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^{o}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^oC 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.

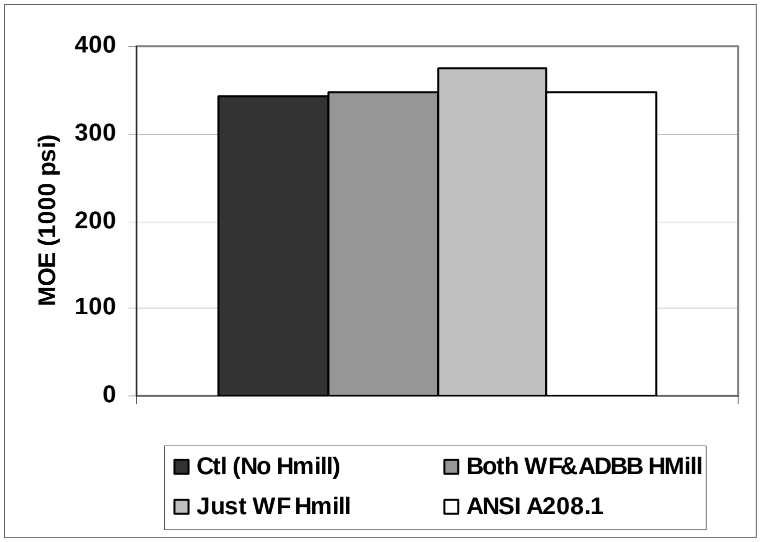
Table 1. Experimental Design of the Phase II Dry-form Fiberboard (500- x 500- x 12.5mm thick) using Hammermilled Wood Fiber and Non-Hammermilled ADBF.

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	≤10
		120	203,100	2030	73	≤10
		130	348,100	3481	87	≤10

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



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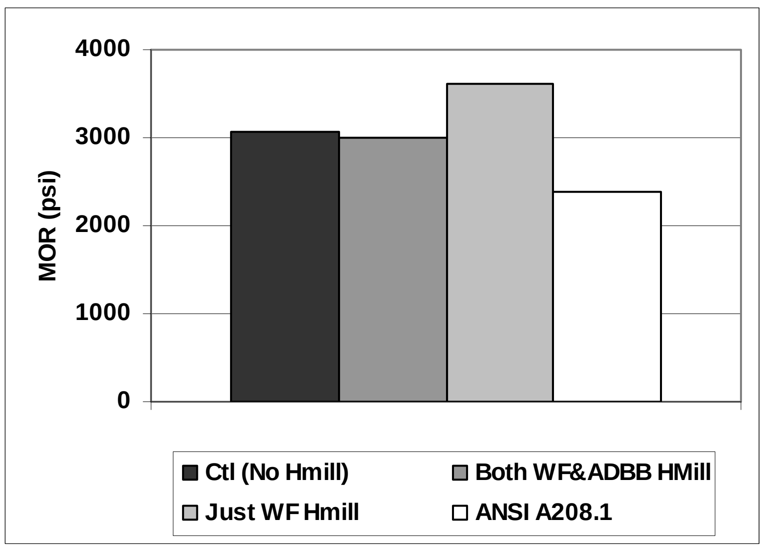

b)

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.

