ADD FINAL Report:
July 28, 2008

WDATCP Contract No. 21034
Development and Evaluation of Engineered Biocomposites from Anaerobic Digested Bovine Biofiber

by
Jerrold E. Winandy, Project Leader
RWU4706 Engineered Composite Sciences
USDA Forest Service, Forest Products Laboratory
Madison WI 53726 USA
608-231-9316, jwinandy@fs.fed.us

Executive Summary
Over the last two years under this project we have develop methods and procedures necessary to process anaerobically digested bovine biofiber (ADBF) and wood fiber into value-added biocomposite products. To do this we also needed understand both the operational and materials aspects and the environmental issues of a working dairy and of ADBF for the anaerobic digestion system of cow manure. Our results have produced two draft manuscripts. The first discusses the completion of the economic analysis of using ADBF in particleboard as a means to assess the economic viability of FPL's ADBF-Wood composites research program. It is attached as Appendix A. The second manuscript related to reporting the overall results of our final study on mixing ADBF and wood fiber to make dry-formed fiberboard. It is attached as Appendix B.

Development of Dry-form Processes for Engineered Fiberboard
In the later stages of 2007 and the first two quarters of 2008, we conducted the final dry-form experimental work involving mixing ADBF fiber in various amounts with wood fiber to make dry-formed fiberboard. The experimental design of this final portion of the study is shown in Table 1. The key parameters in this phase of the research were fiber-type and wood-ADBF fiber-ratio, resin type, resin concentration, and composite-panel density:

(1) Composite Material types:
  a. ADBF fiber from 100-to-0%
  b. mixed wood fiber from 0-to-100%
(2) Resin:
  a: Urea formaldehyde (UF) at 8%
  b. Phenol formaldehyde (PF) at 3.5%
(3) Panel density: 42 pcf (670 kg/m^3) and 50 pcf (800 kg/m^3)
(4) Fiber preparation:
  a. ADBF fiber was NOT hammermiller (based on preliminary work)

b. Aspen wood fiber was hammermilled (based on preliminary work)

(5) Panel thickness: 12.5 mm (most commonly made thickness of product)

(6) Panel size: -500- x 500-mm

(7) Replicate panels made: 2

The properties of the panels made in this study were evaluated according to American Society for Testing and Materials (ASTM) Standard-D1037. The following performance criteria were evaluated:

(1) Modulus of elasticity (MOE),
(2) Modulus of rupture (MOR),
(3) Internal bonding (IB)
    (a) Dry at 65% Relative Humidity
(4) Thickness swelling (TS)/Water absorption (WA)
    (a) 24-hr water soaking

Summary

This evaluation of the physical and mechanical properties of dry-formed fiberboard was conducted in two parts. The results consistently indicated that up to a 50/50% mixture of wood fiber and ADBF-fiber compares favorably with commercial standards for wood-based MDF and particleboard. While to date our work at FPL has not evaluated all mixtures of WF and ADBF, these results indicate that virtually any combination of WF and ADBF is potentially feasible and combinations varying from 67-33% to 33-67% WF-to-ADBF often meet some portions of the ANSI commercial standards for particleboard or MDF. The results varied depending on the product type, density and grade being considered. A critical factor for composite producers to consider that might significantly benefit the analysis of whether or not to use ADBF concerns the potential "marketing" opportunity to employ more "green manufacturing" practices. ADBF-fiber dovetails well into this because it falls into the post industrial waste classification. Commercial wood-composite manufacturing companies might be able to market a hybrid WF-ADBF product as an opportunity to attract new "green-minded" customers who are seeking more environmentally beneficial products.

We have prepared a final technical report on this part of the entire project and it is now under external peer-review by professors at Univiersity of Wisconsin-Platteville and Iowa State University. That draft report is attached as Appendix B.

Development of Economic Model for Market Analysis

Henry Spelter of FPL completed his development of the economic and marketing potential of using ADBF in combination with other woody fibers to manufacture particleboard. His economic analysis estimates were based on production and ADBF cost information based on commercial data confidentially supplied by a Wisconsin particleboard mill. This economic assessment model was developed in the 3rd and 4th quarters of 2007 and 1st quarter of 2008. A manuscript was developed and on March 11th, it was sent to external peer-review. After addressing the comments from that first round of reviewers, we then submitted the manuscript of our economic analysis to a peer-reviewed technical journal (***Bioresource Technology*** (http://ees.elsevier.com/bite/). We are currently awaiting notificiation of its acceptance. The submitted DRAFT manuscript of that economic assessment is attached as Appendix A.

Summary

This study explored the physical and economic potential to substitute anaerobically digested bovine biofiber (ADBF) for wood in the making of particleboard. Laboratory tests indicated that replacement of one-half the wood in particleboard with ADBF produced panels that compared favorably to the requirements for commercial particleboard performance (specified by ANSI Standard A208.1–1999). The economic question hinges on the opportunity costs of alternative uses for ADBF. The current use is primarily animal bedding, and prices appear to be greater than those paid by particleboard plants for sawdust and planer shavings but less than for chips. ADBF is most similar in size to, thus most likely to be substitutable for, sawdust and shavings. At current bedding values, use for particleboard appears a less favorable alternative. However, this could be overcome by large-volume, long-term contractual arrangements that provide a secure long-term outlet for excess ADBF fiber that may otherwise not have value. For a particleboard operation, the opportunity for fiber diversification and the incorporation of post-industrial waste in the process offer strategic advantages.

Development of Wet-form Processes for Engineered Fiberboard

After the third quarter of 2007, all work on wet-formed fiberboard using ADBF fiber under this grant was concluded. A final report is in progress. Our industrial cooperators on this project have entered into a contractual agreement with a third-party commercial party and additional work by those parties is underway, but no longer performed under this project. A final report on the details of FPL's development of wet-formed fiberboard using ADBF fiber that was funded under this grant was included in the economic analysis paper.

APPENDIX A.

Anaerobically Digested Bovine Biofiber as Source of Fiber for Particleboard Manufacturing: An Economic Analysis.

Henry Spelter, Economist, Jerrold Winandy, Research Wood Scientist
Forest Products Laboratory, Madison, WI, and
Timothy Zauche, Professor of Chemistry, University of Wisconsin, Platteville, WI.

ANAEROBICALLY DIGESTED BOVINE BIOFIBER AS A SOURCE OF FIBER FOR PARTICLEBOARD MANUFACTURING: AN ECONOMIC ANALYSIS

Henry Spelter,[a*] Jerrold Winandy,[a] and Timothy Zauche[b]

This paper explores the physical and economic potential to substitute anaerobically digested bovine biofiber (ADBF) for wood in the making of particleboard. Laboratory tests indicated that replacement of one-half the wood in particleboard with ADBF produced panels that compared favorably to the requirements for commercial particleboard performance (specified by ANSI Standard A208.1–1999). The economic question hinges on the opportunity costs of alternative uses for ADBF. The current use is primarily animal bedding, and prices appear to be greater than those paid by particleboard plants for sawdust and planer shavings but less than for chips. ADBF is most similar in size to, thus most likely to be substitutable for, sawdust and shavings. At current bedding values, use for particleboard appears a less favorable alternative. However, this could be overcome by large-volume, long-term contractual arrangements that provide a secure long-term outlet for excess ADBF fiber that may otherwise not have value. For a particleboard operation, the opportunity for fiber diversification and the incorporation of post-industrial waste in the process offer strategic advantages.

Keywords: Anaerobically digested bovine biofiber; Particleboard; Economics

*Contact information: a: U.S. Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726;b: Dept. of Chemistry & Engineering Physics, University of Wisconsin–Platteville, Platteville, WI 53818; *Corresponding author: hspelter@fs.fed.us*

INTRODUCTION

Trends in modern farming have been to increase the size and specialization of farms. Dairy operations and other confined animal feedlots in Wisconsin have followed suit with more mega facilities that contain larger numbers of animals concentrated in one location. This has raised the challenge of managing manure at a scale heretofore rarely encountered but has also created opportunities to manage this waste to extract value from it.

Of Wisconsin's approximately 21,000 dairy farms, most are small, with 150 or fewer head per farm (Ag Environmental Solutions, LLC 2002). However, based on 2007 permit applications, at least 110 of these held 700 or more dairy cows, with associated large volumes of manure (WDNR 2008). The number of animals at these 110 facilities was 175,000 (~1,600 average), which, with planned expansions, was set to rise to 226,000 by 2009. At that time, the average number of animals per farm for this group will therefore be almost 2,100. Each such operation would generate about 105,000 L (28,000 gallons) of manure per day at an average rate of 3 kg (8 lb) per animal, or 0.3 million dried metric tons per year for the 110 units in aggregate (Burke 2001).

Such volumes have led to concerns over potential environmental problems, such as odor, catastrophic spills, or groundwater contamination, and regulations have been issued intending to control them. Such pressures have stimulated interest for ways to mitigate the concerns and possibly turn a business cost into a revenue stream. Anaerobic digesters to transform bio-wastes into usable products have received growing attention for their potential to accomplish this.

