The Fourth International Conference
on Woodfiber- Plastic Composites

Wheat Straw as a Reinforcing Filler in Plastic Composites

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Abstract

In 1995, Pinnacle Technology, Inc., entered into a Cooperative Research and Development Agreement with the USDA Forest Products Laboratory to pursue the commercialization of wheat straw as a reinforcing filler for commodity thermoplastics. The initial results have been proven on a laboratory scale and in initial test manufacturing trials. The work to date has consisted of detailed characterization of the mechanical properties of the plastic, preliminary engineering and economic analysis, assessment of fiber processing, and chemical additives on final characteristics of the plastics, market surveys, and test manufacturing. Based on a detailed cost assessment for the process, the emphasis of the current research is to increase the fiber loading from 30 percent to 50 percent in the final product without substantially altering the physical characteristics of the composites or greatly impacting the ease of final molding. As a percent of sales, in a 30 percent filled material the feedstocks account for 65 percent of the cost. However, in a 50 percent

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Pinnacle would like to thank all the individuals and companies which made this research possible. Our utmost gratitude goes to the USDA Forest Products laboratory who not only developed all the initial background research but also did all the compounding, material property testing, and SEM photography in this paper. Special thanks are due to: the plastics companies for their enthusiasm, trust, and technical curiosity in allowing the agroplastic to be tested in their injection-molding equipment; Jeff Morrow and several of his students (Aaron Franz, Chad Huffman, and Dexter Phillips) in the Univ. of Kansas Business School for “adopting” Pinnacle Technology and this project as their class project; Kansas Technology Enterprise Corp., especially Sherry Schoonover, for their initial faith and funding in agroplastics research and their continued advisory support; and the USDA’s Small Business Innovation Research Program and the U.S. Dept. of Energy’s Western Regional Biomass Energy Program for their financial support.

filled product, feedstocks only account for 48 percent of the cost. If these increases can be successfully implemented, the rate of return to the investor increases substantially.

Introduction

The USDA Forest Product Laboratory in Madison, Wisconson, is developing the technology to use agricultural crops and coproducts as fibrous reinforcements or fillers for commodity thermoplastics. Pinnacle Technology, Inc., entered into a Cooperative Research and Development Agreement with the Forest Products Laboratory in 1995 to develop and commercialize the agroplastics technology developed by the Laboratory using wheat straw agrofiber.

Fillers have been used in the plastics industry for almost 90 years. Wood flour was first used to extend and improve the processability of thermosetting resins in 1907. Currently, over 500 million pounds of fibrous material (primarily glass) is being used by the plastics industry The total amount of all fillers used in 1993 in the plastics industry was estimated to be 7.7 billion pounds.

To optimize the properties of melt-blended agrofiber thermoplastic composites, we initiated a fundamental materials science approach to investigate some of the major factors that govern composite characteristics. The primary goal was to provide insights into processing to tailor the composite for optimized fiber dispersion and fiber lengths. Homogeneous fiber distribution is a prerequisite that cannot be compromised in short fiber composites, while long fiber length is necessary to enhance composite reinforcing efficiencies that control tensile, impact, and creep behavior. In general, high shear processing is necessary to attain uniform fiber distribution, yet high shearing action results in significant fiber breakage and poor composite strengthening efficiencies. It is important to maximize uniformity of fiber dispersion and, at the same time, minimize fiber damage. The study aimed to preserve fiber length by altering processing parameters, using minimal additives to improve fiber dispersion and stress transfer between matrix and fiber. Analytical techniques were used to evaluate and select appropriate additives and processing techniques. Properties that are strongly dependent on fiber lengths (tensile, flexural, and impact) were measured.

Mechanical properties

Compounding methods

All of the composite blends were compounded in a Davis & Standard (Pawcutuck Conn.) twin-screw extruder. The extruder has 32-mm diameter corotating intermeshing segmented screws with a length-to-diameter ratio of 32:1. There are eight electrically heated, water-cooled barrel sections, two which have vents for removing volatile materials. Power is supplied by a 15-hp DC drive, and a four-hole strand die is fitted to the discharge end. The machine's capacity is 45 kg (100 lb.) of unfilled polypropylene per hour. The extruded strands of wheat straw / polypropylene composites were cooled in a water slide trough and then pelletized in a Cumberland (Providence, R.I.) pelletizer. A flow diagram of the process is shown in Figure 1.

