Ecocomposites*

David A. Bainbridge
Associate Professor
GLS Department
Alliant International University
10455 Pomerado Road
San Diego, CA 92131

Human history is often marked by the materials and technology that reflect human capability and understanding. Many time scales begin with the Stone Age, which led to the Bronze, Iron, Steel, and Plastic ages as innovations and improvements in refining, smelting, manufacturing and science made these materials available at reasonable prices. In the 1980's the Composite Age began, represented at its extremes by the Stealth bomber and the sun powered Solar Challenger. A composite material combines two or more materials that work together to improve overall performance of the material. Innovative developments and market forces now herald the beginning of the Ecocomposite Age using biological fibers and natural or synthetic matrix materials (Bainbridge, 2001).

Ecocomposites can be very strong and selections can be made for ultimate strength, elastic modulus, fracture resistance or impact resistance. Ecocomposites are also more environmentally friendly and less hazardous to human health. The ideal ecocomposite material will be made of all natural materials that are non-toxic and biodegradable and renewable. The term ecocomposite is also used for materials that are made of natural materials and recycled materials, or made entirely of recycled materials.

Over the millennia evolution has helped select the most efficient and elegant uses of materials. Anyone who has attempted to open a macadamia (*Macadamia ternifolia*) nut can attest how tough natural materials can be. These nuts resist twice the force needed to fracture annealed aluminum yet have comparable hardness (Niklas, 1992). Plant cell walls and plant structures are natural composite materials with regular arrangement of reinforcing materials (Niklas, 1992; Vincent, 1982). One of the great challenges of developing new ecocomposites is learning to use plant structures effectively, rather than breaking materials down to small fibers or particles. Slitting straw rather than chopping it is a good example of what needs to be improved.

Over the long course of human history humans have relied on ecocomposite materials to meet most of their needs. Industrial materials are a recent phenomenon, with widespread use of plastics for less than 50 years and steel for only a little more than 100. Long before the bronze age skilled craftsmen and women made boats, weapons, tools and homes with ecocomposites. Long before the bronze age skilled craftsmen and women made boats, weapons, tools and homes with ecocomposites. We can learn from their experience and discoveries. We may not need to use sinew backed bows, made using fish bladder glue and sinew fibers to dramatically improve performance (casting arrows up to 1000 meters) to hunt for food; and we may not find the thin walled *kotni* (granaries) of India built with a mix of clay, cow dung and husks in our kitchens. Thankfully we no longer need the linen armor used by the Roman legions; but we may reconsider the straw/clay in-filled timber frames from Germany, wattle and daub walls from around the world, thick oiled starch and paper floors of traditional Korean homes, and a wide range of building products made with new ecocomposites.

**The term biocomposites has come to be used for biological materials used in medicine, and the term ecocomposites is increasingly used for all other uses.*

Composite materials combine more than one material or substance, most commonly a matrix material and high strength fibers. Glass fibers have been the most common reinforcing materials for composites, but pose health and environmental problems and are energy intensive. Biological fibers and structures and natural or synthetic matrix materials can be used to make ecocomposites that are equally strong, but environmentally friendly.Plant fibers are low cost, lightweight, and surprisingly strong on a weight basis, Table 1.

Table 1. Specific tensile strength (strength on a weight basis)

Material	MPa
Plastic	
polypropylene	74
nylon	67
Metals	
annealed aluminum	21
steel	25
Man-made Fibers	
graphite, intermediate	142
e-glass	136
Aramid	191
Natural fibers	
flax	73-220
jute	245-337
coir	107-173
Sitka spruce	256

Robson and Hague, 1993; Rosato et al., 1991; Venkataswamy et al., 1987; Niklas, 1992; McClintock and Argon, 1966: Stamm, 1964; Roff and Scott, 1971; Balaguru and Shah. 1992.

Wood is a complex natural ecocomposite material, a fiber reinforced structural foam. Sitka spruce is clearly a remarkable material and is still used for some airplanes, but it is prohibitively expensive for widespread use because of mismanagement of forest resources. Wood, despite its variation and increasing cost, is still extensively used and recognized as a structural material in homes and commercial buildings and fixtures. Balsa wood is widely used in yachts, and in the modern Corvette. Many other plant components are excellent raw materials for fabricating materials, structures, tools, and equipment. Natural fibers or plant structures (kept as long as possible) can be combined with natural plastics, resins and foams to make strong materials with high strength and light weight.