Anaerobic digestion is a natural process that uses bacteria to convert biomass (any organic matter derived from plants, animals, or their wastes) into methane gas in an oxygen-free environment. Anaerobic digestion has been used for over 100 years to stabilize municipal sewage and a wide variety of industrial wastes (Burke 2001). Transforming manure solids into methane gas, which can then be purified and fed into the natural gas pipeline distribution system or burned on site to generate heat or electricity, is a potential way for large farms to reduce odors and flies, improve nutrient management, and produce renewable energy, thus resulting in income to offset costs (Roos 1991).

Along with gas, anaerobic digestion also transforms the raw manure, yielding a nutrient rich liquid effluent that has applicability as fertilizer and a wet cellulosic-based fibrous residue that, when dewatered and dried, has utility as animal bedding, soil amendment, or potting soil. Because of the potentially huge volumes, however, these applications by themselves may not be enough to economically utilize all the supply. Other uses might be needed, and one such possibility may be using mixtures of the fiber in combination with wood for making particleboard or medium-density fiberboard (MDF).

An associated paper details the processing techniques and physical and mechanical properties of various mixtures of wood fiber and ADBF fiber for particleboard and fiberboard (Winandy and Cai 2008). The present paper explores the potential for savings in operating costs by using this processed fiber in composite panels manufacturing in general and within Wisconsin in particular. Two particleboard manufacturing plants in Wisconsin had a combined annual capacity of 221,000 m^3 (125 million square feet, 3/4-in. basis) (Composite Panel Association 2005). However, one of these closed in 2006. At an approximate average panel density of 600 kg/m^3 (45 lb/ft^3), the remaining plant requires approximately 92,000 metric tons (101,000 short tons) of fiber per year. This plant lies within a 200-km (125-mile) radius of most large dairy operations, thus making the transportation of fiber to it a potentially feasible proposition.

OVERVIEW OF ANAEROBIC DIGESTERS FOR ANIMAL MANURE

Although a widely used process with an extensive history, operating a digester requires some expertise. In the 1980s, federal tax credits spurred the construction of more than 100 digesters across the country, but many failed because of poor design, faulty construction, improper operation, and lack of service infrastructure (Nelson and Lamb 2002). The current wave of interest follows considerable subsequent experimentation and development by universities, government, and private entities.

Several different types of digesters are suited for specific methods of waste collection. Most farms collect their manure deposits either by flushing them with water down a sloped channel towards a central reception point or by using a front end loader to periodically "scrape" the material to the same destination. For operations that scrape, the least demanding type of digester is the "plug-flow" system in which the waste enters on one side of a reactor chamber and pushes older material toward the discharge end in the form of a semi-solid "plug." To function as such, this requires a high solids concentration of about 10%, or manure in "as excreted," undiluted condition, which is provided by the scraping collection method. This system requires few moving parts, has minimal maintenance requirements, and is intermediate in its gas conversion efficiency (Burke 2001). It is thus the most widespread digester in use. For that reason, we focus on the economics of this type of digester.

Once collected and fed into the reactor, the slurry undergoes chemical reactions caused by acid-forming bacteria (acetogens), which convert the soluble contents to carbon dioxide and a variety of short-chain organic acids, and methane-forming bacteria (methanogens), which use the acids to produce methane. These types of bacteria function best in a medium temperature range of 35–38°C (95–100°F).

A second key process variable is pH. If the slurry is too acidic, the methanogenic bacteria are inhibited. Likewise, in an environment that is too basic, growth of the acid-forming bacteria is retarded. Thus, the process operates within a relatively narrow pH window of 6.5 to 8.0. Further, because acid-forming bacteria operate faster than the methanogens, an appropriately larger population of methane-forming bacteria must be maintained. Controlling the amount of organic matter fed into the digester is also important because if the organic loading is too high, the acid-forming bacteria produce too much acid and overwhelm the methane producers, causing system failure.

The process of generating methane reaches the point of diminishing returns after about 20 days. The gas produced consists roughly of 58% methane; the rest is mostly carbon dioxide, with slight amounts of hydrogen sulfide. This produces a low-grade combustible gas that can be burned to produce electrical power or heat. Alternatively, it can be "scrubbed" by removing carbon dioxide and hydrogen sulfide to create a nearly pure methane gas stream that can be injected into the pipeline system for distribution.

The remaining processed material can be separated into an odorless liquid discharge effluent with highly concentrated nutrients and a wet lignocellulosic slurry. When dewatered, the slurry yields a relatively dry mass of lignocellulosic biofiber. This has a moisture content after separation but before drying of ~70% +/-10%. After drying the composition of the lignocellulosic biofiber is about 10-15% lignin and 25-30% cellulose. Other major components are ash (10-20%), non-cellulosic fibers (20-25%), starches (1%), proteins (1%), and fats (<1%). A variety of other carbon containing compounds (e.g. non cellulosic fibers) make up the remainder.

Overall, from the operational perspective, the demands of the process are fairly straightforward, requiring only periodic monitoring of temperature, pH, and organic content of the inflow to operate properly.

OVERVIEW OF THE PARTICLEBOARD PROCESS

Particleboard emerged in the United States after World War II as a lower cost substitute for lumber and plywood in furniture, millwork, cabinetry, and sub-flooring end

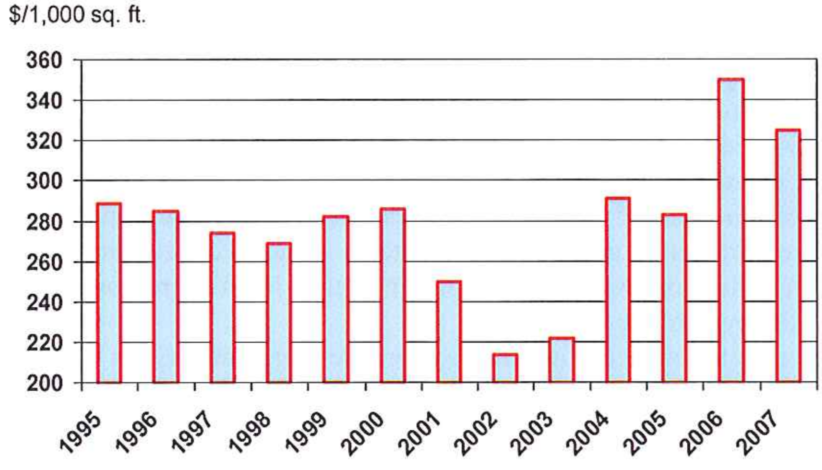


Figure 1. Price of ¾-in. industrial grade particleboard (eastern markets). From Random Lengths Publications, Inc.

uses. It is a largely standardized commodity whose price, and thus how much can be afforded for inputs, fluctuates with the forces of supply and demand (illustrated by its recent price history, Fig. 1).

Particleboard production is largely based on wood fiber residues—mostly planer shavings and sawdust—obtained as a byproduct of sawmilling or other wood processing activities. As such, the fiber must be admitted largely in the shape in which it is received, and the amount of further milling that can be performed is limited (Maloney 1977).

Wood residues brought to a particleboard plant are initially placed in storage. They may receive further processing in a hammermill or similar machinery to modify the size distribution. The residues are subsequently dried in a rotary dryer, screened, and separated by size, mixed with resin (usually urea formaldehyde) and wax, and formed into thick layered mats. The mats are conveyed into a multi- or single-opening platen press, where they are compressed and heated until the adhesive sets. At the end of the press cycle the pressure is slowly relaxed to allow any moisture buildup to escape, after which the press opens and the boards are discharged onto a rotating cooling rack. After cooling they are trimmed and cut to final size, stacked, strapped, and made ready for shipment.

Modern particleboard mills are capable of handling two or three fiber streams, such as sawdust, planer shavings, or chips. A possible viable substitute for sawdust used in the process would be non-clumped biofiber material screened between 12 and 16 mesh. Larger material could also be used, provided that it did not clump. However, much smaller material would result in increased resin use and lower physical properties and thus should be avoided.

WOOD–ADBF HYBRID PARTICLEBOARD PERFORMANCE

Particleboard mills are large users of woody biomass. Anaerobically digested bovine biofiber (ADBF) could potentially replace (or supplement) wood fiber (WF).

Recent work at the Forest Products Laboratory (FPL) evaluated the compatibility of woody fiber and ADBF for both traditional wet-formed fiberboard and dry-formed particleboard.

The dry-formed particleboard work was done in two stages. In the first stage, compatibility and requirements of ADBF with wood with and without mechanical separation (i.e., hammermilling) were evaluated. Using 50/50 mixes of dried WF and ADBF (~5% moisture), the following combinations were studied: (1) neither WF nor ADBF hammermilled; (2) both WF and ADBF hammermilled; and (3) only WF hammermilled.

