THE LIMITS OF DESIGN POTENTIAL IN PLANT FIBER PRODUCTS

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ABSTRACT

The present wood-based composite industry mainly produces two dimensional (flat) sheet products. In some cases, these flat sheets are cut into pieces and glued/fastened together to make shaped products such as doors, windows, furniture, packaging, etc. Wood veneers have also been used to form two dimensional, and in some limited cases, three dimensional, designs. Plant fibers can be used as designer components to form complex profiles using a molding press. And, if the final shape can be produced during the primary product step, the secondary manufacturing profits can be realized by the primary composite producer. It is possible to make complex shaped composites directly using fiber mat technologies. Successful application of this technology depends on the development of a fiber mat which will maintain its physical integrity until it is used to form a final product. Fiber mats can be made by physical entanglement (carding), nonwoven needling, or thermoplastic fiber melt matrix technologies. During mat formation an adhesive can be added and then a shaped product can be made using a thermopressing step. The adhesive can be a thermoset or a thermoplastic depending on the end product performance properties required. Within certain limits, any size, shape, thickness, and density is possible.

Plant fiber resources are renewable, widely distributed, available locally, moldable, anisotropic, hydroscopic, recyclable, versatile, non-abrasive, porous, viscoelastic, easily available in many forms, biodegradable, combustible, compostible, and reactive. Plant fibers have a high aspect ratio, high strength to weight ratio,and have good insulation properties (sound, electrical and thermal). The fiber structure is hollow, laminated, with molecular layers and an integrated matrix. Some might consider part of these properties as problems, such as biodegradable and combustible, but these features provide a means of predictable and programmable disposal not easily achieved with other resources.

Plant fibers can be combined with other resources such as plastics, glass, metals and synthetics. The objective is to combine two or more materials in such a way that a synergism between the components results in a new material that is much better than the individual components. The properties of plant fibers can also be modified through physical and chemical technologies to improve performance of the final composite.

INTRODUCTION

As we approach the 21st century, there is a greater awareness of the need for materials in an expanding world population and increasing affluence. At the same time, we have an awareness that our landfills are filling up, our resources are being used up, our planet is being polluted, that non-renewable resources will not last forever, and that we need more environmentally friendly materials (Rowell 1998).

Composite materials made from plant fibers are receiving a great deal of attention today since they are considered to be an environmentally friendly resource. This conference is evidence of this. However, until a creditable, non-biased life cycle assessment is done comparing all resources used to make the wide variety of composites we now have, this position of Environmental friendliness of plant fibers will remain open. Certainly plant fibers are renewable and sustainable if good ecosystem management practices followed.

Humans have lived with and developed plant fiber composites since the beginning of human existence. These composites were used as a source of energy, to make shelters, construct tools, make clothing, keep records, and produce weapons. Collectively, society learned very early the great advantages of a resource that was widely distributed, multi functional, strong, easy to work, aesthetic, biodegradable, and renewable.

We traditionally think of plant fiber composites as solid, i.e. wood. As the availability of large diameter trees decreased (and the price increased) the wood industry looked to replace large timber products and solid lumber with reconstituted wood products made using smaller diameter trees and saw and pulp mill wastes. There has been a trend away from solid wood for some traditional applications and toward smaller element sizes. The new products started with very thick laminates for glue laminated beams, to thin veneers for plywood, to strands for strandboard, to flakes for flakeboard, to particles for particleboard, and, finally, to fibers for fiberboard (Marra 1979). For the most part, all of these were made using wood. As the size of the furnish element gets smaller, it is possible to either remove defects (knots, cracks, checks, etc) or redistribute them to reduce their effect on product properties. Also, as the element size becomes smaller, and became more consistent, uniform, continuous, predictable, and reproducible. Getting down to the fiber level also allows a wide variety of plant fibers other than wood to be considered.

When we consider using plant fibers in structural composites, we must remember that they were designed, after millions of years of evolution, to perform, in nature, in a wet environment. Also, that nature is programmed to recycle these resources, in a timely way, back to their basic building blocks of carbon dioxide and water through biological, thermal, aqueous, photochemical, chemical, and mechanical degradations. We isolate fibers from a plant, dry them, recombine them in some sort of a matrix, and we make a plant fiber composite that swells and shrinks as moisture conditions change, decays, burns, a``˜and is degraded when exposed to ultraviolet radiation. Knowing the performance restrictions of plant fiber composites, we have lowered our expectations of performance, which, ultimately, limits our ability to accept new concepts of creative design which could greatly expand the application of plant fiber composites in structural and non-structural materials.

Given our past traditions using plant fiber composites, what can we do to revisit the issue of performance and design using plant fibers? What would convince us that this is an issue worth revisiting? What are the advances in materials science, chemistry, biology, and engineering that have created new opportunities? What are the limitations? This paper will explore some of the opportunities and limiting factors that exist in our use of plant fiber-based composites in terms of design.