Linoleum, a once widely used ecocomposite made with linseed oil and wood fiber, is gaining favor as builders try to detoxify new homes. The pressed straw panels known as Easiwall from Stramit, used in England in more than 300,000 homes, are simply compressed straw with a paper facing.

Starch and paper construction (Appropriate Paper Technology) has been encouraged in Zimbabwe for a wide range of uses, and shows what can be done with a little inspiration and research and testing (Packer, 1995). APT products are very strong, it recreates woodlike grain and strength. The primary developers and researchers of APT set goals that are appropriate for ecocomposite development:

All products should be useful
Products should be made from materials that cost nothing!
Products must be attractive
Products must be kept friendly

Materials made with natural fibers and recycled or natural materials are also called ecocomposites, many of these are already in use including wood fiber reinforced cement siding (Hardie board and others) and wood fiber reinforced recycled plastic lumber (Trex and others). Manufacturing Trex currently uses 150 million pounds of waste polyethylene plastic every year, with new factories being built. The EcoStar slates are made of recycled rubber (80% post industrial), yet have a 50 year warranty, Class 4 hail resistance, 100 mph wind warranty and Class A fire resistance ratings.

These ecocomposites will become increasingly common as the price of wood continues to climb, environmental problems with plastics disposal increase, and agricultural fibers pose increasing costly disposal problems (as field burning of rice straw is curtailed for example), ecocomposites may be equally well recognized and understood.

Natural fibers compare favorably with man-made fibers on a strength basis and are attractive because they have chemically reactive surfaces which make more complete fiber-matrix bonding possible (Bolton, 1991). Flax (linen), hemp, coir and many other fabrics and fibers can replace more energy costly and less degradable fibers in a wide range of applications. During WWII a Spitfire airplane fuselage was built with linen fiber when it was feared that aluminum supplies would run short, but more aluminum arrived from the U.S. and the linen Spitfire was never completed.

Natural plastics and resins have also been used for many thousands of years and discoveries in recent years suggest they may well return as critical components of a sustainable society based on industrial ecology. The traditional natural plastics include materials like: keratin (hoof and horn), silk, natural rubber, gutta percha, bois durci, shellac, lacquer, varnish, starch, isinglass, hide glue and hundreds of other resins and saps (Mathias, 2001; Plastics Historical Society, 2001). Keratin is particularly interesting in some animals, with self-healing characteristics as a result of the complex structure. This might someday lead to a self-healing auto fender. These natural polymers include polysaccharides, peptides, enzymes, proteins and other complex molecules.

Gutta percha is a good example of an early and widely used natural plastic. It was used in Asia for hundreds, or perhaps thousands, of years before it was introduced to the west in 1843 by Dr. William Montgomery (Plastics Historical Society, 2001). Michael Faraday discovered that gutta percha was an excellent electric insulator and it became a key part of submarine telegraph cables, serving in more than 250,000 miles of submarine cable before eventually being replaced by polyethylene.

The polysaccharides include both wood and sugar, which formed the basis for many early modern plastics including cellulose acetate and the highly flammable cellulose nitrate. Many of these very early cellulosic plastics are still used today, including Tenite™ acetate the first of the modern thermoplastics, created in 1929 (Eastman, 2001). Tenite™ acetate is made from softwood chips, with 2.6 pounds of chips making 1 pound of plastic.

The leading edge of ecocomposite research is focussing on the innovative uses of waste materials. Two areas of research suggest what can be done: plastics from chicken feathers and resin from cashew nutshell waste.

If we feed a chicken some grain, water and crushed eggshells it will grow and produce an elegant plastic in the quills and feathers. Writers for thousands of years used this quill plastic to make pens that are still preferred by some calligraphers today. A chicken can do this at room temperature with no toxic wastes. We are just starting to learn what can be done with this keratin plastic, which has become a serious waste disposal problem as a byproduct of producing billions of chickens every year in the U.S. (Martindale, 2000). The feathers are dried, sterilized and shredded and separated in a density based air separator. The barb fibers which are stronger and more flexible are separated from the quill. The fiber powder has been used to make polymer films that may replace cellophane in food packaging. The powder is also excellent as a reinforcing fiber, replacing fiberglass fibers in mixes of other plastics. Five billion pounds could be produced every year in the U.S. if all feather waste was utilized. This would dramatically reduce the pollutant loading and landfill space lost to feather waste.

