Chapter 5

Composite Materials from Forest Biomass: A Review of Current Practices, Science, and Technology

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Renewable and sustainable composite materials can be produced using forest biomass if we maintain healthy forests. Small diameter trees and other forest biomass can be processed in the forest into small solid wood pieces, sliced veneers, strands, flakes, chips, particles and fiber that can be used to make construction composite products such as glued-laminated lumber, plywood, structural composite lumber, flakeboard, particleboard, fiberboard, and molded materials. It can also be combined with other resources to make new materials taking advantage of the unique properties of each resource. Non-construction composites can also be made such as geotextiles, filters, sorbents, packaging and nano-materials. The adhesive used in the various products depends on the intended application.

Introduction

We have used wood, in its natural form, for many applications since the beginning of the human race. The earliest humans used wood to make shelters, cook food, construct tools, and make weapons. There are human marks on a climbing pole that were made over 300,000 years ago. We have found wood in the Egyptian pyramids, Chinese temples and tombs and ancient ships that attest to the use of wood by past societies. Collectively, society learned very early the great advantages of using a resource that was widely distributed, multifunctional, strong, easy to work, aesthetic, sustainable, and renewable.

In 1900, almost half of the materials used in the United States, on a per weight basis, came from renewable resources. By 1995, materials from renewable resources had decreased to less than 8%.

The United States ranks third in the world in the volume of standing forest biomass and is the largest producer of industrial timber products. These products contribute over $240 billion to the gross national product and employ over 1.1 million people.

Forest biomass is defined as all photosynthetic mass that is produced within a forest. This includes all trees, large and small, and underbrush. There are 749 million acres of forest lands in the United States. Of this, 319 million acres are held by the public (local, state and federal) and 430 million acres are privately owned. Of the private sector, 363 million acres are non-industrial. These forests produce approximately 368 million dry tons of biomass per year. Biomass from agricultural sources is approximately 998 million dry tons per year making a total of 1.366 billion dry tons of biomass produced ever year that could potentially be used to produce composite materials *(1)*. The total global inventory of all biomass is over 4 billion metric tons of which wood represents 1.75 billion, straw, 1.15 billion, stalks, 0.97 billion, and 0.13 billion for all other (grass, leaf, core, bagasse, etc). This chapter will concentrate only on the biomass from US forests that could be used to make composite materials.

Wood is not renewable! It comes from trees and trees are renewable. So any discussion of renewable and sustainable development for wood, must concentrate on sustainable forests. Sustainable forests are healthy forests. And, healthy forests have many demands put on them including: recreation, biodiversity, source of clean water, a buffer against storms, a vast carbon storage, animal habitat, aesthetics, as well as a source of products such as lumber, fuels, composites, pulp and paper, and chemicals. Healthy forests are also critical in converting carbon dioxide to oxygen. Because of this, a discussion of composite materials from forest biomass must start with a consideration for managing and maintaining healthy forests.

Healthy Forests

There will be increased competition for land use as the world population increases. In 1830, the world population was 1 billion. Over the next hundred years, it doubled to 2 billion. At the present rate of growth, the population increases by 1 billion people every eleven years. Composite materials from forest biomass provide an opportunity to fill a growing need for materials, however, there will be a greater and greater need for food and feed. Forest lands are being converted to agricultural lands and to industrial and residential lands.

Healthy forests play an important role in providing clean air and water as well as to regulate the climate. About 80% of the fresh water in the United States originates on the 650 million acres of forestlands that cover about 1/3 of the Nation's land area.

In order to insure a continuous supply of forest biomass, management of the forest land should be under a proactive system of land management whose goal is both sustainable forestry and the promotion of healthy ecosystems. Ecosystem management is not a euphemism for preservation, which might imply benign neglect. Sustainable forests denotes a balance between conservation and utilization of forest lands to serve both social and economic needs, from local, national and global vantage points. Sustainable forestry does not represent exploitation but rather is aimed toward meeting all the needs of the present generation without compromising the ability of future generations to meet their needs. It encompasses, in the present case, a continuous production of biomass for composites but also considerations of multi-land use, and the protection, restoration, and conservation of the total ecosystem.