HISTORY OF DESIGN USING PLANT FIBER COMPOSITES

(Lets start by taking a historical look at how we have designed both structural and non-structural products using plant fiber composites. Perhaps the earliest plant fiber composite was an inorganic based brick made from straw and mud or clay. These came in simple shapes and were easy to design structures by positioning the structural elements one on top of the other to create the desired design. Some of these designs were very creative but ultimately limited by the shape and weight of the structural element.

Glue laminated beams were introduced in an auditorium using a casein adhesive in 1893 in Basel, Switzerland (Wood Handbook 1987). These early laminated beams created a new dimension in design away from the solid wood beam that had been used in construction for hundreds of years. Now it was possible to create a structure from solid wood with graceful lines. A new structural element that was aesthetic as will as functional. A design element is still very much in use today. Figure 1 shows the curved arches of the 500 foot dome structure built in Tacoma, WA.

The modern plywood industry began around 1910 but the furniture industry had used veneers over solid wood for several hundred years before this.

Overlaying thin sheets of wood or paper over another material created the wood look without actually using very much wood, if any, at all. Furniture designs using plywood were created using rather complex designs but still limited to the bending properties of thin wood veneers. Today, very thin veneers are made backed with a thermoplastic sheet that can be overlaid onto many different materials. The best known example of this technology are in business cards made using these thin wood/thermoplastic laminated sheets.

The particleboard industry started in the 1940's, the hardboard industry around 1950, flakeboard and the medium density fiberboard (MDF) industries in the early 1960's (Maloney 1996). In general, all of these products are produced in flat sheets and used in two dimensional designs. It is possible,

Figure 1 - Laminated dome structure. However, to produce all of these composites in three dimensional products. Flakes and particles have been formed into pallets and packing materials using an adhesive and a rather simple mold.

The problems in all of these technologies to form more complex shapes was trying to achieve a uniform layer of furnish in all parts of a mold to produce a product with uniform wall thickness and density.

NEW IDEAS IN DESIGN USING PLANT FIBER

In order to change our thinking of plant fiber composites as only two dimensional materials, we need a way to create complex shapes from what we have considered for centuries as a solid, stiff, flawed resource with limited ability to be shaped. There are several new technologies that are either available today or in the final development stages. These are composites made using plant fibers in the form of mats that can be thermo-formed either using a thermosetting resin or a thermoplastic matrix in a hot press, fibers in combination with thermoplastics that can injected molded, extruded, or made into flat sheets that can be formed into complex shapes by a thermo-pressing process, or using plant fibers in one of several liquid composite molding processes.

FIBER MAT FORMATION

The greatest opportunity for making complex shapes with uniform thickness and density comes from the idea of using plant fibers that have been formed into a continuous, flexible, and uniform fiber mat. These mats can be made using short or long fibers in one of several processes including physical entanglement (carding), nonwoven needling, or using a thermoplastic matrix.

In carding, the fibers are combed, mixed and physically entangled into a felted mat. These are usually of high density but can be made at almost any density. A needle-punched mat is produced in a machine, which passes a randomly formed machine made web through a needle board that produces a mat in which the fibers are mechanically entangled. These webs are made using a long fiber alone or a combination of long and short fibers. The long fiber is needed as a needling fiber that is driven through the mat using a special short barbed needle. The density of this type of mat can be controlled by the amount of fiber going through the needle board or by overlapping needled mats to give the desired density. In the thermoplastic fiber matrix, the plant fibers are held in the mat using a thermally softened thermoplastic fiber such as polypropylene or polyethylene. These mats can be made using short fibers alone and can be made to very uniform thickness and densities. These fiber mats can be made incorporating an adhesive and the mats containing the adhesive can be placed in a mold and pressed to any desired shape (Figure 2).

Any of the mats described above can have a thermoset resin incorporated in the mat before pressing which will result in a shaped composites that can be used for structural applications.

Figure 2 - A fiber mat made using needling technology applications.

If the fiber mat is made incorporating a thermoplastic, then the shaped composites will be used for non-structural applications since the thermoplastic matrix will creep under heat and load.

THERMOSETTING MATRIX

Thermosetting resins are used today in plant fiber composite for inner door panels for the automotive industry. Jute and flax are the two most widely used fibers. Thermoplastic fibers are mixed with jute fibers to produce a high density mat that are used as sound insulators in headliners and sound and heat insulation in trunks and hoods for both automobiles and trucks.

It is now possible to design wall/floor/ceiling units, furniture, trim, window and doorframes, and a large variety of other complex shaped composites using plant fibers and the mat forming process. Designs never before possible are now possible. We are no longer limited to two dimensional designs but an entirely new world of three dimensions are available (see Figure 3). So, it is time to revisit the restricted vision we once held that plant fiber composites were restricted to simple two dimensional shapes. And, wood like grain patterns can be added to these plant fiber-based molded products by dying long fibers a dark colour and adding them to the surface of the mats before molding

Figure 3 - Complex shapes made in a molding press.

These molded composites can be made very lightweight and used as core materials for lightweight furniture or insulated panels.