Cashew nutshell resin is made from cashew nutshell liquid (CNSL), a mixture of phenolics extracted from cashew nut shells. CNSL is the only naturally occurring alkenyl phenolic material in world trade at the moment. Research at the BioComposites Centre in Wales has found a way to make a formaldehyde free resin that can be water sprayed. This resin could be used to make strong "bioboards" with no formaldehyde emissions (BioComposites Centre, 2001).

Some very promising areas for research where we haven't yet managed to figure out how nature works include chitin, the polysaccharide made by many crustaceans. This is hard, insoluble, yet flexible. Like chicken waste plastic there are many millions of pounds of chitin disposed of every year. We are also still working to unravel the mysteries of spider web materials, which come in many formulas with often remarkable properties. Spider dragline silk is five times stronger than steel on a weight basis, five times tougher than Kevlar and elastic (Benyus, 1997). If you hang weight on equivalent diameter spider silk and steel threads they will break at about the same time, but the spider silk will stretch to 40 percent longer than its original length and bounce back if the weight is removed.

In the area of new products from renewable resources we find sugar based epoxies that outperform petroleum based products for binding concrete, wood, metals, and plastics (Anon, 1999a). Depending on the formula used these epoxies set clear, glassy or rubbery and flexible. The production process leaves only vinegar and salt (Anon, 1999b). These are now being evaluated in composite board production by Acadia Board and CMGI companies. These might provide a use for genetically contaminated agricultural products such as Star-link tainted corn. Research in India has explored bamboo and epoxy and bamboo and polyester resin composites (Jain et al., 1993). The tensile strength of the epoxy based material was 112.5 MN m^{-2} and the polyester material was 102.6MN m^{-2}. The authors note this material could be used in crash helmets, windmill fins and low cost housing. Unavailable in 1993, the sugar epoxies should provide comparable performance with bamboo if the materials were retested today. Gregory Glenn has developed starch based microcellular foams and lightweight concrete (Glenn and Irving, 1997; Glenn, 2001).

Cargill-Dow and Monsanto are working on bioplastics from corn and other plant materials (including from genetically engineered plants). Dow Cargill, working under the name Nature Works, expect to produce 300 million pounds of polyactide (PLA) plastic a year. PLA will be the first new biodegradable plastic made entirely from renewable resources (Anon, 2000).

There is also much to be learned about linseed oil based polymers. These were used in many traditional ecocomposites. The linseed comes from a flax plant, as does linen. The linseed oil can be polymerized by setting it in the sun, and violin builders for centuries have tested and refined methods for getting just the right properties in their linseed oil based varnishes. Methods for purifying linseed varnish with cycles of freezing have also been developed, making for a potentially very environmentally benign manufacturing process. Farm fields with flax and linseed plants could feed raw materials to solar and freezing based refining, polymerization, and manufacturing.

There are also many interesting possibilities with shellac and lacquer. Shellac is based on the a resin made by an insect (*Laccifer lacca* and others) (McLaughlin, 1996). The shell like casing made of resin and wax protects the mother and her young and is collected from the trees after the lifecycle is completed. Most shellac today is used as a coating on food products, including such things as gummy bears. Shellac has a reputation as a water sensitive finish, but pure shellac is totally water resistant (Minick, 1999). The problem arises as esterification takes place in the alcohol/shellac mixture. Shellac ester is not only water sensitive but also prevents complete hardening of the shellac.

Ecocomposites can be completely based on sustainable resources. They are also attractive because they are usually safer to handle and work with and more environmentally friendly. Most ecocomposite materials can be recycled (composted or digested) or burned, without the residues that are left with glass and silica fiber composites. Plant fibers can be produced by sustainable agricultural systems (Mitchell and Bainbridge, 1991), with low embodied energy, with atmospheric carbon rather than mined "carbon" from petroleum or coal.

The most elegant ecocomposites combine naturally occurring materials without extensive processing. The traditional light straw clay infill insulation of a timber frame house in Germany is a perfect example (Volhard, 1983). The clay slip provides fire resistance and stabilizes the straw. The straw provides a matrix to retain air and insulation. The straw may today be replaced with wood chips to make a denser material. A cob house with straw stabilizing an earthen wall is also a good use of low embodied energy materials. Bill and Athena Steen's work on straw rich adobe blocks in Mexico is very exciting. This improves a traditional building material with a waste resource.