The wheat straw was processed using different fiberization and size reduction technologies. Pinnacle has developed two grades of 30 percent wheat straw / 70 percent polypropylene for market (WS-01 and WS-02). In addition, a third grade has been developed which is 30 percent wheat straw / 70 per-

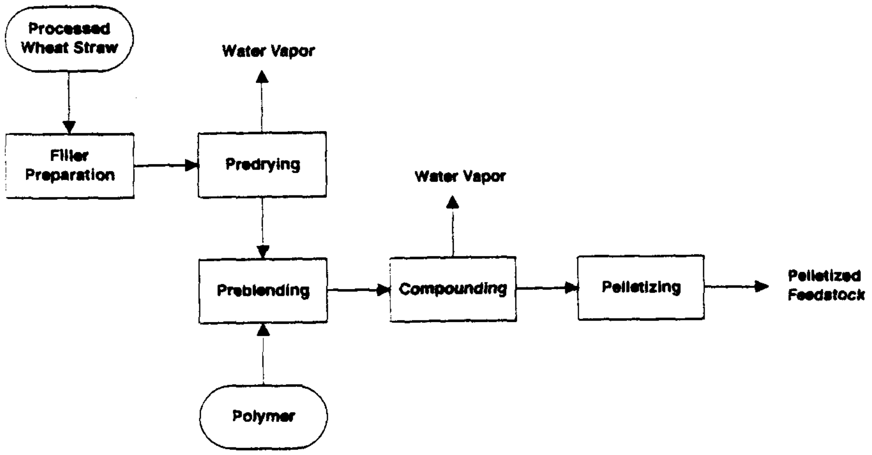

FIGURE 1. –General schematic of the compounding process.

cent polyethylene (WS-03). Prior to compounding, all the wheat straw samples were predried from an ambient moisture content of 10 to 12 percent to approximately 1 percent. This predrying stage is critical before the compounding stage since excess moisture in the straw will produce steam. This causes the final pellet to foam and can trap moisture inside the pellet. Vacuum is applied to the vent zones of the extruder to remove the final 1 percent moisture and the final composite pellets are ready for further testing. After the compounding stage and pelletizing, the blends were dried at 105°C from 2 to 4 hours and injection-molded into standard ASTM test specimens on a Cincinnati Milicron 33-ton reciprocating screw-type 33 molding machine. The screw diameter is 32 mm with a length-to-diameter ratio of 20:1 and a nozzle size of 3.12 mm.

Testing methods

Tensile tests were conducted according to ASTM 638-90 and flexural testing according to ASTM 790-90 in the Engineering Mechanics Laboratory testing facility at the Forest Products Laboratory. The crosshead speed during the tension and flexural tests was 5 mm/min. Analysis of the stress-strain curves involved application of a three-parameter hyperbolic tangent model (1) that has been shown to accurately represent the stress-strain behavior. The composite specimens were all tested to failure. The information obtained from the tensile tests included tensile strength at failure, tensile modulus, and failure strain in tension. In bending, the tests included both flexural strength and flexural modulus. In both types of tests, a quantity that represents the energy absorption can also be evaluated from the integrated area under the stress-strain curve. High-speed impact performance of the composite materials was assessed from Izod impact strength tests according to ASTM D 256-90. Both notched and unnotched Izod test results are reported. A discussion of the test results is found in the remainder of this section.

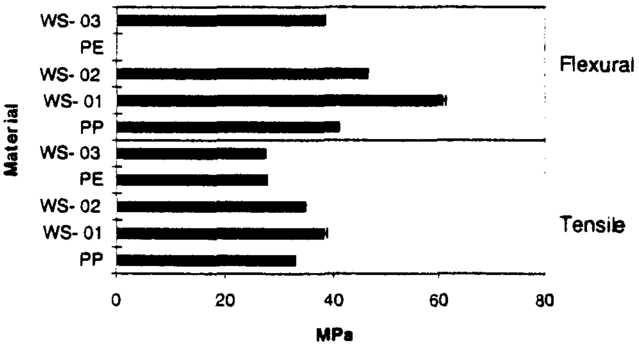

FIGURE 2. —Tensile and flexural strength of agroplastics.

Tensile and flexural properties

The tensile and flexural strength of wheat straw-polypropylene composites are enhanced. Tensile strength increases 3 to 16 percent and flexural strength increases 13 to 48 percent (Fig. 2) when compared to virgin polypropylene.

