-based MDF (>12 – 19) mm thickness are included. (Standard deviations are presented in parenthesis.)

Property Straw MDF	Unit	Straw MDF Type 1	Straw MDF Type 2	Straw MDF Type 3	EN-Standard Thickness >12-19 mm
Internal bond (IB)	MPa	0.74 (0.04)	0.67 (0.11)	0.77 (0.09)	> 0.6
Modulus of Rupture (MOR)	MPa	27.8 (3.2)	26.8 (4.5)	29.5 (2.9)	> 20
Modulus of Elasticity (MOE)	GPa	3.2 (0.22)	3.4 (0.65)	3.4 (0.23)	> 2.2
Thickness swelling (TS), 24h.	%	7.2 (1.42)	7.8 (0.94)	7.1 (0.86)	< 12
Resin Content (RC)	%	12.5 (0.5)	13.1 (0.1)	14.0 (0.6)	
Average Density	kg/m^3	856 (30)	766 (57)	818 (30)	
Density Range	kg/m^3	820–890	700–880	770–860	

Another chemical component that can affect the thickness swelling of straw MDF is the silicon or silica content. Analysis of rice straw MDF shows acceptable thickness swelling compared with wheat straw MDF even if the ash content is much higher in rice straw and can reach up to 19% (Halvarsson et al. 2010).

In this investigation MDI-resin was used as adhesive and the thickness swelling was within 15 to 30% of 3 mm thick straw MDF/HDF. The amount of hemicellulose/lignin and type of hemicellulose/lignin are probably basic elements that have a notable influence of the thickness swelling of MDF. In addition, pressurized refining of wheat straw will, under appropriate processing conditions, disintegrate the waxy layer and remove other hydrophobic components, such as extractives, from the refined fiber. The generally accepted methods to reduce the thickness swelling of MDF and PB are adding an external hydrophobic component, such as synthetic wax, or chemically modifying the adhesive or refined fibers. Chemically modifying the fiber raw materials by acetylation or increasing the melamine content of the UF resin are common methods to reduce the thickness swelling of wood-based MDF (Gomez-Bueso et al. 2000; Hervillard et al. 2007; Halvarsson et al. 2008). Even adding divalent ions as (Ca^{2+}) can reduce the water swelling properties of fiberboard (Westin et al. 2001; Halvarsson et al. 2009). Excessive amounts of low-melamine or non-melamine-containing UF resin may not be sufficient to significantly improve the water resistance of straw MDF. The poor water resistance of the added UF resin itself will not contribute to acceptable hydrophobic properties of the produced straw MDF.

The thickness swelling (TS) of straw MDF samples was measured after 24 h of soaking in water. For all wheat straw MDF panels manufactured, the thickness swelling was remarkably low, i.e., in the 6 to 10% range. The improved wetting properties of the

pressurized straw fibers and improved bondability between the straw fibers in the finished wheat straw MDF, together with the removal of small particles and dust, contributed to low TS. Moreover, the absence of curing-retarding components in the produced fiber pulp most likely enhances curing behavior during pressing. However, two possibilities exist to improve panel properties. The RC can be raised, though this will raise the cost. Alternately, the amount of low-cost material can be increased, though this will increase the handling and processing costs. Increasing either core density or RC would undoubtedly improve the strength properties.

CONCLUSIONS

1. Analysis of four wheat straw fractions found variation in the ash contents. The ash contents of the four straw fractions varied between 7 and 15%, the maximum level of ash (15%) being observed in the finest particle fraction comprising materials smaller than 0.2 mm.
2. The silicon content of wheat straw ash samples of the different straw fractions was in the range of 13 to 18%. Reduced particle sizes of wheat straw increased both the ash and silicon contents. The ash and silica contents of wheat straw were much higher than those of wood.
3. Increased pH buffering capacity of the fine wheat straw fractions was observed versus the coarser fractions.
4. The properties of the produced wheat straw MDF panels met the EN 622-5 MDF standards (2006). The produced MDF with an average density exceeding 750 kg/m^3 had IB levels above 0.60 MPa. The bending properties (i.e., MOR) were in the 23 to 37 MPa range, while the thickness swelling was below 10%.

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