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Natural Fiber Reinforcement Materials

Lower Cost Technology for Composites Applications

By Scott W. Beckwith

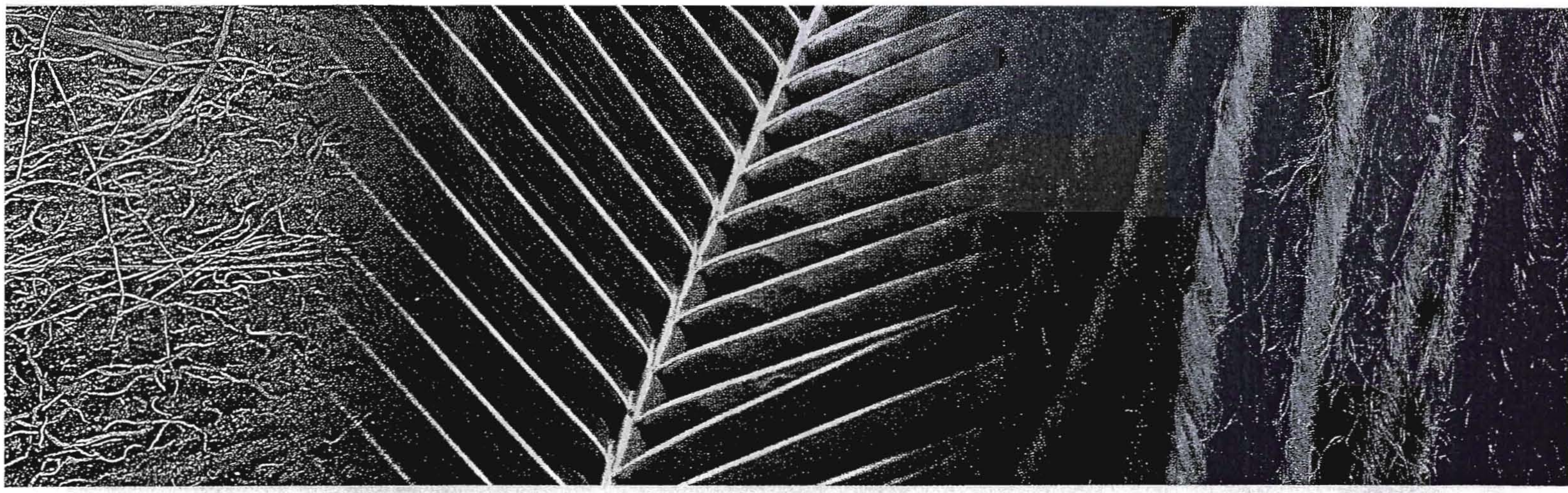
Natural fibers and composite materials: both have a history dating back several thousands of years when people used anything they could readily find to construct shelters, homes, walls and buildings. Clay materials were loaded with straw fibers to build walls and buildings at least 3000 years ago in Egypt according to written records. Wood products have also been around for an equal period of time in some form or another. These natural, environmentally friendly materials come in many shapes and forms.

Natural fibers abound in nature in numerous forms and vary from region to region around the world. They have been used primarily as structural filler material in mud and clays to make bricks and other construction blocks where the fiber adds rigidity, stiffness and holds the "mortar" together structurally. Fibers have also been used in many textile products in woven or fabric forms within the clothing, upholstery, floor coverings and related consumer products markets.

However, E-glass fibers, an artificially fabricated structural fiber, have been the dominant reinforcement material over the past 40-50 years. E-glass is essentially the lowest cost reinforcement fiber outside of the natural fiber realm and has provided the fiber reinforced plastics (FRP) composites industry with essentially the "low cost" fiber and widest use structural fiber forms for numerous composites applications. However, E-glass, while essentially "low cost" when compared with the advanced reinforcement fibers (carbon, graphite, Aramid, Boron, etc.), is a fairly "heavy" fiber because its density is roughly 2.5-2.6 gm/cm^3. And, it's not exactly a natural fiber from an "environmentally friendly" standpoint in that it does not recycle as easily as natural fibers.

Consequently, natural fibers available within our environmental surroundings have continued to be assessed and considered for a number of composite applications where the trade-offs in cost, performance and aesthetics appear reasonable. Natural fibers still appear to be somewhat of a laboratory curiosity on the research scale as far as composites are concerned. However, they seem to have found niche applications in the automotive, sports, and transportation markets using sheet molding compound (SMC), bulk molding compound (BMC), laminating and resin infusion (RTM and VARTM) manufacturing processes.