The tensile modulus characteristics can be seen in Figure 3. On average, the tensile modulus of all the 30 percent wheat straw composites have a value twice that of virgin polypropylene. Polypropylene has a tensile modulus of 1.7 GPa, while the average value of all wheat straw composite blends is 3.3 GPa. Depending on the fiber processing technique and the final fiber size, the comparison of strength values varied. There are also changes in the modulus values depending on the fiber size. In comparing all of the wheat straw composites to polypropylene, the average value of the flexural modulus is 2.5 times greater than virgin polypropylene.

Impact properties

The values for Izod notched impact toughness are shown in Figure 4. The reported value for 100 percent polypropylene is 24 J/m. All of the wheat straw composites decreased anywhere from 9 percent to 28 percent compared to virgin polypropylene. The introduction of 30 percent wheat straw into the poly-

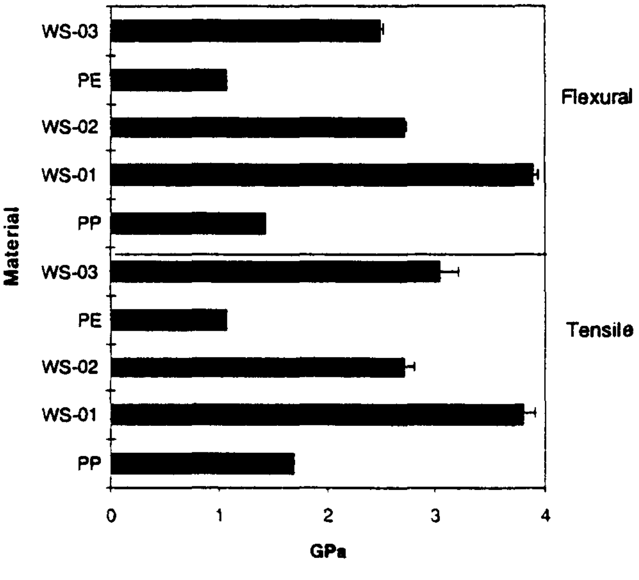

FIGURE 3. —Tensile and flexural modulus of agrophstics.

propylene creates point defects in the composite. During Izod impact testing, the l/8-inch notch is the critical flaw where crack initiation starts. The crack then propagates and final failure results. Izod notched impact testing is an indication of the amount of energy absorbed during crack propagation, and the amount of failure due to energy-absorbing mechanisms such as fiber pull-out, crack bridging due to the reinforcing fiber, crack deflection, micro- fibril debonding of the cellulose fibers, and the creation of new polymer surfaces.

The unnotched Izod impact toughness values are shown in Figure 4. There is approximately an 85 percent reduction in unnotched Izod impact toughness verses 100 percent polypropylene. This type of reduction in unnotched toughness is typical of most filled commodity thermoplastics.

SEM fractography

Figure 5 is a scanning electron micrograph (SEM) of a typical wheat straw composite. The top fiber shows an excellent interface region (300 to 400 µm) with the polymer matrix. At the bottom of the micrograph is a good example of microfibril tearing of the wheat straw fiber, as well as good bonding of the fiber at the fracture surface.

Economics

Two methods were used to determine a price, and several assumptions were made. Polymer and delivered wheat straw were assigned costs of $0.50 and $0.03 per pound, respectively It was also assumed that compounding can be profitably conducted at $0.20 per pound at maximum efficiency This figure is derived from the cost of capital, operating costs, and return on investment at an 80 percent operating time and is taken from a USDA Forest Products Laboratory report (No. FPL-GTR-91, “Waste-Wood-Derived Fillers for Plastics,” pages 309–324 in this proceedings). Hence, the following formula:

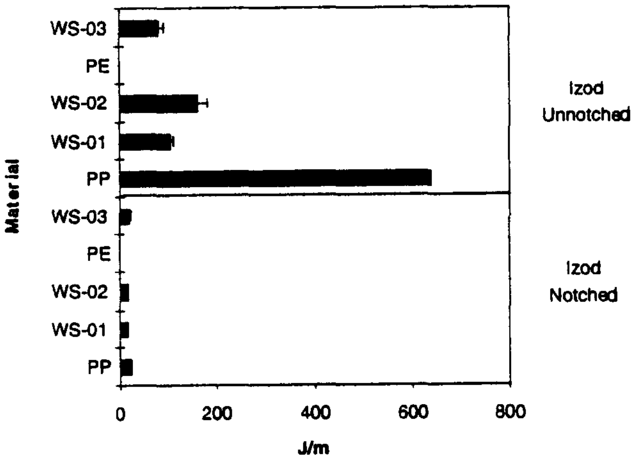

FIGURE 4 .—Izod notched and unnotched impact strength for agroplastics.