Many of our forests, especially forests in the Western part of the US, are over crowded with small diameter timber. This, so called "fire-prone forest biomass" is responsible for the devastating forest fires we have had recently. With a healthy forest where, at least, 60-75% of the ground is covered with vegetation, only about 2% or less of rainfall becomes surface runoff and erosion is low (less than 0.05 tons loss per acre). After a forest fire, burned land usually sorbs water more slowly than unburned land.

So, it is important to forest health for this fuel load to be removed. But, the argument is always that it is too expensive to remove and there is no demand for such a large amount of biomass. The question might be that while it is too expensive to remove this biomass, it is more costly not to remove it. In a study of the cost to fight forest fires, Lynch has shown that is more expensive to fight a fire (reactive) than to remove the forest biomass (proactive) *(2)*. Looking at the cost to fight fires in Colorado over a seven year period, he concludes that it costs approximately $600 per acre to fight a fire and that does not include costs such as restoration of watersheds, equipment loss, loss of productivity, and loss of life.

Based on the results of the Lynch study, one strategy for producing composites from forest biomass is to go into an overgrown area and harvest all small diameter and other fuel load material and convert it to composites. This biomass with be crooked, have a large percentage of bark, diverse mixed species, and hard to handle but it can processed in the woods into transportable furnish. Mara has suggested that this material can be converted to a mixture of fibers that can be used to produce high valued products *(3).* The total removed biomass can also be converted to chips, flakes or particles that can be more easily transported to a mill for processing into composites. There will be a high percentage of bark and many mixed species in the furnish that will require a higher level of adhesive in the composites. Fractionation of various sizes and types of elements can also be done in the forest. The objective of this approach of producing composites from biomass is not based on the recoverable cost from the composites, but to clean the forest of the fuel load.

The in forest processing can be done using the biomass as fuel to run small-scale power units *(4, 5).* The units are portable and can be used in remote locations to process the small diameter forest biomass into a usable, transportable furnish.

Composites from Forest Biomass

A composite can be defined as two or more elements held together by a matrix. The matrix can be physical or chemical. Chemical matrixes include anything from hydrogen bonding to covalent bonding using resins and adhesives. Physical matrixes include anything from physical entanglement and non-woven technologies to porous containers (bags).

Solid wood is a three dimensional composite composed of cellulose, hemicelluloses and lignin polymers with smaller amounts of inorganics and extractives held together in a lignin matrix. Solid wood can be broken down into smaller and smaller elements, i.e. veneers, flakes, strands, chips, flakes, particles, fiber and cellulose. As the element size becomes smaller, it is possible to either remove defects (knots, cracks, checks, etc.) or redistribute them to reduce their effect on product properties and uniformity increases. Composites made from these smaller elements become more like a true material, i.e. consistent, uniform, continuous, predictable, and reproducible. Size reduction, however, requires energy and may increase water consumption.

Composite materials from forest biomass can be classified by several different systems: density (for example, medium density fiberboards), application (for example, insulation board), raw material form (for example, particleboard) and process type (for example, dry process fiberboard). The breakdown of forest biomass can include large timbers, dimensional lumber, very thick laminates for glued-laminated beams, thin veneers for plywood, strands for strandboard, flakes for flakeboard, chips for chipboard, particles for particleboard, and fibers for fiberboard. However, since the bulk of this chapter deals with the utilization of small diameter biomass, only composites made using small solid wood members, strands, chips or flakes and fiber will be covered.

Two major types of composites will be reviewed in this chapter: construction composites used for building and non-construction composites.

Construction Composites

The largest single use for forest-based composites is for residential construction. We have used wood for light wood-framed housing for over 100 years. Over 95% of the approximate 1.5 million homes built in the United States each year are framed using wood. Many wood-based composites are also used in this application and are also used for non-residential construction, especially exterior wall paneling.

Table 1 shows the number and size of the average American home from 1970 to 2000 and the projection of growth in both number and size for 2020 and 2050. The number of homes has increased with the increase in population and the size of the average home has also increased. It is projected that the average size of a home will continue to increase but this will depend on income, energy costs and raw material availability.

Table 1. Sizes of Single Family Houses in the US Past and Future Projections

Year	Households (Millions)	Average size (Square Meters)
1970	63.9	140
1980	79.1	162
1990	93.2	193
2000	102	204
2020	138.5	210
2050	178.1	240

Glued-Laminated Lumber

From the large diameter trees and to some extent smaller diameter trees as well, structural glued-laminated beams (glulam) can be made using thick, wide wood members that are used as structural elements in large open buildings.