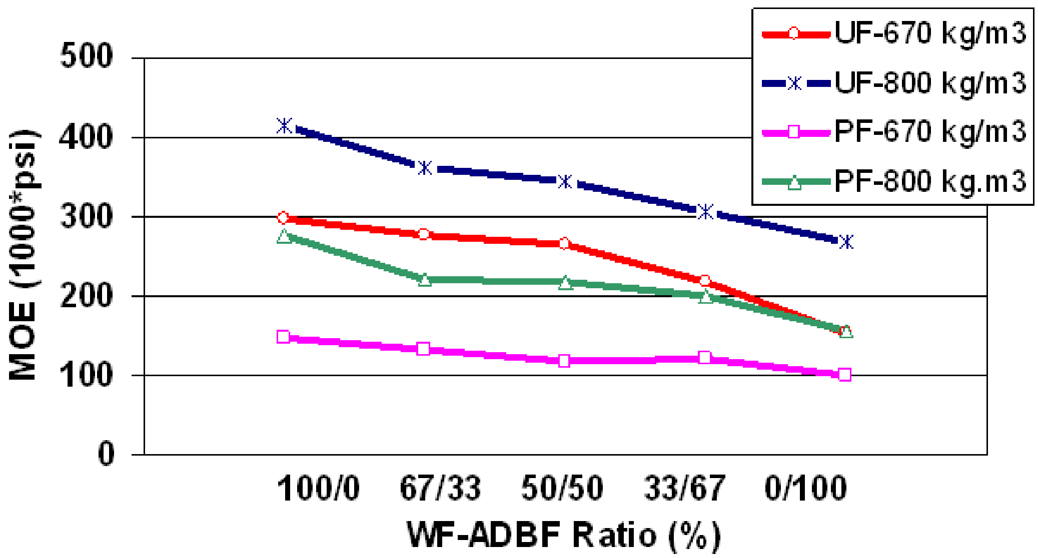

Figure 2. Effects of various WF and ADBF fiber mixtures and fiberboard density on Modulus of Elasticity (MOE)

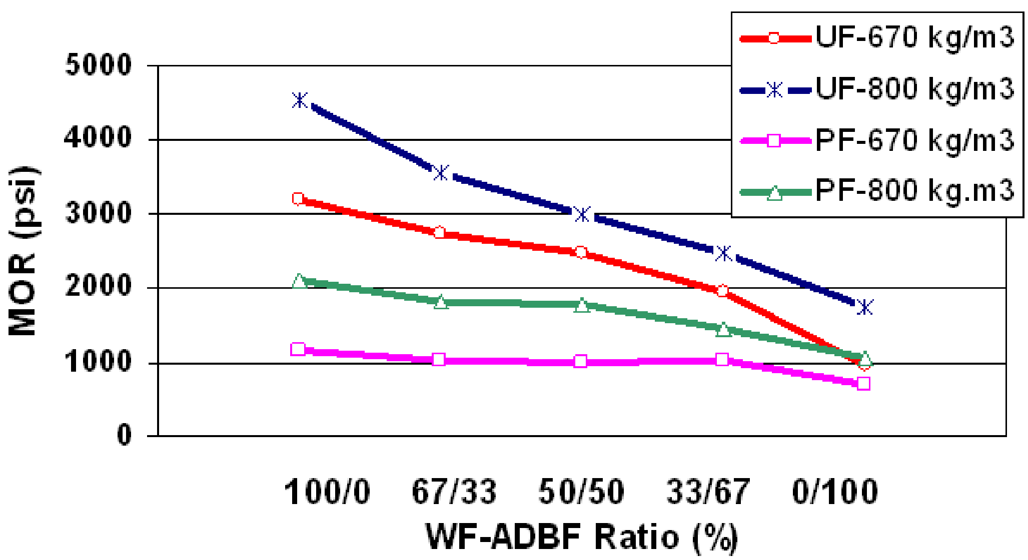

Figure 3. Effects of various WF and ADBF fiber mixtures and fiberboard density on Modulus of Rupture (MOR)

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 ≥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 ≤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 ≤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 ≤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 ≤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 ≤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 ≤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 ≤50% ADBF fiber, while the higher-density fiberboard met the Grade 110 requirements when having a WF level of at least 67% and ≤33% ADBF fiber.

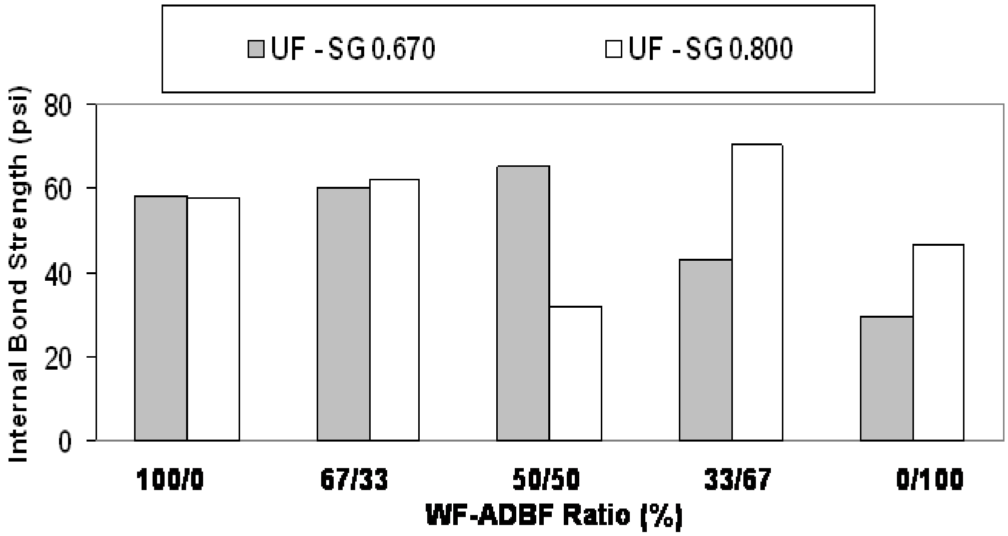

Figure 4. Effects of various WF and ADBF fiber mixtures and fiberboard density on internal bond strength (IB)

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.