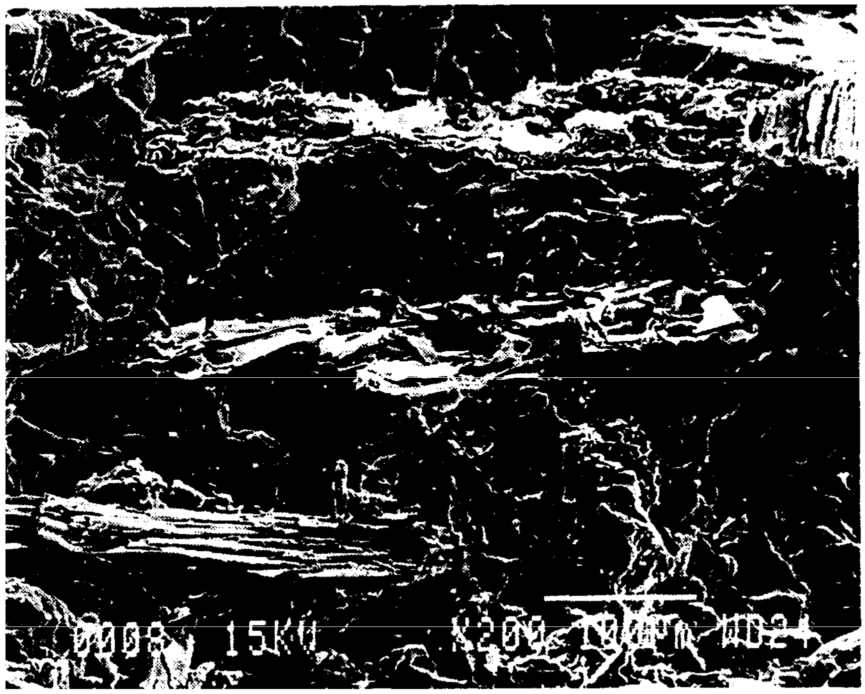

FIGURE 5. – SEM micrograph of a typical wheat straw-polypropylene composite.

$$\text{price per pound} = \frac{p(0.50)+f(0.03)+.20}{e}$$

where:

p = polymer weight percentage

f = filler weight percentage

e = efficiency at 80 percent operating time

Therefore, a 30 percent wheat straw/70 percent polypropylene formulation yields $0.559 per pound. A 50 percent wheat straw/50 percent polypropylene formulation yields $0.465 per pound.

This price does not reflect any premium pricing strategies that may be used for filled plastics with properties that compare favorably with more expensive engineering resins. In this case, a competitive pricing strategy-till be implemented to compete with traditional fillers. A second more refined method was also used to calculate prices based on detailed proformas. These figures assume all costs paid, including principle and interest, but have a net profit margin of 0 percent (thus the break-even price).

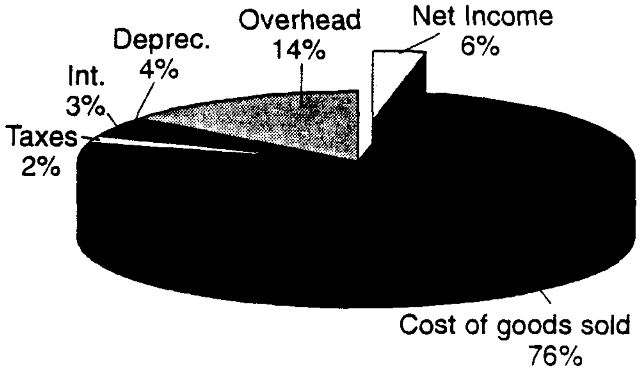

FIGURE 6. — Breakdown of percent of sales distribution.

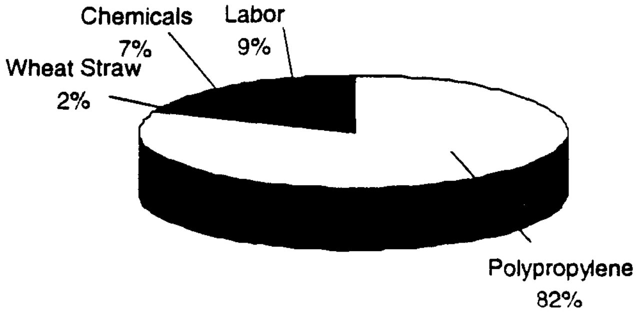

FIGURE 7. —Breakdown of costs associated with costs of goods sold.