In the second stage, these three variously processed fiber mixtures were made into a dry-formed particleboard using phenol formaldehyde resin at 3.5% and a hot-press temperature of 180°C. Results indicated that woody fiber and ADBF could be mixed in a 50/50 mixture either with or without hammermilling (Fig. 2). Results also indicated that the three variously processed 50/50 mixed-fiber types produced a particleboard that compared favorably to the requirements for commercial particleboard performance (specified by ANSI Standard A208.1–1999 (ANSI 1999)). To date our work at FPL has concentrated mostly on 50/50 mixtures, but virtually any combination is potentially feasible. Local economics will probably determine the optimal mixture at each plant. Such decisions will undoubtedly affect the critical price-point for ADBF in woody composites. To help in such determinations, a study now underway at FPL is focusing on five mixed fiber combinations from 0/100 to 100/0 using multiple resin systems and board densities.

The wet-formed hardboard work was done using a 50/50 mixture of WF and wet ADBF (~70% moisture). The wet-formed WF–ADBF hardboard was produced without resins or additives. Tensile strength perpendicular to panel surface (i.e., internal bond strength), thickness swell, and water absorption of WF–ADBF hardboard were evaluated using procedures of ASTM D 1037 (ASTM 2007). Tensile strength perpendicular to panel surface (i.e., internal bond strength), thickness swell, and bending strength of WF–ADBF hardboard were compared to performance specifications required for various grades of commercial hardboard (ANSI A135.4–1995 (ANSI 1995)) (Figs. 3–5).

From this comparison of wet-formed WF–ADBF hardboard with various commercial grades of hardboard made with WF alone, tensile strength perpendicular to panel surface was superior to all commercial grades of basic hardboard (Fig. 3). However, the WF–ADBF hardboard without additives or resins did not meet commercial requirements for thickness swell (Fig. 4). This result was generally expected, as no resin or additive oils were used in these laboratory trials. Because most commercial hardboard commonly uses various resins and additives to promote resistance to moisture, it is probable that the commercial requirements for resistance to thickness swelling and water absorption could be met with the additional use of resins/additives and with greater processing experience. Finally, we note that our wet-formed laboratory WF–ADBF hardboard compared favorably with 4 out of 5 commercial grades of hardboard made with WF alone.

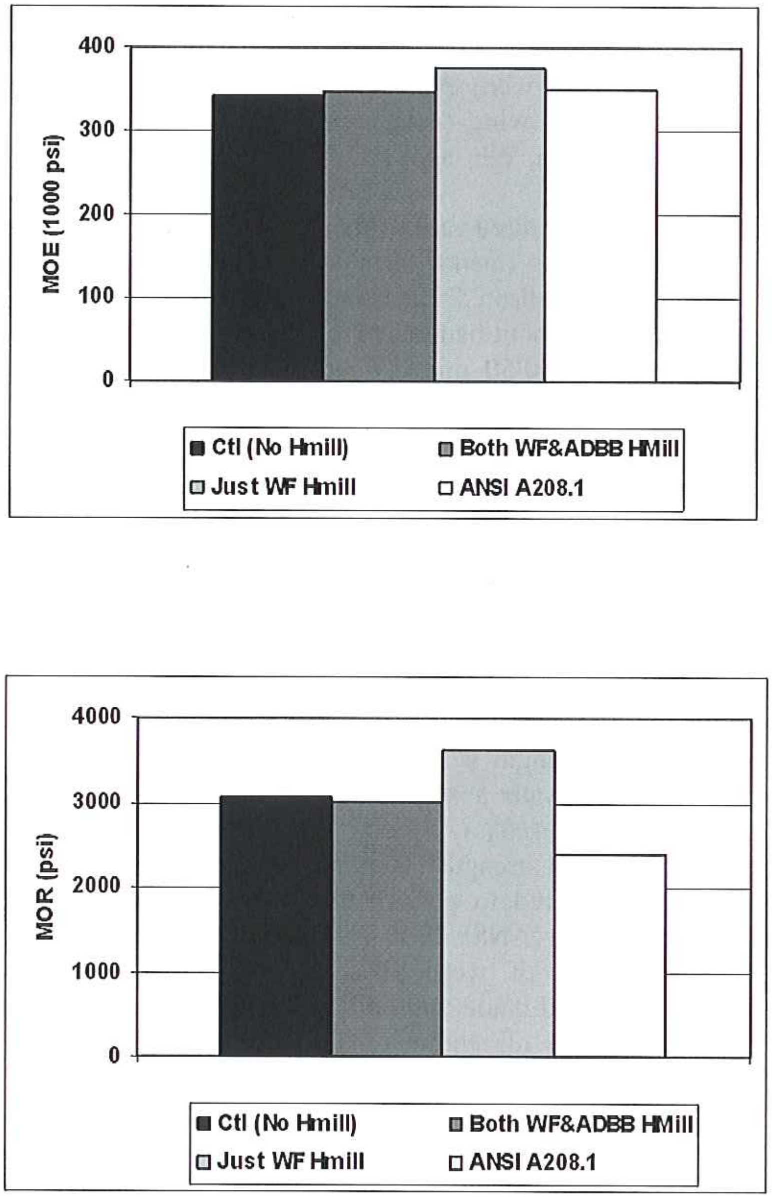


Figure 2. Effects of pre-process hammermilling of fiber on modulus of elasticity (MOE, top) and bending strength (modulus of rupture, MOR, bottom) of 50/50 hybrid wood–ADBF dry-formed particleboard compared with the commercial particleboard requirements in ANSI Standard A208.1 (1999).

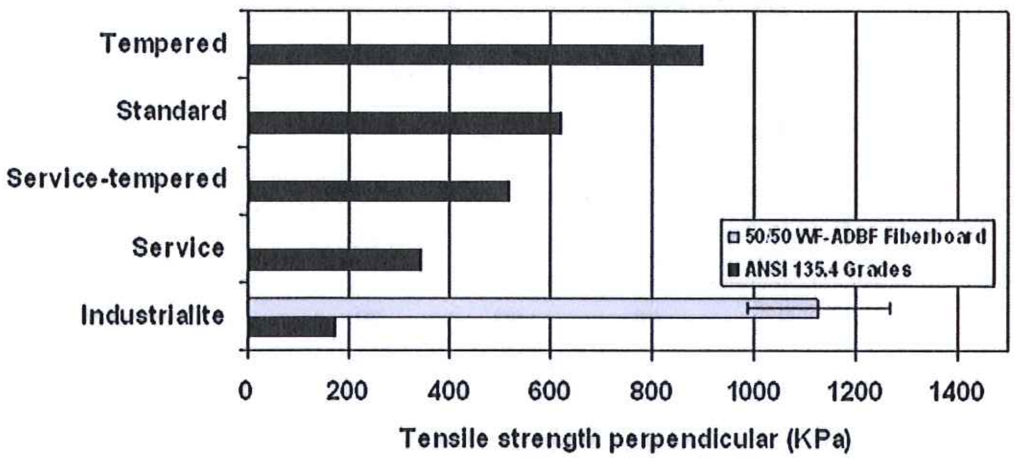


Figure 3. Comparison of tensile strength perpendicular to panel surface for 50/50 hybrid wood–ADBF wet-formed hardboard compared with commercial requirements of ANSI A135.4–2004.

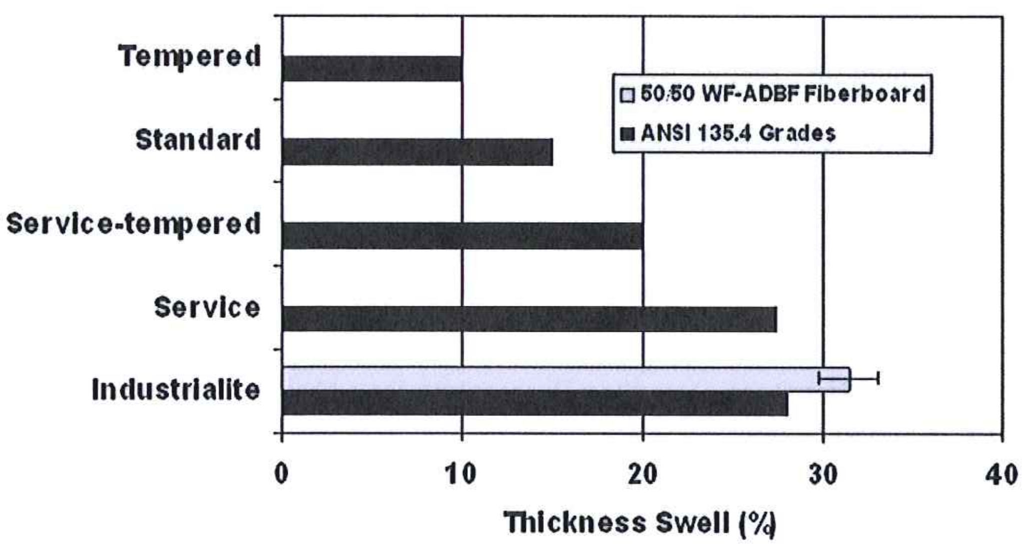


Figure 4. Comparison of 24-h thickness swell for 50/50 hybrid wood–ADBF wet-formed hardboard compared with commercial requirements of ANSI A135.4–2004.