Glued-laminated lumber could be produced from small diameter trees using small pieces finger-jointed together. Glulam is a structural product that consists of two or more layers of lumber glued together with the grain all going parallel to the length. The laminated beam is usually fitted into a steel plate that joins the beam to the ground. It can be formed straight or curved depending on the desired application. Typically the laminates are 25 to 50 mm in thickness. Douglas fir, southern pine, hem-fir and spruce are common wood species used in the United States *(6)*. Lower quality wood can be used, thinner lumber can be dried much faster than large thick beams and a variety of curved shapes can be produced. Solid wood and glulam have a specific gravity of 0.4 to 0.8.

Plywood

The modem plywood industry began around 1910 but the furniture industry had used veneers over solid wood for several hundred years before this. Plywood is made using thin veneers which are glued together and are used as a structural underlayment in floors and roofs and in furniture manufacturing. The veneers are produced from large diameter tree bolts by peeling but they can also be produced by slicing small diameter trees bolts.

Structural Composite Lumber

Structural composite lumber (SCL) is manufactured by laminating strips of veneers or strands of wood glued parallel to the length. There are several types of SCL: oriented strand lumber (OSL), parallel strand lumber (PSL) and laminated veneer lumber (LVL). Laminated strand lumber (LSL), oriented strand board (OSB) and OSL are produced using different lengths and sizes of strands. LSL uses strands that are about 0.3 m in length while OSB is produced from shorter strands. OSB is usually made of three to five layers of strands that are oriented at right angles to each other and the product is used for exterior sheathing. Table 2 shows some of the mechanical properties of sheathing grade OSB. PSL is made from strands that are 3 mm thick, approximately 20 mm wide and 100 to 300 mm in length. Usually Douglas-fr, southern pines, western hemlock and yellow-poplar are used but other species are also used. LVL is produced from veneers that are approximately 2.5 to 3.2 mm thick and of varying lengths. The major adhesives used to produce SCL products are phenol-formaldehyde or isocyanates. All of these SCL products are used as replacements for solid wood and have a specific gravity of 0.5 to 0.8.

Table 2. Properties of Sheathing Grade OSB (Wood Handbook 1999)

Property	Value	ASTM test method
Modulus of rupture	20.7 - 27.6 MPa	D3043-87
Modulus of elasticity	4.8 - 8.3 GPa	
Tensile strength	6.9 - 10.3 MPa	D3500-90
Compression strength	10.3 - 17.2 MPa	D3501-76

ASTM D304-87, Standard methods for testing structural panels in flexure. ASTM D3500-90, Standard test methods for structural panels in tension. ASTM D3501-76, Standard method of testing plywood in compression.

By combining several elements, composite structural beams can be produced. An I beam can be made of curved plywood sides and laminated plywood top and bottom. They can also be made using a flakeboard center with plywood top and bottom or plywood, hardboard, flakeboard and oriented strandboard. Prefabricated I-beams are used by builders because they are light weight, have increased dimensional stability, uniform, easy to use and meet codes and standards. In most, if not all cases, performance requirements of these composites are spelled out in codes and/or in specifications set forth by local or national organizations.

Waferboard and Flakeboard

Waferboard is a structural panel used in exterior applications bonded with a phenolic adhesive. Large thin wafers or smaller flakes can be produced by several methods and used to produce a composite board. Wafers are almost as wide as they are long while flakes are much longer than they are wide. Wafers are also thicker than flakes. A waferizer slices the wood into wafers typically 38 mm wide by 76 to 150 mm long and 7 mm thick with a specific gravity between 0.6 and 0.8.

The first waferboard plant was opened in 1963 by Macmillan Bloedel in Saskatchewan, Canada. Aspen was the raw material and the wafers were randomly oriented. In the late 1980’s, most wafers were oriented resulting in oriented waferboard (OWB) that is stronger and stiffer than the randomly oriented board. The orientation distribution may be tailored to the application. OWB and OSB compete with plywood in applications such as single layer flooring, sheathing, and underlayment in lightweight structures, however, OSB has largely replaced OWB in most places in the US. Pines, firs and spruce are usually used as well as aspen.