Ecocomposites may be made with natural plastics extracted from plant materials or produced in bio-engineered processes using yeasts, bacteria and other organisms. It is entirely plausible to imagine a car that is predominantly made of ecocomposite materials, from the body to the wheels, springs, and interior.

Combinations of plant fibers and recycled plastic may make suitable composite materials for many uses. Despite glowing promises in the late 1980's the plastic industry has been unable or unwilling to develop recycling programs for many plastics (Kleiner and Dutton, 1994). While some progress has been made on PET (24% recycled), recycling of LD and LLD polyethylene (0.7%), HD polyethylene (5%), PVC (0.2%), PP (3%), and PS/HIPs (0.8%) is so low it be considered non-existent. More than 11 billion pounds of LD and LLD polyethylene are produced each year, and 8 billion pounds of HDPE and PVC. Because the plastic is being recycled into a building material rather than a food contact product the difficulties in cleaning the waste stream would be minimized.

Composites of biological fiber and recycled plastic will become important building materials. Capturing even a few percent would provide sufficient material to manufacture much of the framing used in the U.S. Combining recycled plastics with slit long straw fiber may provide a useful material for many products and environments. This composite material would have a density comparable to Douglas fir.

Summary

The age of ecocomposites has begun. Agricultural and industrial ecology should make it possible to grow plastic resins and reinforcing materials economically and safely. These materials can be used to make lighter, stronger and more durable products that save resources and energy. Long life and eventual recycling can be engineered into these products. The potential economic benefits include production of biofibers in farming areas beset with economic and environmental problems. The introduction of straw based building materials can reduce air pollution problems, absorb some of the plastic waste stream, and improve the energy efficiency of the homes and commercial buildings. The use of current wastes such as feathers and nut shells is also important. The can reduce the increasing impact of agricultural operations on the environment.

This is an exciting new frontier that requires the talents, skills and enthusiasm of engineers, hobbyists, builders, farmers, chemists, botanists, ecologists, mycologists, agronomists, anthropologists, historians and economists. Integrated, holistic, systems oriented development will be needed to recognize the full potential of these materials in the development of Industrial Ecology based on ecocomposite materials. We can hasten this transition and improve the performance of ecocomposite materials by learning from past uses, successes and failures.

References and further reading

Anon, 1986. New building panels reduce cost, increase design flexibility. Construction Data 16(24):1.

Anon. 1994. From straw to Stramit. The Last Straw 7:26-27.

Anon. 1999a. The sugar/epoxy connection. Evergreen Newsletter 4(3).

Anon. 1999b. Getting sweet on epoxies. Resource 6(12):5-6.

Anon,. 200. New plant-based plastic set for production. PSR Environment and Health Update 4(1):3.

Atkins, A.G. and Y.W. Mai. 1985. Elastic and Plastic Fracture. John Wiley and Sons, NY.

Balaguru, P.M. and S.P. Shah. 1992. Fiber Reinforced Cement Composites. McGraw Hill, NY.

Benyus, J.M. 1997. Biomimicry. William Morrow, NY 308 p.

BioComposites Centre. 2001. CNSL Resin formaldehyde free. www.bc.bangor.ac.uk/cnsl.htm, Northern Lights 5/7/2001.

Bainbridge, D.A.. 2001. Ecocomposites. www.ecocomposite.org Northern Lights 6/2/2001.

Glenn, G.M. and D.W. Irving. 1997. Starch based microcellular foams. Cereal Chemistry 72:155-161.

Glenn, G.M. 2001. Aquagel-based lightweight concrete. U.S. Patent 5,595,595.

Jain, S., U.C. Jindahl and R. Kumar. 1993. Development and fracture mechanism of the bamboo/polyester resin composite. Journal of Materials Science Letters 12:558-560.

Kleiner, A. and J. Dutton. 1994. Time to dump plastics recycling? Garbage 6(1):44-51

Martindale, D. 2000. Car parts from chicken feathers? Scientific American (4): www.sciam.com/2000/0400issue/0400scicit4.html

McLintock, F.A. and A.S. Argon. 1966. Mechanical Behavior of Materials. Addison Wesley, Reading, MA.