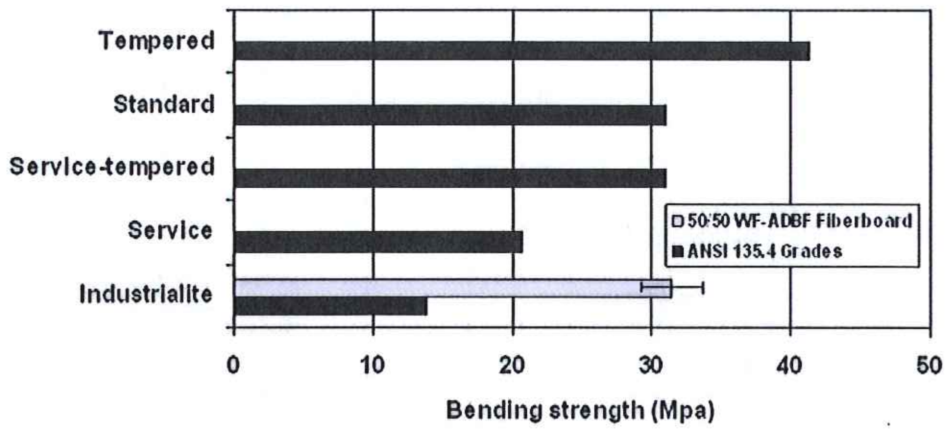


Figure 5. Comparison of bending strength for 50/50 hybrid wood–ADBF wet-formed hardboard compared to commercial requirements of ANSI A135.4–2004.

PARTICLEBOARD ECONOMICS

For the evaluation of ADBF's economic suitability for particleboard, we focus on a generic medium size plant whose salient operating parameters are depicted in Table 1.

Few residues or byproducts are normally generated in a particleboard plant, so the only outputs are the boards themselves. Unit prices and costs attached to the output and inputs used here were in the range generally experienced in 2007 and are shown in Table 2 along with the annual revenue streams derived by combining the unit values in Table 2 with the volume amounts in Table 1. Such a plant would essentially be at break even under the economic circumstances embedded in assumptions used for this study.

Table 1. Base Case Operating Parameters for a Medium-sized Particleboard Plant

	Amount	U.S. units	Amount	SI units
Output	80,000,000	ft^2 (3/4-in. basis)	141,600	m^3
Panel density	45	lb/ft^3	593	kg/m^3
Wood fiber, chips	78,066	odt	70,800	odmt
Wood fiber, dust	39,000	odt	35,400	odmt
ADBF	—	odt	—	odmt
Resin @ 7%	17.7	$\times 10^6$ lb	6.6	$\times 10^6$ kg
Wax @ 0.5%	1.3	$\times 10^6$ lb	0.5	$\times 10^6$ kg
Production labor	50	People		
Technical labor	20	People		
Electricity	260	$kWh/10^3 ft^2$	147	kWh/m^3
Natural gas	2	$10^6 Btu/10^3 ft^2$	1.2	GJ/m^3
Propane	1.5	$gal/10^3 ft^2$	3	L/m^3

Table 2. Base Case Prices and Revenue Streams Generated for a Medium-Sized Particleboard Plant in 2007.

Production item	Prices	Unit	Costs	Revenue
Particleboard	300	$\$/10^3\,ft^2$ (3/4-in. basis)		$24,000,000
Wood chips	65	$/odt	$4,474,148	
Shavings/sawdust	32.50	$/odt	$1,124,137	
ADBF	55	$/odt		
Fiber waste (trim, etc.)	12	%	$671,794	
Urea formaldehyde	0.4	$/lb	$7,056,000	
Wax	0.56	$/lb	$708,750	
Labor, production[a]	21.25	$/h	$2,146,048	
Labor, technical[a]	32.00	$/h	$1,292,671	
Electricity	0.065	$/kWh	$1,300,000	
Gas	8.0	$\$/10^6$ Btu	$ 1,280,000	
Propane	2.5	$/gal	$300,000	
Administration and overhead			$3,272,795	
Total			$23,626,343	
Gain (loss)			$373,657	

[a] Consists of base salary, fringe benefits, and social insurance payments.

Of particular interest is the amount paid for the fiber. Wisconsin has relatively few sawmills, and the amounts of planer shavings and sawdust available are therefore more limited than in regions that are richer in wood-processing facilities. Accordingly, plants in this region need to source fiber from a wider and often more expensive range of sources. Even in regions with more sawmills, however, periodic cycles in the sawmilling industry cause residue supply interruptions that disrupt particleboard production. Thus, ADBF offers a chance to diversify fiber procurement from a less cyclical source.

The $65/bdt (bone dry ton) for virgin chips and $32.50/bdt for sawdust used above are based on prices for delivered material typical for Wisconsin in 2007. To the extent ADBF can substitute for chips, the potential price limits are therefore $65/bdt. If it is only feasible to substitute it for sawdust, then the upper limit is half that. As noted above, ADBF has current uses as animal bedding. Biomass sold for this purpose fetches about $25/wet ton at 70% moisture, which translate to over $80/dry ton (Wagner 2007). A separate report cites $50/dried ton as an expected price for such material (Energy Solutions 2002). Thus, the further use of this material depends on (1) what it can be technically substituted for (i.e., chips or sawdust) and (2) demand for the material as animal bedding and other uses in relation to its supply.

Our material property comparisons we present here provide a positive answer to the question of technical substitutability. The answer to the economic question appears more tentative. Adding in $5/dry ton for delivery to an expected price of $50/ton, a resulting mill cost of $55/dry ton offers an economic advantage for chips but not for sawdust or shavings. We simulated the impact of ADBF on particleboard economics by replacing 75% of the chip input with ADBF. This creates an input mix consistent with our physical tests of 50% ADBF and 50% wood fiber (of which 2/3rd is sawdust/shavings and 1/3rd is chips). The resulting change in the gross income statement is a gain of $551,000 per year (Table 3). Stated another way, $551,000 are available per year should the substitution require other changes, such as increased resin use.

Table 3. ADBF Case Prices and Revenue Streams Generated for a Medium-Sized Particleboard Plant in 2007.

Production item	Prices	Unit	Costs	Revenue
Particleboard	300	$\$/10^3$ ft^2 (3/4-in. basis)		$24,000,000
Wood chips	65	$/odt	$1,118,537	
Shavings/sawdust	32.50	$/odt	$1,124,137	
ADBF	55	$/odt	$2,863,150	
Fiber waste (trim, etc.)	12	%	$612,699	
Urea formaldehyde	0.4	$/lb	$7,056,000	
Wax	0.56	$/lb	$708,750	
Labor, production[a]	21.25	$/h	$2,146,048	
Labor, technical[a]	32.00	$/h	$1,292,671	
Electricity	0.065	$/ kWh	$1,300,000	
Gas	8.0	$\$/10^6$ Btu	$ 1,280,000	
Propane	2.5	$/gal	$300,000	
Administration and overhead			$3,272,795	
Total			$23,074,786	
Gain (loss)			$925,214	

[a] Consists of base salary, fringe benefits and social insurance payments.

CONCLUSIONS

1. Our comparisons of the physical and mechanical properties of particleboard indicated that a 50/50 mixture of wood fiber and ADBF compares favorably with commercial standards for wood-based particleboard. The economic analysis indicates that replacing 75% of the chip input to a particleboard plant in Wisconsin with ADBF results in an economic gain of over a half-million dollars at prices and costs for particleboard and ADBF typically prevailing in 2007.
2. However, we note that the quoted ADBF prices were typically for relatively small volume sales to local purchasers. To be of interest to particleboard producers, fiber supply arrangements for ADBF will require large volumes contracted to be delivered regularly over extended periods.
3. Our familiarity with industry practices indicates that high-volume, long-time-horizon contracts are likely to be negotiated at lower prices than those typical of small-volume transactions. Thus, the ultimate negotiated cost of this fiber will likely be lower than assumed here. Whether this would still be attractive to dairy operators depends on the amounts of fiber generated by the industry over and above their own needs for bedding. Because such long-term, high-volume contracts currently do not exist, we can only speculate on what such terms might be.
4. An additional factor for particleboard producers to consider is the prospect of diversifying supply fiber to less cyclical sources, thus reducing procurement risk. Another factor is the regulatory and environmental pressures on industry in general to engage in more "green manufacturing" practices. ADBF dovetails well into this because of its post-industrial waste classification.

REFERENCES CITED

Ag Environmental Solutions, LLC (2002). *Tinedale Farms Anaerobic Digestion—A Biomass Energy Project*, Final Report 212–1, Energy Center of Wisconsin, Madison, WI.

ANSI (1999). *American National Standards Institute ANSI A208.1–1999: Particleboard*, Composite Panel Association, Gaithersburg, MD.

ANSI (2004). *American National Standards Institute ANSI A135.4–2004: Basic Hardboard*, Composite Panel Association, Gaithersburg, MD.

ASTM (2007). *ASTM Standard D 1037-06a: Standard Test Methods for Evaluating Properties of Wood-Based Fiber and Particle Panel Materials*, American Society for Testing and Materials, West Conshohocken, PA.

Burke, D. A. (2001). *Dairy Waste Anaerobic Digestion Handbook*, Environmental Energy Company, Olympia, WA.