The key to their continued growth appears to be the continued development of natural fiber treatments to enhance handling, processing, matrix wet out of the fiber, and improving the fiber-matrix interfacial bonding while keeping the cost to a reasonable level. Conversion of naturally occurring reinforcement materials to short fibers, intermediate fibers, continuous fibers and more advanced fiber forms (fabrics, textiles, etc.) is important to developing a manufacturing process base for utilizing these fiber materials in future applications.



Categories of natural fibers

Natural fiber materials are derived from several sources within nature and the agricultural community. These materials are basically "cellular" in form and structure with a degree of inherent strength and stiffness built in "naturally" due to the geometric internal structure. One of the basic cellular materials is cellulose. As a natural polymer itself, it possesses very high strength and stiffness per unit weight—exactly the type of performance that drives today's advanced composites technologies. Cellulose forms long, fiber-like cell structures that are found in wood cores and stems, leaf materials, and seed materials. These are the three dominant sources for natural fiber materials.

Table 1 shows the three basic categories of natural fiber sources and their characteristics. Each of these sources has a spot for their use within the composites industry. Natural fiber resources also provide materials more commonly used in sandwich construction (core) designs with more well known materials such as balsa wood, reed, and bamboo forms. For this article, we will not cover the sandwich structures but will concentrate more on short fiber and continuous fiber forms.

Bast Fiber: The "bast" fiber family generally consists of flax, hemp, jute, kenaf, and ramie ("China Grass"). These fibers are derived from wood core and stem materials. The wood core is basically surrounded by the stem and the stem consists of a number of fiber bundles. Cellulose is the primary chemical basis for the filament structure that makes up the fiber bundles. The cellulose is the essential filament and is bonded or held together by a natural "resin" from either the lignin or pectin family. (Note: The intent is not to get too heavy on "chemistry stuff" here, so we will tread lightly and just cover things in general.)

During the processing to obtain the natural bast-type fibers, the pectin is removed during the system that leaves only the filaments and lignin. The fibers are processed into suitable reinforcement forms that include short fibers (5-30 mm), continuous fibers or textile-type fiber forms. In order to fabricate a traditional composite, the resin system chosen to bond the fibers within the structure is used to impregnate the fiber structure using a number of available processing methods. However, the lignin actually is a weak link in the critical interface bond region between the natural fiber and the incoming structural resin matrix. The lignin material between the cells of the fibers, being the weakest link, is not desirable and every attempt is made to remove it or treat the fibers chemically to enhance the resin bond later.

Flax has a fairly high level of lignin. Consequently, flax fibers are often treated to mitigate the lignin effects. Boiling in alkali is an approach often used to improve the bond characteristics of flax composites.

Flax and jute are probably the most commonly used bast-type fibers today. Jute is the most common because it is fairly inexpensive. It has fairly good strength but is not as strong or as stiff as flax fibers.

Leaf Fiber: Leaf fibers include sisal, abaca (from the banana plant), and palm materials. These fibers tend to be much coarser than the bast-type fibers overall. We have probably heard of sisal more than any of the others in the group. Sisal is the most important and has a relatively high stiffness compared to the others.

Seed Fibers: The last group, seed fibers, covers cotton, coir (coconut husk materials), and kapok materials. Cotton is easily recognized for its widespread international use in textiles and other fibrous products within the clothing and rope industries. Coir obviously is a much more durable, thick and course fiber material as we probably know just from picking up a coconut husk. Many of these materials are used for upholstery and "stuffing" furniture products.

Natural fiber properties provide variety

We have already noted that there are basically three fiber categories as shown in Table 1 and that there are many subclasses within those three categories. Table 2 shows some of the critical performance properties of these natural fibers in comparison to conventional E-glass fiber. The range of prices currently in the marketplace is also shown in relation to E-glass fiber.

The densities of all of the natural fibers lie roughly in the 1.25-1.51 g/cm^3 range. With E-glass fiber sitting at 2.57 g/cm^3, this means that

Table 1. General categories of natural fiber materials

FIBER TYPES	FIBER CLASSES	CHARACTERISTICS
Bast Fibers (from wood cores/stems)	• Flax • Hemp • Jute • Kenaf • Ramie/China Grass	• Filaments are made from cellulose • Lignin or pectin bonds filaments together • Lignin is weak link in system • Jute is most common material
Leaf Fibers (from leaf materials)	• Sisal • Abaca/Banana • Palm	• Coarser than bast fibers • Used extensively in textiles • Sisal most important
Seed Fibers (from seed sources)	• Cotton • Coir/Coconut • Kapok	• Cotton most commonly used • Coir most durable fiber