Minick, C. 1999. Shellac: a marvelously versatile finish. Fine Woodworking #134:129-130.

Mitchell, S.M. and D.A. Bainbridge. 1991. Sustainable Agriculture for California: A Guide to Information. University of California Division of Agriculture and Natural Resources, Publication #3349, Oakland 196 p

Niklas, K.J. 1992. Plant Biomechanics. University of Chicago Press, Chicago, IL 607 p.

Packer, B. 1995. Appropriate Paper-based Technology APT. IRED, Harare, Zimbabwe 176 p. (available from styluspub@aol.com)

Robson, D. and J. Hague. 1993. The properties of straw fibre. pp P#03: 1-19. In Proceedings Straw-A valuable raw material: Volume 1. Pira International, Leatherhead, Surrey, UK.

Rosato, D.V., D.P. DiMattia, and D.V. Rosato. 1991. Designing with Plastics and Composites: A Handbook. Von Nostrand Reinhold, NY.
Roff, W.J. and J.R. Scott. 1971. Fibres, Films, Plastics and Rubbers. Butterworths, London.
Venkataswamy, M.A., C.K.S. Pillai, V.S. Prasad, and K.G. Satyanarayana. 1987. The effect of weathering on the mechanical properties of midribs of coconut palms. Journal of Material Science 22:22:3167-72.
Vincent, J.F.V. 1982. The mechanical design of grass. Journal of Material Science 17:856-60.
Volhard, F. 1983. Leichtlebau-alter baustoff-neue Technik. Verlag CF Muller, Karlsruhe, GDR.

An Ecocomposite Reading List See also: www.ecocomposite.org

Although **ecocomposites** are just developing as a field for research and development there are several books that will help you understand and participate in this materials revolution. The most accessible information on small scale composite manufacturing and design can be found in magazines such as Professional Boatbuilding, Primitive Archer, kit and experiment aircraft magazines, and advanced auto racing magazines such as Race Car Engineering. They are not about ecocomposites -- and any innovation should be carefully tested, evaluated and monitored if there is any danger involved in failure.

Vogel, S. 1998. **Cats' Paws and Catapults**. W.W. Norton, NY 382 p. ISBN 0-393-04641-9

A delightful and well illustrated introduction to the workings of nature and biomechanics. Clear explanations, broad vision and specific examples make this a must read.

Niklas, K.J. 1992. **Plant Biomechanics: An Engineering Approach to Plant Form and Function.** University of Chicago Press, Chicago, IL 607 p. 0-226-158641-6

A fairly technical book with clear descriptions of engineering principles, limitations on organisms and test data. Niklas shows how basic physical laws apply to plant form and function. Chapter 2: The Mechanical Behavior of Materials is required reading for non-engineers and may inspire mechanical engineers to explore natural materials.

McBeath, S. 2000. **Competition Car Composites**. Haynes Publishing, Newbury Park, CA 208 p. ISBN 1-85960-624-5

Much of the most interesting work on composite materials is being done in race car engineering. This book provides a clear description of composite materials and design and describes simple testing and layout procedures that will prove invaluable for ecocomposite experimenters.

Perkowitz, S. 2000. **Universal Foam: From Cappuccino to the Cosmos**. Walker and Company, NY 194 p. ISBN 0-8027-1357-2

Wood can be thought of as a fiber reinforced foam and many of the promising materials for ecocomposite use are foams. This delightful book introduces the reader to foam and the properties of foams that make them so important.

Benyus, J.M. 1997. **Biomimicry**. William Morrow, NY. 308 p. ISBN 0-688-16099-9

A delightful look at the applications of nature in materials and structures. Emulating nature to survive. A very good introduction to the field.

Packer, B. 1995. **Appropriate Paper-based Technology APT**. IRED, Harare, Zimbabwe 176 p. ISBN 1-85339-268-5

This is a hands on manual of making things with little more than waste paper and starch. From bookcases, to desks to facilities for handicapped children. Comprehensive instructions and suggestions for working with APT.

Pearce, P. 1978. **Structure in Nature as a Strategy for Design**. MIT Press, Cambridge, MA 245 p. ISBN 0-262-16064-1

One of the first books to look at natural structures and explain their workings. Fabulous pictures and good descriptions of principles and their engineering lessons.