Composite Panel Association (2005). *2005 North American Capacity Report*, Composite Panel Association, Gaithersburg, MD.

Maloney, T. M. (1977). *Modern Particleboard Manufacturing*, Miller Freeman Publications, San Francisco, CA, 681p.

Nelson, C., and Lamb, J. (2002). *Haubenschild Farms Anaerobic Digester*, The Minnesota Project, St. Paul, MN.

Random Lengths Publications, Inc. (2007) *2007 Yearbook.* Jon P. Anderson, Publisher, Eugene, OR.

Roos, K. F. (1991). *Profitable Alternatives for Regulatory Impacts on Livestock Waste Management. National Livestock, Poultry and Aquaculture Waste Management National Workshop*, USDA Extension Service, Kansa, MI.

Wagner, R. (2007). Personal communication with Richard Wagner, Chief Technical Officer, Quantum Dairy, Inc., Weyeauwega, WI.

WDNR (2008). *Wisconsin CAFO Permittees*, Wisconsin Department of Natural Resources (http://dnr.wi.gov/runoff/agriculture/cafo/permits/cafo_animals_spreadsheet.asp) (*viewed 27 June 2008*).

Winandy, J. E., and Cai, Z. (2008). "Potential of using anaerobically digested bovine biofiber as a fiber source for wood composites," *BioResources* 3(4), 1244-1255.

Article submitted: July 3, 2008; Peer review completed: Aug. 6, 2008; Revised version received and accepted: Sept. 22, 2008; Publication: Oct. 10, 2008.

APPENDIX B.

Potential of using anaerobically digested bovine biofiber as a fiber source for wood composites

Jerrold E. Winandy, Supervisory Research Wood Scientist,
Zhiyong Cai, Materials Research Engineer
USDA Forest Service, Forest Products Laboratory, Madison, WI

POTENTIAL OF USING ANAEROBICALLY DIGESTED BOVINE BIOFIBER AS A FIBER SOURCE FOR WOOD COMPOSITES

Jerrold Winandy,[a*] and Zhiyong Cai[a]

Manure, an animal waste product with many negative economic and environmental issues, can today be converted using anaerobic digestion technology into a number of commercial products ranging from fertilizer, compost, animal bedding, and plant bedding. A number of new uses are now being explored such as bioenergy (both electrical and biofuel) and a lignocellulose-rich potential feedstock for engineered biocomposite products for building materials. This paper explores the engineering potential of using anaerobically digested bovine biomass (ADBF) as a feedstock material for biocomposite building materials. Our evaluation generally indicated that making dry-formed fiberboard using up to a 50/50% mixture of wood fiber and ADBF-fiber compared favorably with some commercial requirements for wood-based medium-density fiberboard and particleboard.

Keywords: Anaerobically digested bovine biofiber; Fiberboard; Mechanical properties

*Contact information: a: U.S. Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726; *Corresponding author: jwinandy@fs.fed.us*

INTRODUCTION

Anaerobic digestion is a natural process that uses bacteria to convert biomass (e.g., any organic matter derived from plants, animals or their wastes) into three primary components in an oxygen-free environment. Anaerobic digestion yields methane gas, a liquid nutrient-rich effluent that has applicability as fertilizer, and a wet lignocellulosic-based fibrous residue that, when dewatered and dried, has utility as animal bedding, soil amendment, or potting soil. These lignocellulosic residuals are called anaerobically digested bovine biofiber (ADBF). Another possibility includes using mixtures of the ADBF in combination with wood for the making of engineered wood composites such as hardboard, particleboard, or Medium Density Fiberboard (MDF) (Spelter et al. 2008, Matuana and Gould 2006, Kuo 2008, Barron 2000). Others have evaluated bio-based thermoplastic composites (Rowell et al. 2007).

This research project involved two parts and identified the economic and engineering potential of using ADBF biomass as a feedstock material for biocomposite building materials. Another part of this project evaluated the economic potential of using ADBF biomass as a supplement to wood fiber for manufacturing engineered biocomposite products (Spelter et al. 2008). This second part of the project more fully developed an understanding of the engineering potentials of using ADBF biomass to meet the structural and utilitarian performance requirements for engineered building products and other related value-added user products. The information from this project is critical for policy makers and venture capitalists to fully understand and appreciate the economic and engineering potentials for this new technology. This work is made even more critical because as the world population grows, our need for safe, affordable, environmentally-friendly building materials is increasing. This research project provided an important opportunity to begin to develop critically needed new raw materials for future sustainable biocomposite products.

BACKGROUND

As the world population's grows, our need for safe, affordable, environmentally-friendly building materials has correspondingly increased. It is also in the best interests of the U.S. and the world's economies to decrease our dependence on non-renewable energy and materials based on petroleum. Many believe that we should increase our use of renewable, sustainable, bio-based resources. One critical part of any new bio-based economy will be to seek additional bio-based alternatives for building materials. While wood and woody fiber in North America will continue to have a preeminent place in any such move to sustainable building materials in a bio-based economy, alternative biofiber sources will also present important opportunities. Recent developments in agriculture and the increased use of anaerobic digesting systems for animal wastes offer one such opportunity to develop new value-added bio-based composites.

Trends in modern farming have been to increase the size and specialization of farms. Dairy operations and other confined animal feedlots across the U.S. have followed suit with more mega facilities that consolidate larger numbers of animals concentrated in one location. This has raised the challenge of managing manure to a scale heretofore rarely encountered, but at the same time has created opportunities to manage this waste to extract maximum value from it. This consolidation has also led to concerns over potential environmental problems such as odor, catastrophic spills or groundwater contamination, and regulations have been issued intending to control them. In addition, with the ever increasing concerns of urban sprawl encroaching on agricultural lands, the need to control and mitigate manure products produced by farm livestock is growing. Such pressures have stimulated interest in anaerobic digesters as ways to mitigate the concerns and possibly turn a business cost into a revenue stream.

Using **anaerobic digestion** (AD) technology, these agricultural "waste" materials have recently begun to be recognized as underutilized natural resources that have unrecognized value. Thus, technologies need to be developed and markets created for deriving value-added products from these supposed "waste" materials. Such technologies will decrease environmental issues, minimize odor-related concerns stemming from urban-encroachment on agricultural land, and increase the profitability for farmers.

From an environmental and a farmer's perspective, the major benefits of AD are a virtual elimination of point-source waste-water run-off problems and secondary benefits such as elimination of odor, pest, and weed control problems for farmers using AD to convert bovine wastes. Another large environmental benefit of an AD approach to handling bovine wastes is the ability to harvest and use the methane gas collected from the AD digester to reduce greenhouse gas emissions. Still another more tangible economic benefit is that the methane gas can then be collected and converted into either electricity or heat. One yet unanswered concern is what to do with the residual lignocellulosic solids from digested wastes. One currently used possibility is for animal bedding or potting soil (Zauche and Compton 2006). However, neither of these uses is an inherently high value-added use. Thus, a critical need exists to develop alternative high value-added uses for these residual lignocellulosic solids from AD digested wastes.

OBJECTIVES

Wood composite manufacturing uses large quantities of woody biomass, and anaerobically digested bio-fiber (ADBF) could be a potential replacement (or supplement) for wood fiber (WF) in some composites. This study evaluated the compatibility and performance of mixed WF-ADBF fiberboard and related it to commercial fiberboard and particleboard.

METHODS

This study evaluated composite boards made from mixtures of WF-ADBF using dry-form fiberboard technology. When the ADBF fiber arrived, a screen test was performed to classify the ADBF according to size. The results showed that 34.3% of the ADBF were +12 in the mesh screen size, 56.4% were in +20 screen size, 8.5% were in +40 screen size, and the rest were the fines. The size of ADBF was larger than the traditional MDF fiber (in the +40 to +120 screen size range) and smaller than the wood particles (generally in the +4 to +16 screen size range) commonly used for particleboard. The unique geometry characteristics of ADBF could make it suitable to substitute or replace either fiber for MDF or wood particle for particleboard. The investigation was carried out in two parts. A small preliminary Phase I study was first performed to define the implications of various pre-production fiber processing methods. This was followed by a larger primary Phase II study to evaluate various parameters including fiber mixture ratios, resin options, and fiberboard densities. All wood fiber used in both Phases of this study was a mixture of various southern pines (*Pinus spp.*) and obtained from a commercial fiberboard plant. This thermomechanical pulp (TMP) pine fiber was manufactured from steamed wood chips using a pressurized refiner. This TMP pine fiber was then quickly shipped to our laboratory and dried at 103°C for 24 hrs to approximately 4% moisture in our laboratory tray driers prior to its use. During drying the TMP fiber tended to ball together, and a hammermill (without a screen) was used to break the fiber balls and bundles into loose fibers.

Phase I

In the preliminary (i.e., Phase I) part of this investigation, the ADBF was considered as being closer to the wood particles, and 50/50% mixtures of dried WF and ADBF-fiber (both ~5% moisture content) were studied for their potential use as particleboard. Because Phase I materials were a combination of various hammermilling processes, resulting in an array of fibers sizes and morphologies, the results were compared to commercial particleboard (ANSI 1999), which allows for this greater diversity of fiber/particle sizes and shapes. The hammermilling process used in this study was different than the processes used in traditional industrial particleboard manufacturing, which are intended for size reduction of wood chips and shavings into fine particles.