The flakeboard industries started in the early 1960's. These are made using an exterior grade adhesive and are used as the structural skin over wall and floor joists. The specific gravity of flakeboard is usually between 0.6 and 0.8 and made using a waterproof adhesive such as phenol formaldehyde or an isocyanate *(6)*.

Particleboard

The particleboard industry started in the 1940's out of a need to use large quantities of waste products such as sawdust, planer shavings and other mill residues. Particles of various sizes are formed into an air or mechanically formed mats and glued together to produce a randomly oriented flat panel. Almost all particleboards are produced by a dry process. Particleboard is usually made in three layers with the faces made using fine particles and a core of coarser material. Most applications of particleboard are for interior use and are bonded using a urea-formaldehyde adhesive. Paraffin or microcrystalline wax emulsion is usually added to improve short-term moisture resistance. Phenol-formaldehyde, melamine-formaldehyde and isocyanates are rarely used but are when increased moisture resistance is required. The resin content ranges from 4 to 10% but is usually made using 6 to 9%. The resin content of the two faces is usually slightly higher than the core. Table 3 shows some properties of different grades of particleboard.

Particleboard is often used as a core material for veneers and laminates. These are often used in counter tops, shelving, doors, room dividers, built-ins and furniture. Particleboard generally does not warp in use. It is available in several thicknesses from 6 to 32 mm in sheets of 120 by 240 cm.

Fiberboard

Wood can be broken down into fiber bundles and single fibers by grinding or refining. In the grinding process, the wood is mechanically broken down into fibers. In the refining process, wood chips are broken down into fibers between one or two rotating plates in a wet environment to fibers. If the refining is done at high temperatures, the fibers tend to slip apart due to the softening of the lignin matrix between the fibers, and the fibers have a lignin rich surface. If the refining is done at lower temperatures, the fibers tend to break apart and the surface is rich in carbohydrate polymers. Fiberboards can be formed using a wet forming or a dry forming process. In a wet forming process, water is used to distribute the fibers into a mat and then pressed into a board. In many cases an

Table 3. Properties of Particleboards

Grade*	Modulus of rupture (MPa)	Modulus of elasticity (MPa)	Internal bond MPa)
H-1	16.5	2400	0.90
H-2	20.5	2400	0.90
H-3	23.5	2750	1.00
M1	11.0	1725	0.40
M-2	14.5	2225	0.45
M-3	16.5	2750	0.55
LD-1	3.0	550	0.10
LD-2	5.0	1025	0.15

H = density greater than 800 kg/m^3, M = density 640 - 800 kg/m^3, LD = density less than 640 kg/m^3. (National Plywood Association 1993 Particleboard, ANSI A208.1-1993. Gaithersburg, MD.)

adhesive is not used and the lignin in the fibers serves as the adhesive. In the dry forming process, fibers from the refiner go through a dryer and blowline where the adhesive is applied and then formed into a web which is pressed into a board.

Low density fiberboards (LDF) have a specific gravity of between 0.15 and 0.45 and are used for insulation and for light weight cores for furniture. They are usually produced using a dry process using a ground wood fiber. Medium density fiberboard (MDF) has a specific gravity of between 0.6 and 0.8 and is mainly used as a core for furniture and is usually made using a dry process. High density fiberboard (HDF), sometimes called hardboard, has a specific gravity of between 0.85 and 1.2 and is used as an overlay on workbenches, floors and for siding. It is usually made using a dry process but is also made using a wet fiber process. The hardboard industry started around 1950 and is produced both with wax (tempered) and without wax and sizing agents. The wax is added to give the board water resistance.

Urea-formaldehyde resin is usually used for interior applications and phenol-formaldehyde for exterior applications. Table 4 gives the mechanical properties of LDF, MDF and HDF. Standard (without wax) and tempered (with wax) hardboards come in many different thicknesses from 2.1 to 9.5 mm and have required standard minimum average modulus of rupture of 31.0 MPa for standard and 41.4 MPa for tempered. Standard hardboard must have a required standard minimum average tensile strength parallel to the surface of 15.2 MPa and 20.7 MPa for tempered. The required standard minimum average tensile strength perpendicular to the surface is 0.62 MPa for standard and 0.90 MPa for tempered.