THERMOPLASTIC MATRIX

By combining plant fibers with other resources advanced composite materials that take advantage of the properties of both types of resources can be produced. It allows a person to design materials based on end-use requirements within a framework of cost, availability, recyclability, energy use, and environmental considerations. Since plant fibers have low densities, are low in cost, non-abrasive, and have excellent specific mechanical properties, they are potentially outstanding reinforcing fillers in thermoplastic composites. The specific tensile and flexural moduli, for example, of a 50% by volume of kenaf-polypropylene composite compares favourably with a 40%, by weight, of glass fiber-polypropylene injection molded composite.

Table 1 - Mechanical properties of aspen fiber-polypropylene composites

Property	30% aspen 70% PP	30% aspen 68% PP, + 2% MAPP
Flexural strength (MPa)	53.7	76.6
Flexural modulus (GPa)	3.1	3.4
Tensile strength (MPa)	29.6	48.2
Tensile modulus (GPa)	2.5	2.7
Izod-notched (J/m)	28	27
Izod-unnotched (J/m)	119	149
Rockwell hardness	79.1	92.3
Taber Wear Index (mg)	152	102

By adding a compatibilizing agent to help form a stronger attraction between the hydrophobic plastic and the hydrophilic plant fiber, the properties of these composites can be improved. Adding 2%, by weight, of maleic anhydride grafted polypropylene (MAPP) to polypropylene compounded with aspen fiber increases flexural strength, tensile strength, and unnotched Izod toughness as shown in Table 1 (Sanadi et al. 1994, 1995, 1997). Flexural modulus, tensile modulus and notched Izod toughness are about the same for both sets of composites. Rockwell hardness is higher in the compatibilized composite indicating that the compatibilizer improves hardness. The Taber Wear Index is higher for the non-compatibilized composite.

Figure 4 - Chair made by injection molding using Plant fibers and polypropylene.

If the fiber content is below about 60%, by weight, pellets made using plant fibers and thermoplastics can be injected molded, extruded molded, or made into flat sheets that can be formed into complex shapes by a thermo-pressing process (See Figure 4). Above about 60% fiber content, by weight, complex shapes can only be made using the flat sheet thermo-pressing process. Since these composites are thermoplastic based, these can not be used for structural applications. Since plant fibers are non-abrasive, mold life is increased.

These new plant fiber-thermoplastic composite materials are finding new applications in such areas as packaging, furniture, housing, and automotive.

LIQUID COMPOUND MOLDING

Another new application of plant fibers that can be used in complex design is in liquid composite molding (LCM. LCM is an umbrella term covering a variety of molding technologies using liquid thermoset resins. Early studies of this technology were centered on phenol-formaldehyde and melamine resins. The simplest example of LCM is hand lay-up. Within this technology are several specific semi-automated molding systems discussed below.

Resin transfer molding - RTM

RTM literally means the transfer of a resin mix from one machine to a closed mold containing the reinforcing fiber for molding a product. In the technology a fiber mat is laid in the mold cavity and a matching mold half is mated to the first half and the two are clamped together tightly. A pressurized resin system mixed with a free radical initiator is then pumped from one or more ports into the closed mold containing the fiber mat. The resin and fiber remain in the mold until crosslinking occurs, then the composite can be removed. The material can be cured at room temperature or in the heated mold by proper choice of initiator. Figure 5 shows parts that have been made using a jute fiber mat and an epoxy resin.

Figure 5 - Resin transfer molded parts using plant fibers.

Structural Reaction Injection Molding - SRIM

In SRIM, two or more reactive component streams are rapidly mixed and then injected into a closed mold containing a reinforcing fiber where polymerization and cross-linking occur. In many cases, the fiber mat is premolded using a small amount of thermoplastic in the fiber (called a preform).

Reinforced Reaction Injection Molding - RRIM

RRIM uses chopped fiber, which is premixed with the two or more reactive components before very rapid injection into a mold. Along with reinforcing fibers, inorganic fillers are often used. Higher viscosity means higher injection pressures must be used, as compared to SRIM.

Sheet Molding Compound - SMC

Plant fiber (chopped or continuous) is used in SMC with unsaturated polyester resin, a free radical initiator, a thickening agent, a particulate filler and is extruded between release sheets (plastic). The sheets are rolled up and refrigerated to thicken the resin. The sheets are then compression molded under moderate pressure. Heated presses are used to initiate the curing resulting in short cycle times.

PULTRUSION

In pultrusion technology, fibers, fiber bundles, twine or cloth are pulled through a solution of resin and then through a mold to give the desired shape. Glass fiber is the standard used today, however, long plant fibers such as jute, flax, and other bast fibers are being tried with success. Jute fibers both in the form of rovings and woven cloth have been pultruded into doorframes, ceiling channels, and other structural products using a phenolic resin. The plant fibers are much cheaper than glass and the strength properties of the products produced meet performance standards.

CONCLUSIONS

There are several new forming technologies that allow plant fibers to be injected, extruded or molded into complex shapes. These new technologies greatly expand the possibility of using plant fibers in new exciting and creative designs never before possible. Perhaps the largest limitation in using plant fibers in these new designs lies in the lack of knowledge of the new developments. The purpose of this conference is to bring these new technologies to light. This author hopes this has happened.

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