In Phase I, we compared mixtures of WF and ADBF prepared in three different ways. This comparison included fiberboard made from: a) WF and ADBF that were both hammermilled, b) virgin WF and ADBF (neither hammermilled), and c) a mixture of hammermilled WF mixed with virgin ADBF. The three variously processed WF-ADBF fiber mixtures were made into a dry-form fiberboard with a target density of 800 kg/m^3. Urea formaldehyde resin (47% solids) was applied at a rate of 8% (w/w solids) to the fiber mixtures while circling at high speed in a tube blender for 5 minutes. No wax was used. The resinated fiber mixtures were then formed into 610- by 610-mm loose mats and hot-pressed at 200°C using the following pressing schedule: close to target thickness (90s), hold at 12.5-mm target thickness (150s), and slow release of pressure to open (160s).

Two replicate boards for each mixture were made and evaluated. Each 610- by 610-mm board had 100-mm trimmed off each edge and test specimens (ASTM Standard-D1037) were cut out. The fiberboard specimens were then evaluated for various physical and mechanical performance criteria using standard methods (ASTM Standard-D1037). The following fiberboard performance criteria were evaluated:

(1) Modulus of elasticity (MOE),

(2) Modulus of rupture (MOR),

(3) Internal bonding (IB) at 65% Relative Humidity

(4) Water absorption (WA) after 24-hr water soak

(5) Thickness swelling (TS) after 24-hr water soak

Phase II

The results of the preliminary Phase I investigation were used to select the appropriate pre-production fiber processing methods regarding whether or not to hammermill the various WF and/or ADBF fibers used for the subsequent Phase II work. In Phase II, the ADBF fibers were not hammermilled, while the wood fibers were hammermilled to break down the fiber clumps and provide a uniform fiber geometry. After hammermilling, the wood fibers were similar in size and shape and thus more comparable to the commercial thermomechanical pulp (TMP) fibers normally used for commercial fiberboard, especially MDF. Thus, in Phase II the boards made were similar to the commercial MDF boards and thus their performance was compared to the commercial requirements for MDF (ANSI 2004). This larger Phase II study specifically studied five mixed fiber combinations from 0/100 to 100/0 using two commercial resin systems and multiple board densities. In Phase II, forty medium-density fiberboard (MDF) panels were manufactured as indicated in Table 1. The same blending, forming and pressing procedures were used as described in Phase I except that two resins (UF at 8% and PF at 3.5%) were evaluated. The UF and PF resins had 47% and 51% solids content, respectfully. It was visually noted that after applying resin on the wood and ADBF fiber mixtures using the high-speed tube blender the resinated fiber mixtures were uniform in size and resin distribution. The blender provided resinated fiber mixtures that were loose and easy to form into 500- x 500-mm mats. After hot-pressing and cooling, each panel had 50-mm of trim along each edge removed before the ASTM D-1037 test specimens were cut out. The MDF composite materials were evaluated for physical and mechanical performance using the same standard evaluation techniques (ASTM Standard-D1037). The same five performance criteria for fiberboard were evaluated as in Phase I.

RESULTS AND DISCUSSION

Phase I

This preliminary dry-form fiberboard study evaluated the compatibility of ADBF-fiber and wood both with and without mechanical separation (i.e., hammermilling). The actual board densities were 800 kg/m^3 ($\pm$3 kg/m^3) and board moisture contents at time of physical and mechanical testing were 3.7% ($\pm$ 0.3%). The strength and stiffness results clearly indicated that woody fiber and ADBF-fiber could be successfully mixed in a 50/50 mixture either with or without hammermilling (Fig. 1). The results also indicated that the three variously processed 50/50 mixed-fiber types produced a fiberboard that compared favorably to the requirements for H-1 grade commercial particleboard as specified by ANSI Standard A208.1 (1999) (Table 2). The internal bond strength for mixtures of virgin ADBF and hammermilled WF were generally equal to fiberboard made with neither the WF or the ADBF being hammermilled (both ~70psi $\pm$ 5psi). The fiberboard made from hammermilled WF and hammermilled ADBF was ~20% lower in internal bond strength than the other two groups. There were no practical differences between the three tested fiberboards in either thickness swell (~35% $\pm$3%) or water absorption (~90% $\pm$5%). As such we decided that the most appropriate mixture of WF and ADBF to study further in Phase II would be to select hammermilled WF and non-hammermilled ADBF, because it appeared to maximize performance and minimize required processing. We thought this combination as appropriate because virgin corn stover usually needs to be hammermilled to mechanically break down the waxy cuticle layer on that corn stove, whereas the natural process of bovine digestion followed by anaerobic digestion of that residue would probably eliminate the need for hammermilling the ADBF fiber.

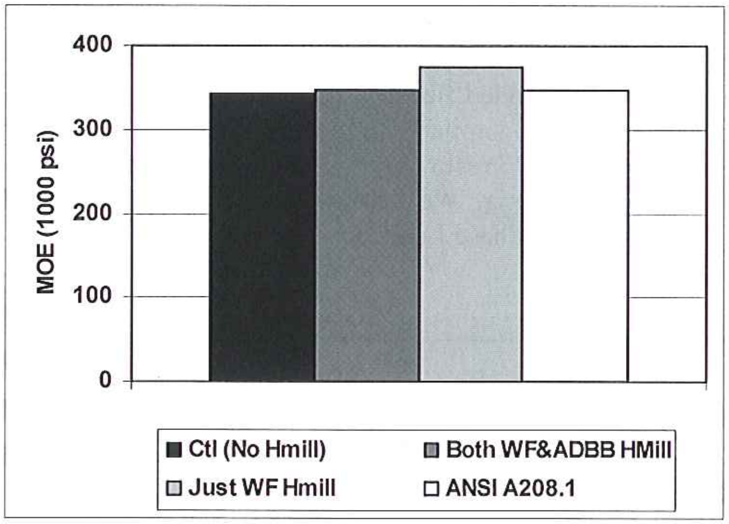
Table 1. Experimental Design of the Phase II Dry-form Fiberboard (500- x 500- x 12.5mm thick) using Hammermilled Wood Fiber and Non-Hammermilled ADBF.

Wood TMP fiber	ADBF-fiber	UF/PF	Density	Replicates[1]
(%)	(%)	(%)	(kg/m^3)	
100	0	PF 3.5	670	2
67	33	PF 3.5	670	2
50	50	PF 3.5	670	2
33	67	PF 3.5	670	2
0	100	PF 3.5	670	2
100	0	PF 3.5	800	2
67	33	PF 3.5	800	2
50	50	PF 3.5	800	2
33	67	PF 3.5	800	2
0	100	PF 3.5	800	2
100	0	UF 8.0	670	2
67	33	UF 8.0	670	2
50	50	UF 8.0	670	2
33	67	UF 8.0	670	2
0	100	UF 8.0	670	2
100	0	UF 8.0	800	2
67	33	UF 8.0	800	2
50	50	UF 8.0	800	2
33	67	UF 8.0	800	2
0	100	UF 8.0	800	2

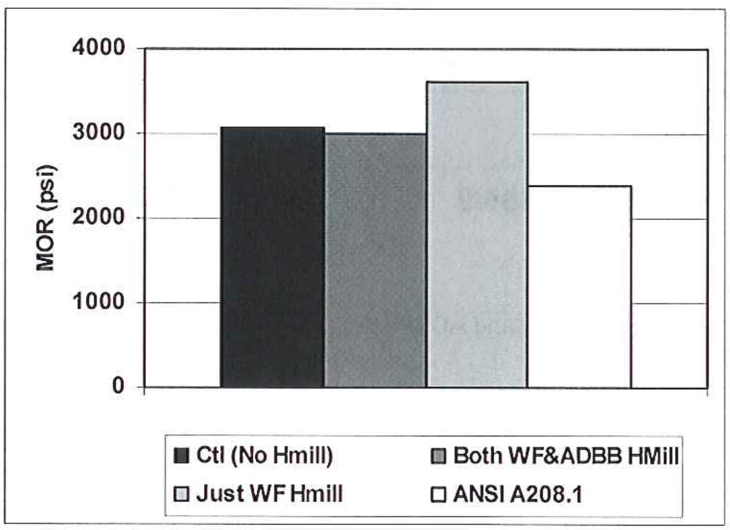
Table 2. Performance Requirements of Various Grades of Commercial Particleboard and Fiberboard

Material Type	ANSI Standard	Grade	MOE (lb/in^2)	MOR (lb/in^2)	Internal Bond Strength (lb/in^2)	Thickness Swell (%)
Particleboard	A208.1	H-1	348,100	2393	130	---
		M-1	250,200	1595	58	---
		M-S	275,600	1813	58	---
		M-2	326,300	2103	65	---
		PBU	250,200	1595	58	---
MDF	A208.2	110	203,100	2030	44	$\leq$10
		120	203,100	2030	73	$\leq$10
		130	348,100	3481	87	$\leq$10

[1] Used 2 replicates because of volume-capacity limits of FPL tube-blender



a)



b)

Figure 1. Effects of pre-process hammermilling of fiber on a) Modulus of Elasticity (MOE) and b) bending strength (MOR) of 50/50% hybrid wood-ADBF dry-formed fiberboard compared to commercial H-1grade particleboard requirements.