Table 4. Properties of Fiberboards

Product	Thickness (mm)	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)	Internal bond (MPa)
Internal MDF				
HDF	<21	34.5	3,450	0.75
MDF	>21	24.0	2400	0.60
LDF	21	14.0	1400	0.30
Exterior				
MDF	21	34.5	3,450	0.90

National Plywood Association 1994. Medium density fiberboard, ANSI A208.2-1994. Gaithersburg,MD.

Molded Products

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 drawers, boxes, and packaging. Flat sheet fiber composite products are made by making a gravity formed mat of fibers with an adhesive, and then, pressing. If the final shape can be produced during the pressing step, then the secondary manufacturing profits can be realized by the primary board producer. Instead of making low cost flat sheet type composites, it is possible to make complex shaped composites directly using the long fibers alone or combinations of long and short fibers.

Wood fiber come in two lengths: short (softwoods) and shorter (hardwoods). So wood fiber is limited to short fiber applications unless it is combined with longer agricultural fibers for applications in a wider array of products. In this technology, fiber mats are made by combining long bast or leaf fibers from such plants as kenaf, jute, cotton, sisal, agave, etc. with wood fiber and then formed into flexible fiber mats. These can be made by physical entanglement (carding), nonwoven needling, or thermoplastic fiber melt matrix technologies. 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. 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 bio-based fibers are held in the mat using a thermally softened thermoplastic fiber such as polypropylene or polyethylene.

During the mat formation step, an adhesive is added by dipping or spraying the fiber before mat formation or added as a powder during mat formation. The mat is then shaped and densified by a thermoforming step. The final desired shape is determined by the mold in the hot press. Within certain limits, any size, shape, thickness, and density is possible.

Combinations with Other Resources

It is possible to make completely new types of composites by combining different resources. It is possible to combine, blend, or alloy woof fiber with other materials such as glass, metals, plastics, and synthetics to produce new classes of materials. The objective will be 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.

Wood-fiber/glass fiber composites can be made using the glass as a surface material or combined as a fiber with bio-based fiber. Composites of this type can have a very high stiffness to weight ratio. Wood fiber can also be used in place of glass fiber in resin injection molding (RIM) or used to replace, or in combination with, glass fiber in resin transfer molding (RTM) technologies. Problems of dimensional stability and compatibility with the resin must be addressed but this could also lead to new markets for property-enhanced forest biomass composites.

Metal films can be overlayed onto smooth, fiber composite surfaces or applied through cold plasma technology to produce durable coatings. Such products could be used in exterior construction to replace all aluminum or vinyl siding, markets where wood-based resources have lost market share.

Metal fibers can also be combined with fiber in a matrix configuration in the same way metal fibers are added to rubber to produce wear-resistant aircraft tires. A metal matrix offers excellent temperature resistance and improved strength properties, and the ductility of the metal lends toughness to the resulting composite. Application for metal matrix composites could be in the cooler parts of the skin of ultra-high-speed aircraft. Technology also exists for making molded products using perforated metal plates embedded in a phenolic-coated fiber mat, which is then pressed into various shaped sections.

Wood fiber can also be combined in an inorganic matrix. Such composites are dimensionally and thermally stable, and they can be used as substitutes for asbestos composites. The inorganic phase can be gypsum, magnesia-cement, or Portland-cement. Inorganic bonded fiber composites can also be made with variable densities that can be used for structural applications.

One of the biggest new areas of research incorporating wood flour or wood fiber in a non-wood matrix is in combination with thermoplastics *(7).* Since prices for plastics have risen sharply over the past few years, adding wood flour or fiber to plastics provides a cost reduction to the plastic industry (and in some cases increases performance as well) but to the forest-based industry, this represents an increased value for the wood component.