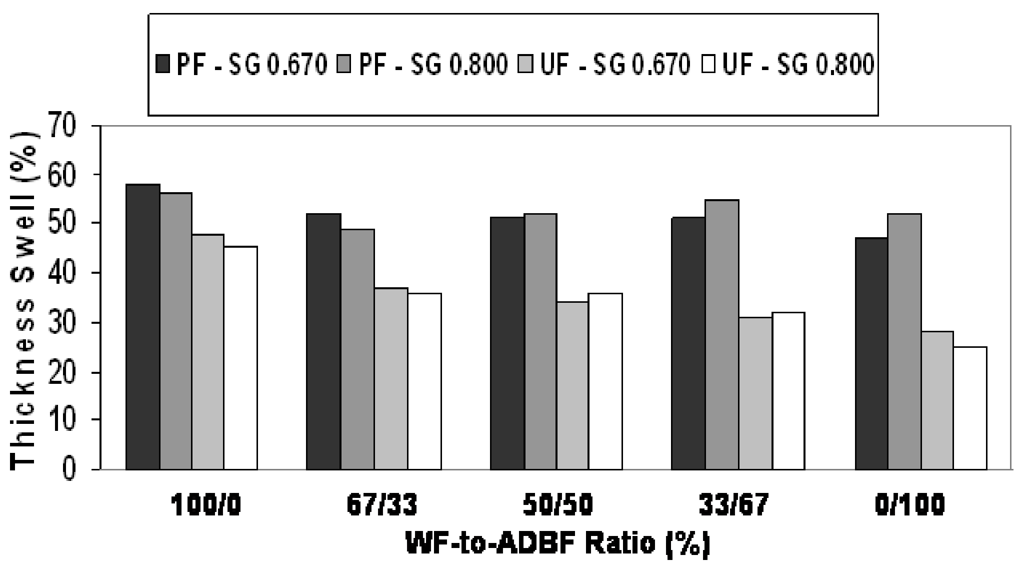

Figure 5. Effects of various WF and ADBF fiber mixtures and fiberboard density on thickness swell (TS) after 24-hr soak

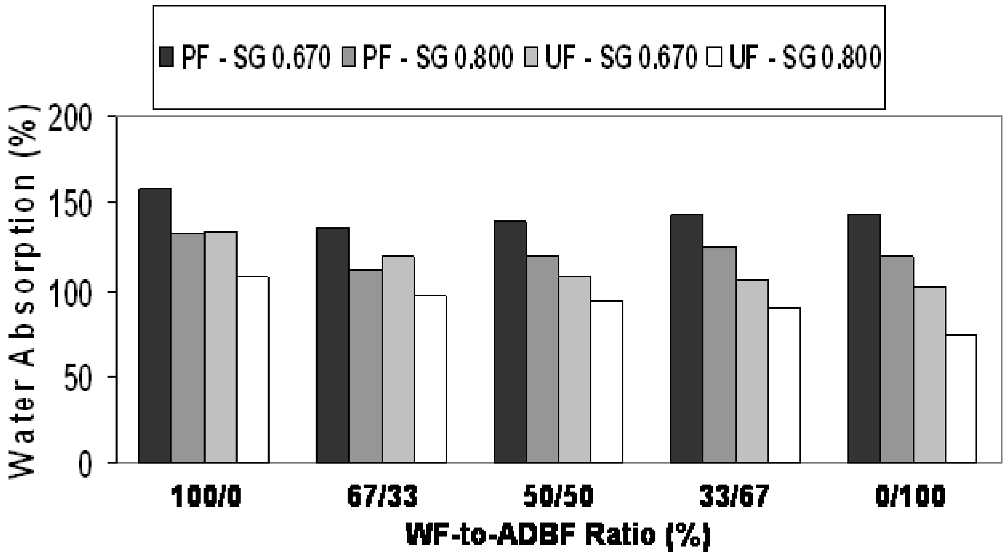

Figure 6. Effects of various WF and ADBF fiber mixtures and fiberboard density on water absorption (WA) after 24-hr soak

In the final analysis all combinations of WF and ADBF failed to meet the thickness swell requirements of $\leq$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.

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