Phase II

The larger Phase II study specifically evaluated five mixed fiber combinations from 0/100 to 100/0 using two commercial resin systems (PF at 3.5% and UF at 8%) and two fiberboard board densities (670 and 800 kg/m^3). The parameters evaluated for the MDF were MOE, MOR, IB, WA and TS.

Bending stiffness and strength

The MOE values of two fiberboard board densities (680 and 800 kg/m^3) made using 8% UF and 3.5% PF resin and five mixture ratios of WF-to-ADBF fiber at mixtures from 0/100 to 100/0 are shown in Fig. 2. Figure 3 shows the same relationships and process factors, but for MOR. From both, it is evident that the UF-bonded fiberboards clearly exhibited superior performance over the PF-bonded fiberboard in Phase II. This was surprising, as the PF-bonded fiberboards made using a 50/50% WF-ADBF mixture in Phase I (Fig. 1) performed similarly to the UF-bonded fiberboard in Phase II (Figs. 2 and 3). We suspect that the PF resin used in Phase II was faulty or that a processing error occurred in blending or pressing. We are now further investigating. Still the results of the UF in Phase II and the PF in Phase I are convincing.

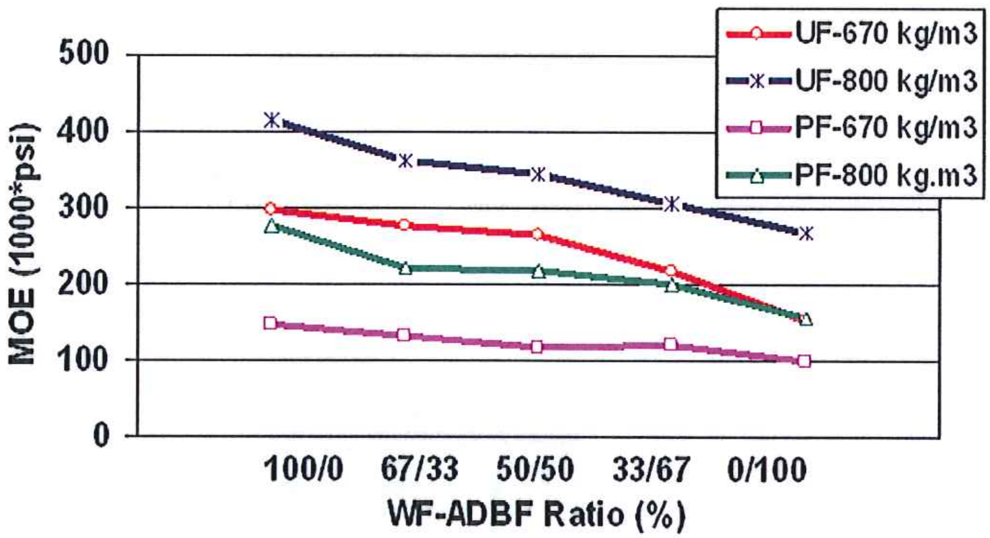


Figure 2. Effects of various WF and ADBF fiber mixtures and fiberboard density on Modulus of Elasticity (MOE)

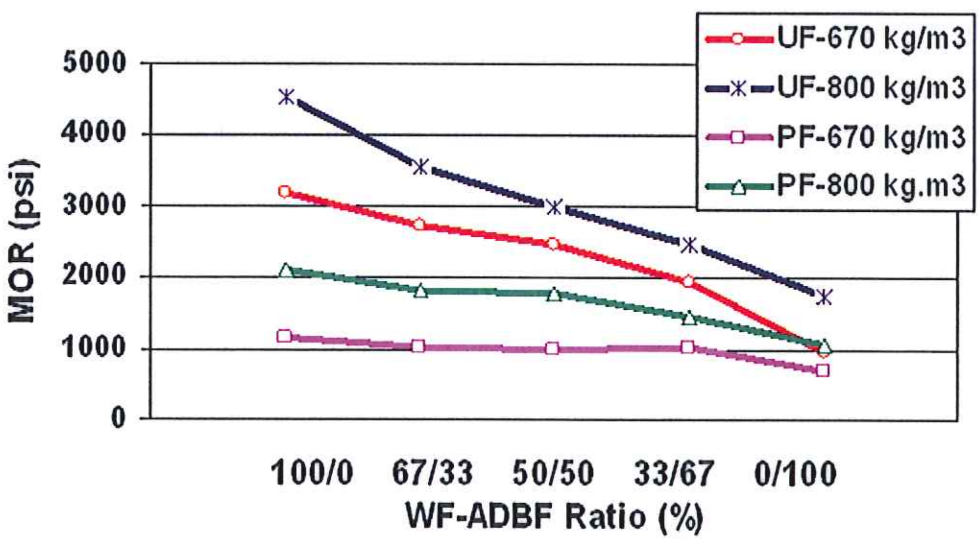


Figure 3. Effects of various WF and ADBF fiber mixtures and fiberboard density on Modulus of Rupture (MOR)

For the UF-bonded fiberboard the results clearly show that as ADBF ratio increased relative to WF, both the MOE and MOR clearly decreased (Figs. 2 and 3). The ANSI 208.1 standard requires that H-1 grade particleboard, which by definition has a density $\geq$800 kg/m^3, have an MOE of at least 348,100 lb/in^2 and MOR of 2393 lb/in^2 (Table 2). From Fig. 2 it is evident that only the high-density, UF-bonded, WF-ADBF fiberboard (density = 800 kg/m^3) having a WF level of at least 50% and $\leq$50% ADBF fiber consistently met the MOE requirements for the H-1 grade of commercial particleboard. Likewise, from Fig. 3 it is clear that both the low- and high-density WF-ADBF fiberboard (density = 670 and 800 kg/m^3, respectively) with a WF level of at least 50% and $\leq$50% ADBF fiber met the MOR requirements for H-1 particleboard.

With respect to the commercial requirements for MOE of 670 kg/m^3 (i.e., medium-density) fiberboard (Table 2), all WF-to-ADBF mixture ratios for the 800 kg/m^3 (i.e., high-density), UF-bonded fiberboard met all requirements for MOE for two of the three most critical MDF grades (i.e., 110, 120). For the third grade (i.e., 130), the low-density WF-ADBF fiberboard (density = 670 kg/m^3) did not meet the Grade 130 requirements for MOE while only the high-density fiberboard (density = 800 kg/m^3) met MOE requirements when having a WF level of at least 67% and $\leq$33% ADBF fiber.

When considering the requirements for commercial medium-density fiberboard, many WF-to-ADBF mixture ratios for the UF-bonded WF-ADBF fiberboard met the requirements for MOR. For the two lower MDF grades (i.e., 110, 120), the lower-density MDF met the requirements when having up to 50% ADBF fiber, while the higher-density MDF met the requirements whenever it had a ADBF fiber level of $\leq$67% ADBF fiber. For the third grade (i.e., 130), the lower-density MDF did not meet the Grade 130 requirements for MOR, while the higher-density fiberboard only met the MOE requirements when having a WF level of at least 67% and $\leq$33% ADBF fiber.

Internal bond strength

When considering internal bond strength (IB) we encountered a problem in achieving adequate bonding of the metal IB blocks to all of the WF-ADBF made using PF resin. All the IB failures occurred by separation of the metal IB from the outer surfaces of the PF-bonded IB specimens. We had not encountered this problem in Phase I or in Phase II when using all-WF specimens or when evaluating the UF-bonded WF-ADBF specimens. This again leads us to suspect the PF-resin or a processing error. Hence, only the results of the UF-bonded WF-ADBF specimens are reported (Fig. 4).

Both the lower- and higher-density UF-bonded fiberboard met the M-1, M-S, and PBU Grade requirements for IB of particleboard when having an ADBF fiber level of $\leq$33% ADBF fiber. Likewise, the lower-density fiberboard met the Grade 110 requirements for IB of MDF when having a WF level of at least 50% and $\leq$50% ADBF fiber, while the higher-density fiberboard met the Grade 110 requirements when having a WF level of at least 67% and $\leq$33% ADBF fiber.