Table 2. Comparison of natural fiber reinforcement materials with E-glass fibers

PROPERTIES	NATURAL FIBER REINFORCEMENT MATERIALS								
	E-Glass	Flax	Jute	Hemp	Cotton	Ramie	Coir	Sisal	Abaca
Density, g/cm^3	2.57	1.40	1.46	1.48	1.51	1.50	1.25	1.33	1.50
Tensile Strength, MPa (Ksi)	3450 (500)	800-1500 (115-215)	400-800 (60-115)	550-900 (80-130)	400 (60)	500 (75)	230 (35)	600-700 (85-100)	980 (140)
Tensile Modulus, GPa (MSI)	72 (10.5)	60-80 (8.7-11.6)	10-30 (1.5-4.4)	70 (10.2)	12 (1.7)	44 (6.4)	6 (0.9)	38 (5.5)	
Specific Modulus	28	25-45	7-20	45	8	30	5	30	
Elongation (%)	4.8	1.2-1.6	1.8	1.6	3-10	2.0	15-25	2.0-3.0	
Moisture Absorption (wt %)	None	7	12	8	8-25	12-17	10	11	
Price ($/lb)	0.80	0.25-0.70	0.15	0.25-0.75	0.70-1.00	0.70-1.10	0.10-0.20	0.25-0.30	0.70-1.15

the natural fibers are 50-60 percent of the E-glass density. This is one of the major drivers for natural fiber composites on a weight basis alone. Aramid fibers, traditionally among the lightest weight materials for true structural composites, is somewhere in the middle of the natural fibers at roughly 1.42 g/cm^3.

The other major factor from Table 2 that often favors natural fiber composites is price per pound (USD/lb). It is important to note that the natural fiber prices cover a fairly wide range. In all cases the natural fiber prices exhibit a lower price than E-glass, but the prices cover a pretty broad range. For example, cotton, ramie and abaca fibers all exhibit a price that can be above E-glass fiber by a fairly significant amount. Jute, coir and sisal appear to consistently show very low prices and, consequently, have been explored for use in composite products more often that the other materials. Part of the problem with the broad price range is the tie-in back to natural fiber availability for actual production use in composites in the forms desired by the manufacturers and the applications. At the present time, it appears that natural fiber production for composites use is not focused enough to drive the prices to more stable levels and product forms.

Natural fiber performance properties are somewhat a mixed bag. The tensile strength of natural fibers does not come up to the level of traditional E-glass. With the exception of coir and cotton at roughly 7-12 percent of E-glass strength, the majority are typically about 15-45 percent of E-glass fiber strength. Consequently the tensile strength of natural fibers alone is not the driver for their use in composite components.

Tensile modulus of the natural fibers fare better. While these fibers are do not surpass E-glass fiber, they do exhibit tensile moduli that are typically 40-95 percent of the E-glass. However, jute, cotton, and coir exhibit quite low modulus values. Jute, when processed from certain sources, can demonstrate modulus values that are at least 45 percent of E-glass fiber and are still attractive for low cost composites. Flax, hemp, ramie and sisal are

Facts on Fibers for Infrastructure

By Scott Reeve

Mining new applications for composite materials is central to the ongoing effort to help the technology advance across commercial and industry boundaries. In evaluating new applications, one of the key decisions is which fiber type will work best. For years, glass fiber was the only choice for most applications. Only aerospace and high-end recreational products could justify the cost of carbon fiber and have an end user willing to pay for the higher performance. Over the past three years, the price of carbon fiber has dropped to the point where it can be considered for more industrial applications including infrastructure. There is also a supplier offering steel fiber as an option to reinforce the polymers.

Glass Fiber

As the lowest cost fiber, glass has been the first option to consider for infrastructure applications. Glass fiber has a modulus of 10 msi. Fiber cost from a US supplier is $0.80 to $1 per pound depending on volume. With this comes a certain amount of customer service to work through fabrication issues such as roving selection and sizing compatibility. Glass fiber cost from China is being quoted at $0.60 per pound.

For the infrastructure industry, glass fiber has proved a good workhorse. The applications include bridge decks, rebar, seawalls, pilings, bridge fairings and reinforcement of wood beams. There were some concerns about alkaline susceptibility of glass, but corrosion resistance forms of glass are available if this is an issue in an application.