Blending of the plastics with the wood fiber may require compatibilization to improve dispersion, flow and mechanical properties of the composite. Extrusion of wood-filled plastics for the automotive industry is well known and has been used for more than twenty years. Typical blending involves the plastic-filler/reinforcement to be shear mixed at temperatures above the softening point of the plastics. The heated mixture is then typically extruded into "small rods", which are then cut into short lengths to produce a conventional pellet. The pellets can then be used in typical injection or compression molding techniques. To reduce the cost of this blending process, direct injection molding of wood-fiber/plastics can be done. The direct injection molding process probably has limitations on the amount of filler/fiber that can be used in the composite, and is also likely to be limited to particulate or shorter fiber. The chemical characteristics of the surface and bulk of the woof fibers are also important in the blending with plastics. The ability of the matrix of the lignocellulosic (hemicellulose and lignin) to soften in the presence of moisture at plastic processing temperature may give these materials unique characteristics to develop novel processing techniques. The performance of injection molded cellulose fiber thermoplastics can be significantly improved by the use of microfibrils *(8).*

The primary advantages of using wood-based fibers as fillers/reinforcements in plastics are: low densities; non-abrasive, high filling levels possibly resulting in high stiffness properties; high specific properties; easily recyclable; biodegradable; the fibers will not fracture when processing over sharp curvatures unlike brittle fibers; wide variety of fibers available throughout the world; generate rural jobs; increase non-food agricultural/farm-based economy; low energy consumption; and low cost.

Non-ConstructionComposites

Geotextiles

Medium- to high-density fiber mats, described previously, can be used in several ways other than for molded composites. One is for use as a geotextile.

Geotextiles derive their name from the two words geo and textile and, therefore, mean the use of fabrics in association with the earth.

Geotextiles have a large variety of uses. They can be used for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats as needed. Medium density fiber mats can also be used to replace dirt or sod for grass seeding around new homesites or along highway embankments. Grass or other type of seed can be incorporated in the fiber mat. Fiber mats promote seed germination and good moisture retention. Low and medium density fiber mats can be used for soil stabilization around new or existing construction sites. Without root stabilization, steep slopes lead to erosion and loss of top soil.

Medium and high density fiber mats can also be used below ground in road and other types of construction as a natural separator of different materials in the layering of the back fill. It is important to restrain slippage and mixing of the different layers by placing separators between the various layers.

It is estimated that the cost of controlling erosion in the United States is in excess of $55 million dollars per year. This is a large potential market for forest resource composites.

Filters and Sorbents

Filter systems are presently used to clean our water but new innovation in filtration technology is needed to remove contaminants from water. The development of filters to clean our water supply is big business. It is estimated that global spending on filtration (including dust collectors, air filtration, liquid cartridges, membranes and liquid macro-filtration) will increase from $17 billion in 1998 to $75 billion by 2020. The fastest-growing non-industrial application area for filter media is for the generation of clean water.

Medium to high density mats can be used as filtering aids to remove particulates out of drinking water, waste water and solvents. Wood fibers have also been shown to sorb oil from water. While not as good as other agricultural fibers such as kenaf, wood fiber can remove oil from both fresh and sea water *(9)*.

Bark has been found to be very effective in removing heavy metal ions from contaminated water. Table 5 shows the effectiveness of several barks in removing copper from solution. Since the size of the bark particle affects its sorption ability, the bark is hammer-milled into small particles and then placed in bags that are put into a filter box where water passes through.

Medium and high density fiber mats or fiber filler containers can be used for air filters. The density of the mats can be varied, depending on the size and quantity of material being filtered and the volume of air required to pass through

Table 5. Effectiveness of Several Barks in Removing Copper from Solution

Bark	Average percent copper removed
Eastern black walnut	88.1
Osage orange	78.1
Ponderosa pine	72.4
American sycamore	63.8
Eastern red cedar	61.7
Burr oak	61.5
Utah juniper	51.7
Eastern cottonwood	48.2
Green ash	46.8
Silver maple	44.6

the filter per unit of time. Air filters can be made to remove particulates and/or can be impregnated or reacted with various chemicals as an air freshener or cleanser.

Packaging

Medium and high density wood-based fiber composites can be used for small containers, for example, in the food industry and for large sea-going containers for commodity goods. These composites can be shaped to suit the product by using the molding technology described previously or made into low cost, flat sheets and made into containers.

Wood-based composites can and have been used for pallets where cost and weight are critical factors. Moldability has been a key factor in the development of the flake-, particle- and fiber-based pallets.

Wood-based fiber composites can also be used in returnable containers where the product is reused several times. These containers can range from simple crease-fold types to more solid, even nestable types. Wood fiber mats can be overlayed with thermoplastic films such as polyethylene or polypropylene to be used to package such products as concrete, foods, chemicals, and fertilizer. Corrosive chemicals require the plastic film to make them more water-resistant and reduce degradation of the wood fiber.