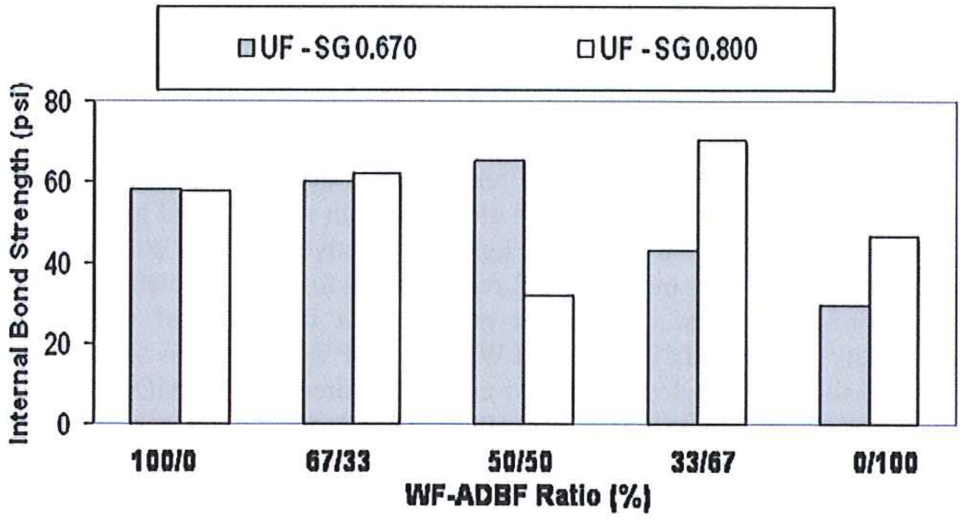


Figure 4. Effects of various WF and ADBF fiber mixtures and fiberboard density on internal bond strength (IB)

Thickness swell/water absorption

Two observations are quickly apparent from Figs. 5 and 6. First, note that both thickness swell and water absorption were greater for PF bonded specimens than for UF-bonded fiberboard. This is probably in part related to the UF at 8% being more compatible with the WF and ADBF than the PF at 3.5% and in-part related to the potential resin or processing problems previously discussed. The second observation is higher-density UF- and PF-bonded fiberboard usually experienced less TS and WA after a 24-hr soak than lower-density fiberboard.

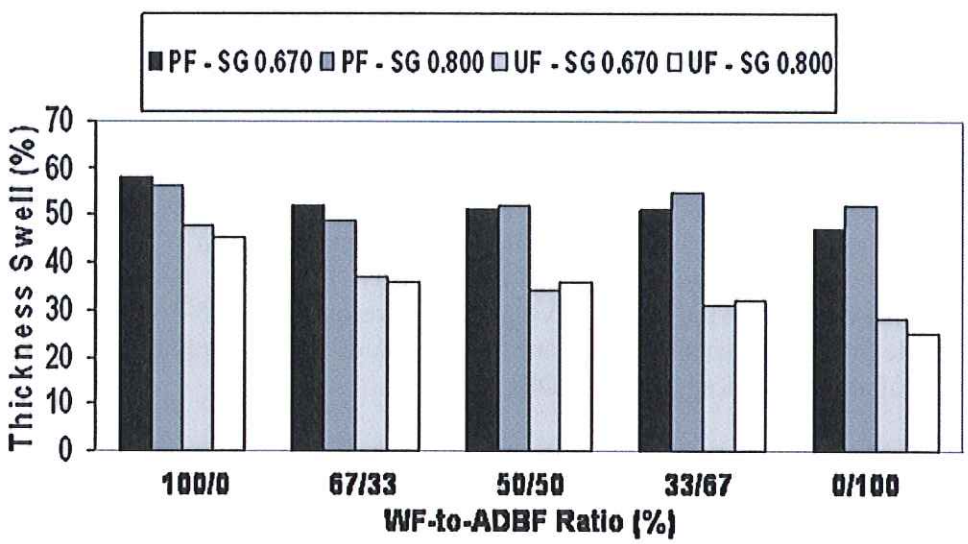


Figure 5. Effects of various WF and ADBF fiber mixtures and fiberboard density on thickness swell (TS) after 24-hr soak

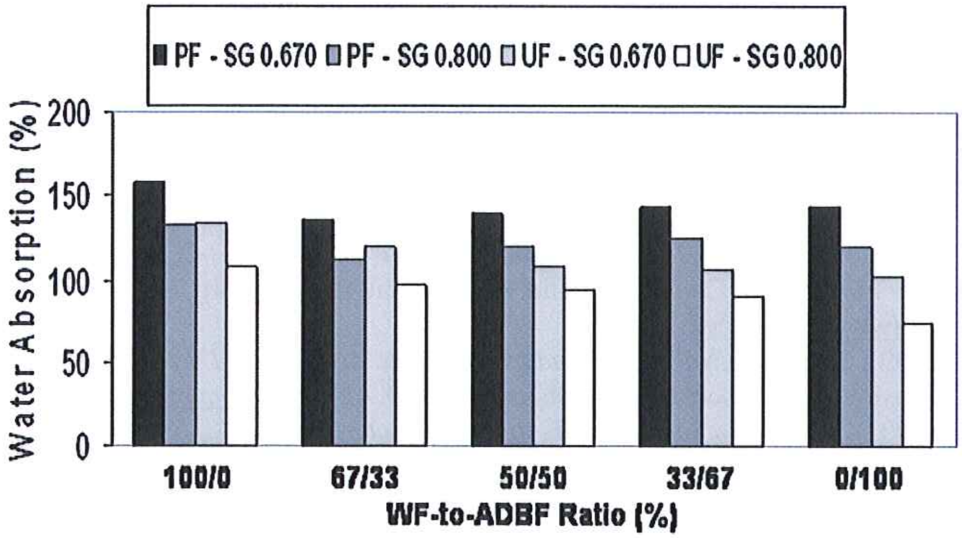


Figure 6. Effects of various WF and ADBF fiber mixtures and fiberboard density on water absorption (WA) after 24-hr soak

In the final analysis all combinations of WF and ADBF failed to meet the thickness swell requirements of ≤10% for MDF. This probably has as much or more to do with our decision to not add wax in fiberboard manufacturing than it had to do with an inherent difference in performance between wood and mixed WF-ADBF fiberboard.

SUMMARY

Our two-part evaluation of the physical and mechanical properties of dry-formed particleboard consistently indicated that up to a 50/50% mixture of wood fiber and ADBF-fiber compares favorably with commercial standards for wood-based MDF and particleboard. While to date our work at FPL has not evaluated all mixtures of WF and ADBF, these results indicate that virtually any combination of WF and ADBF is potentially feasible. It appears that combinations varying from 67-to-33% WF and 33-to-67% ADBF generally will meet many of the performance criteria in the ANSI commercial standards for particleboard or MDF. The results varied depending on the product type, density and grade being considered.

Local economics will probably determine the optimal mixture of WF and ADBF feasible at any commercial fiberboard/particleboard manufacturing facility with these local factors, undoubtedly affecting the critical price-point for ADBF fiber in woody composites. A recent study by Spelter et al. (2008) indicated that at one mill in central Wisconsin up to 25% of the WF could be substituted with ADBF and still be economically viable.

Another factor for composite producers to consider that might significantly benefit the analysis of whether or not to use ADBF concerns the potential "marketing" opportunity to employ more "green manufacturing" practices. ADBF-fiber dovetails well into this because it falls into the post-industrial waste classification. Commercial wood-composite manufacturing companies might be able to market a hybrid WF-ADBF product as an opportunity to attract new "green-minded" customers who are seeking more environmentally beneficial products.

REFERENCES CITED

ANSI (2004). *American National Standards Institute ANSI A201.2-2004: Medium Density Fiberboard.* Composite Panel Association. Gaithersburg, MD. (http://www.pbmdf.com)

ANSI (1999). *American National Standards Institute ANSI A208.1-1999: Particleboard.* Composite Panel Association. Gaithersburg, MD. (http://www.pbmdf.com)

ASTM (2007). *American Society for Testing and Materials (ASTM) Standard D-1037-06a: Standard test methods for evaluating properties of wood-based fiber and particle panel materials.* West Conshohocken, PA. (http://www.astm.org)

Barron, T. (2000). "From cow chips to cow barns," Inside Iowa State (May 19, 2000) http://www.iastate.edu/Inside/2000/0519/cowchips.html

Kuo, M.L. (2006). Personal communication: "Using digested manure for composites," July 25, 2008.

Matuana, L. and Gould, M.C. (2006). "Promoting the use of digestate from anaerobic digesters in composite materials," Final Report: Grant #PLA-06-42. Community Energy Project. Michigan State University, East Lansing, MI. (https://www.msu.edu/~matuana/images/CompositesProjectFinalReport1.pdf).

Rowell, R. M., O'Neill, E., Krzysik, A., Bossman, D., Gallaway, D. F., and Hemenover, M. (2007). "Incorporation of animal manures as reinforcing fillers in high-density polyethylene and high-density polypropylene composites," IN: *Proceedings of 9th International Conference on Wood a & Biofiber Plasitic Composites.* Forest Products Society, Madison, WI. pp. 371-374.

Spelter, H., Winandy, J.E., and Zauche, T. (2008). "Anaerobically digested bovine biofiber as source of fiber for particleboard manufacturing," *BioResources* 3(4), 1256-1266.

Zauche, T. H, and Compton, M. E. (2006). "Use of manure digester solids as a substitute for sphagnum moss peat in horticultural growing media," Report to: WiSys Technology foundation, Inc. Feb. 21, 2006. Madison, WI.

Article received: August 25, 2008; Peer-review completed: Sept. 22, 2008; Revised version received and accepted: Oct. 8, 2008; Published: Oct. 10, 2008.