The cost of goods sold (feedstocks, chemicals, and labor) has the greatest impact on the sales price (Fig. 6). The greatest cost contributor of the overall cost of goods sold is polypropylene (Fig. 7). The primary goal is to increase the amount of wheat straw in the final product, thus reducing the amount of polypropylene and the overall cost of the agroplastic.

Table 1 demonstrates the impact of fill level on plant economics.

Financial analysis

projected income statements are presented based upon estimations and assumptions of factors that relate to production, cost of the building, machinery, feedstocks, labor, overhead, depreciation, taxes, interest, and principle. The amount of loading dramatically changes the rate of return on investment (Table 2) or the competitive advantage that can be obtained by reducing the price of the final product. Each of the proposed plants at full production provides a high degree of return on investment based on three levels of wheat filler (30, 40, and 50%) and assumes 100 percent debt financing.

A business plan and a market survey have been completed for this project while research was underway. At this time, there are numerous companies that wish to test the product with the goal of purchasing pellets, if the product performs as marketed.

Conclusions

The results of this study are exciting and demonstrate the feasibility of using agrofibers as filler for plastics. The response from manufacturers and companies that sell a large amount of plastic goods has been very positive. At this time we are undertaking some large compounding runs in order to work with the numerous manufacturers who have expressed interest in these products.

The resulting product from the first compounding (WS-01) has higher tensile and flexural strength. However, it is also still possible to see the wheat straw

TABLE 1.—Breakeven analysis price and tonnage for different fill levels.

Percent of wheat straw filler	Breakeven at $0.55 sales price	Breakeven price at 100% production
(%)	(tons)	($)
30	4,125	0.523
40	2,962	0.464
50	2,505	0.427
60	2,097	0.378
70	1,793	0.330

TABLE 2. – Return on investment for a 15-ton/day agroplastics plant at three filler levels.

	30% wheat	40% wheat	50% wheat
Total revenue	$5,544,000	$5,544,000	$5,544,000
Cost of goods sold	(4,295,610)	(3,726,493)	(3,358,976)
Gross margin	**1,248,390**	**1,817,507**	**2,185,024**
Overhead	(554,912)	(554,912)	(554,912)
Operating income	**693,478**	**1,262,595**	**1,630,112**
Cash after tax and payment	361,576	731,502	970,388
Total return (%)	**6.5%**	**13.2%**	**17.5%**

in the final composite. To some manufacturers this does not matter for their application. It may even be desirable when the manufacturers are looking to mimic a wood product.

The second method yielded exceptional results (WS-02). The first noticeable advantage was that the find composite exhibited no sign of wheat burn-through. The surface quality was excellent and appeared close to brown polypropylene. The second major advantage was that the composite rheology behaved similarly to standard polypropylene. This process leads the research team to believe that much higher loading levels can be achieved. The amount of loading dramatically changes the rate of return on investment (Table 2) or the competitive advantage that can be obtained by reducing the price of the final product (Table 1). The final potential advantage is that since the wheat is so evenly dispersed, we believe that a uniform black color maybe achieved. If this is possible, than the product could be used for automotive interiors such as ashtrays, cup holders, etc.

The initial work with the polyethylene composites (WS-03) appears promising. The work is still preliminary and we are currently refining the polyethylene composites. Manufacturers are being contacted to test the material in their equipment.

Since the properties of the agroplastic were improved via size reduction technology, the markets which will be available for agroplastics should increase. At the current time, Pinnacle is exploring the low-end filler market for the agroplastics. However, in the course of the research to date, two methods were identified to expand this market. The first method leads to a plastic with increased strength properties which should allow the development of markets, possibly even including the low end of the structural markets. The second method yields a plastic with vastly superior surface properties and the potential for high fiber loading, which will both increase acceptance and increase investor interest.

Literature cited

1. Yeh, J.M. et al. 1991. Influence of moisture on the nonlinear constitutive behavior of cellulosic materials. *In:* Proc. Intl. Paper Physics Conf. Vol. 2. TAPPI, Atlanta, Ga. pp. 695–711.