Nano-composites

The smaller the wood element is, the better the homogeneity and the smaller the variability in properties. The smallest load-bearing element in wood is the cellulose fibril. Wood derives its strength and stiffness fiom cellulose and its respective matrix. Lignin provides some moisture resistance and along with the hemicelluloses, bonds cellulose fibrils together, but the intrinsic mechanical performance comes from the cellulose fibrils. They are strongly aligned at an angle close to the axial direction of the wood cells. The Young's modulus of the cellulose unit cell is 134 GPa, a value similar to that of Kevlar© fibers. The reason for this high value is that the cellulose chains are densely packed and as they are deformed, strong covalent bonds of high energy take the load *(10).*

Cellulose microfibrils are 30 nm in diameter and a few microns in length and can be disintegrated fiom wood pulp fibers using a mechanical milling procedure. It is also possible to take pulp fibers, subject them to acid hydrolysis and then disintegration will take place in conventional mixing equipment used in plastics processing. As with other wood composites, mechanisms of failure such as microcracking and debonding, are delayed to higher stresses and strains. The reason is that small-scale reinforcements also cause damage at a very small scale, which is less detrimental to material performance. Cellulose microfibrils also show interesting properties as a material of their own. If a water suspension of cellulose microfibrils is dried, it forms a hard and tough material, similar to ivory in character. The reason is millions of strong hydrogen bonds forming between the cellulose entities.

The ultimate wood composite would have a high content of cellulose microfibrils oriented in the main direction of loading. Strength and stiffness would be competing with high performance composites used in the aerospace industry. Lightweight sandwich structures could be produced by introducing porosity, for instance through foam cores where the material primarily consists of cellulose.

Yano et al *(11)* has shown that wood veneer layers with significant parts of lignins and hemicelluloses removed and impregnated with a phenol-formaldehyde resin, and then compressed and cured, resulted in a wood composite with a Young's modulus of 40 GPa. This is more than twice the value of any commercial wood material or wood composite.

The most recent research in micro-crystalline cellulose has shown that it can be used to make clear flexible films that are very strong and tough and may be the future television and computer screens. *(12).*

Adhesives

The adhesives that are now used in the wood industry for composites are based on the performance requirements of the composites. That is, phenol-formaldehyde, resorcinol-formaldehyde, phenol-resorcinol-formaldehyde, emulsion polymer-isocyanate, melamine-formaldehyde, and melamine-urea-formaldehyde are all used for exterior grade composites where they must withstand long term water-soaking and drying cycles.

Melairnine-urea-formaldehyde, isocyanates and epoxy resins are used when short-term water resistance is required. Urea-formaldehyde and casein adhesives are used for interior composite products.

Research is underway to develop new adhesive systems that are not petroleum-based, that are based on using resources, and that are based on a better understand of the mechanisms of adhesion (13). These mechanisms require a much better understanding of interface and interphase relationships between the forest resource elements and the matrix. Some of the newest research in this area involves the use of enzymes, surface activation, biotechnology, chemical modification, and cold plasma (14,15).

Conclusions

The future of forest resource-based composite materials will be very exciting and dynamic. It will be driven by traditions, trends, costs, performance, availability of resources, and legislation. Of these, the most critical issue is cost, however, concepts of sustainable development are changing the profit structure focused not only on the profit margin, but developing sustainable industry. There are several competing ideologies today that are driving public opinion. On the one hand, there is a growing need to create jobs, expand recreational opportunities, and improve the standard of living. On the other hand, there are concerns about energy consumption, an expanding world population, maintaining wilderness areas, cleaning up the environment, and the conservation of our natural resources. There is no "right" or "simple" answer.

There is no question that renewable, recyclable and sustainable resources will play a major role in future world developments. Forest resources and composite materials will be part of this dynamic future. We must not allow ourselves to be locked into a mental framework tied to past technologies or close our eyes to exciting new possibilities.

Existing forest resource-based composite markets will continue to grow, but the real excitement will come in the new potential markets we have either lost to other resources or in totally new markets. We are no longer limited by shape, density, size, or texture. We are only limited by our imagination and our knowledge and understanding of how to achieve the highest level of performance from these composites.

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