Carbon Fiber

Carbon fiber provides highly desirable stiffness and strength properties. The most commonly used carbon fibers have a standard modulus of 33 msi (GPA) and a lower bound price of $6/lb to $10/lb depending on filament count (60k to 12k). Carbon fiber has been a mainstay in the reinforcement and strengthening segment of the market. It was first used for concrete pilings, decks and beams. It is now being used instead of steel in some reinforcements of monopoles and guide towers.

Steel Fiber

Steel fibers have now entered the Fiber Reinforced Polymer (FRP) world by offering higher stiffness than glass at a lower raw material cost. Hardwire® has a menu of steel fibers developed for the composites industry in concert with its technology partner Goodyear and distributed by Ashland Distribution Company. With a steel fiber stiffness of 30 msi and a cost of $1/lb to $1.35/lb based on volume and type, Hardwire® steel fibers offer a value quotient that is worthy of consideration, particularly due to the fact that this composite combination provides the comfort of steel performance (ductile behavior) and non-catastrophic failure modes.

The biggest obstacle to the use of FRP in infrastructure is cost. We have often discussed how we could provide a lower cost FRP by using lower cost constituents. Steel fibers provide a very interesting option yet raise some questions. After touting the corrosion resistance of FRP over steel rebar, how will these steel fibers hold up when surrounded by polymers? What will thermal cycling do? Will this lead to resin microcracking? Will the interface be

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the most attractive for composites usage based on modulus performance.

It is interesting to look at specific modulus as a performance parameter. Specific modulus essentially is tensile modulus divided by the density of the fiber. The parameter takes into account the fiber weight and thus is a measure of performance per pound, if you will. On the basis of the specific modulus, a common assessment parameter used by weight-driven and stiffness-driven products, it is apparent that flax, hemp, ramie and sisal fibers actually surpass traditional E-glass. As a result, natural fibers often are used as potential low cost fiber reinforcements for composites where stiffness and weight considerations are the most important design requirement.

Table 3. SMC Comparison of E-glass fiber vs. flax natural fiber materials

PERFORMANCE PROPERTY	E-GLASS SMC	E-GLASS SMC	FLAX SMC	FLAX SMC
	20 wt % 15 vol %	40 wt % 31 vol%	21 wt % 22 vol % (6.25 mm fibers)	21 wt % 22 vol % (25 mm fibers)
Tensile Modulus , GPa	8.5	10.5	7	11
Tensile Strength, MPa	95	130	40	80
Flexural Modulus, GPa	10	13.5	7	13
Flexural Strength, MPa	125	240	83	144
Impact Strength, KJ/m^2	50	85	11	22

Moisture absorption is also an important performance parameter to consider. Moisture control during processing is important to assure low void content, reduce porosity, assure chemical bonding at critical fiber/matrix interfaces, and minimize problems with gel coats and paints surfaces. It is apparent that natural fibers tend to exhibit moisture pickup levels that are much higher than Aramid fibers (about 3 percent) and E-glass fibers (nominally zero percent). The 7-25 percent range exhibited by all of the natural fibers points out the need to thoroughly dry the fiber reinforcement prior to initiating composites processing.

Overall, the properties of natural fibers present both good news and bad news. These properties need to be considered in both the design phase and the manufacturing of composite components. Drying to remove moisture is probably the most important consideration. Designing for stiffness-driven composite product applications where light weight is an important requirement will probably lead to successful market entry.

Composite manufacturing with natural fibers

Natural fibers forms are still somewhat limited in terms of availability, and that in turn limits manufacturing options at present. A number of composite parts using natural fibers have been developed around sheet molding compound (SMC), bulk molding compound (BMC) and resin infusion (RTM, VARTM and variants) processing methods. Table 3 shows a comparison of E-glass SMC composite properties with natural flax fiber SMC properties.

Stiffness properties are pretty much comparable with the flax natural fiber composite parts. Not that the short fiber lengths tried in the flax composite has a significant effect on all of the resultant composite properties. It is obvious that the longer (25 mm) fibers significantly improve every one of the natural fiber composite properties, with particular enhancements seen in the strength-driven properties (100 percent in tensile strength, 75 percent in flexural strength and 100 percent in impact strength). The longer fibers are typical of ranges used with natural fibers. Lengths of 10, 20 and 30 mm are typically used in these products.

Resin infusion processes based on resin transfer molding (RTM), vacuum-assisted RTM (VARTM) and a number of process variations on these two basic infusion methods, have been successfully employed with fairly low fiber volumes (20-35 percent by volume; 18-33 percent by weight). Some limited filament winding composite products have also been demonstrated where stiffness is the dominant performance parameter. In general, the emphasis to date has been on using natural fibers in SMC and BMC applications within the automotive, ground transportation and sports and recreation markets.

A number of researchers have been trying to develop fiber treatment processes for improving the interface of the natural fiber surface so that improved composite strength shows significant increases in performance. Polypropylene (PP) resin matrices have been used to demonstrate natural fibers in thermoplastic composites. A number of thermoplastic resins (PP, polyethylene, nylon) and thermoplastic (epoxy, polyester, resole) resins have been tried in order to develop low cost, light weight composite options.

Natural fibers offer an environmentally friendly option for manufacturing composite parts and components while providing performance comparable to traditional composites in some applications. These materials offer excellent performance with respect to specific modulus (tensile modulus divided by density) to the degree that flax, hemp, ramie and sisal are equal to or better than conventional E-glass fibers. However, strength tradeoffs and matrix wet out with low void contents are the primary challenges facing the use of natural fiber composites. SMC, BMC and resin infusion processes appear to offer the best application entry into several markets where natural fiber composites can provide stiffness-driven parts. The economics of natural fiber materials is often more beneficial to their use over E-glass in certain applications; however, there are situations where the natural fiber costs can be higher than E-glass. This is because of the limited availability of natural fibers as well as the limited number of reinforcement "forms" currently available in production quantities. Ultimately natural fiber composites have a place in the overall composite markets but at present it represents a fairly small percent of the market today. CF

Acknowledgments:

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COMPOSITES 2003

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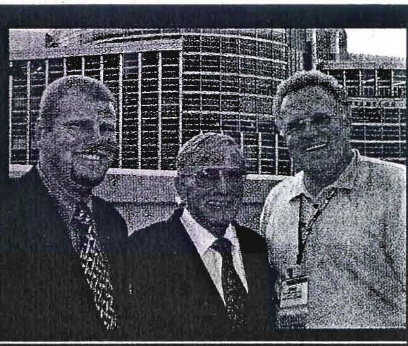

Ben Rowe (left) and his father, former ACMA board member Chan Rowe, who own and operate Plas-Tech Limited in Hawaii, pose for one with two-time ACMA Past President Gary Multanen.

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adequate for load transfer? Hardwire® has developed various coating technologies that act as interface sizings as well as corrosion inhibiters to combat these issues. While new to the composite reinforcement market, the steel cords are a time-tested product manufactured by Goodyear®.

Value Comparison

As mentioned, there are many considerations that go into selecting a fiber for any given application. From the infrastructure side, stiffness is a major design objective. So a basic value comparison is "How much stiffness per dollar am I getting from this fiber?"

The metric for comparing the stiffness per unit cost of various fibers is the Lamina Composite Modulus (E) divided by the product of Cost (C) and Density (ρ).

Metric for Stiffness in a structural application per unit cost = $\frac{E}{\rho C}$

Lamina modulus is used since the resin fraction is an important cost component. Each fiber type needs made into a composite, with appropriate fiber volumes, and its properties and metrics calculated as shown in the table below.

After making a composite with resin at 1.40 $/lb, the steel and carbon fiber composites are much closer to the lower cost glass. The carbon composite has about 23 percent less stiffness per dollar on a direct material cost basis while the Hardwire™ is less than 5 percent. Considering the cost for labor, and the fact that the glass laminates will be more than twice as thick, this starts to make a good case for carbon and an even better case for Hardwire™. The reason that steel and carbon composites are much closer to fiberglass in terms of stiffness per dollar is that fiberglass laminates of equal tensile stiffness to the steel and carbon laminates are more than twice as thick and consequently require more resin. That extra resin adds to the absolute cost.

Of course, there are other factors that will affect the overall cost equation as well. These also point to strongly considering carbon and steel fibers. Fewer plies mean less layup labor. Resin infusion is different for each of the reinforcements; tighter filament bundles are more difficult to fully wet out. The Hardwire™ material is the easiest to wet out, followed by glass, and carbon is the most difficult. All factors of the design and fabrication process need to be evaluated to truly determine the cost in using selected fibers. CF

Scott Reeve is Engineering Director at the National Composites Center, where project management responsibilities include NCC's Composites for Infrastructure (C4I) initiative and the P4A aerospace project for the United States Air Force. He also teaches courses on composites technology and stress analysis, and is co-chair of the data working group of the Composite Material Handbook (MIL-HDBK-17): 937.297.9450; sreeve@compositecenter.org.

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