COMPOSITES FROM BAST FIBRES - PROSPECTS AND POTENTIAL IN THE CHANGING MARKET ENVIRONMENT

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ABSTRACT

Composite materials reinforced with natural fibres, such as flax, hemp, kenaf and jute, are gaining increasing importance in automotive, aerospace, packaging and other industrial applications due to their lighter weight, competitive specific strength and stiffness, improved energy recovery, carbon dioxide sequestration, ease and flexibility of manufacturing and environmental friendliness besides the benefit of the renewable resources of bast fibres. The market scenario for composite applications is changing due to the introduction of newer bio-degradable polymers, such as PLA synthesized from corn, development of composite making techniques and new stringent environmental laws requiring improved recyclability or biodegradability for industrial applications where stress bearing capacities and micro-mechanical failures dictate serviceability. Bast fibre reinforced composites, made from bio-degradable polymers, will have to compete with conventional composites in terms of their mechanical behaviour. Bio-composites, in which natural fibres such as kenaf, jute, flax, hemp, sisal, corn stalk, bagasse or even grass are embedded in a biodegradable matrix, made as bioplastics from soybean, corn and sugar, have opened-up new possibilities for applications in automotive and building products. Obviously, new approaches to research and development will be required to assess their mechanical properties and also their commercial

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competitiveness against petroleum based products. This paper will review the newer products and techniques that can improve the properties of bast fibre based composites as well as potential applications which can increase their market share.

Key Words: Fibre-reinforced composite, biodegradable, natural fibres, bast fibres, hemp, flax, kenaf, particle boards, automotive components, biocomposites, thermoset, thermoplastic.

INTRODUCTION

A *composite material* is a heterogeneous combination of two or more different constituents (reinforcing elements, fillers and binders), differing in form or composition on a macroscale. The combination results in a material that maximizes specific performance properties. The constituents do not dissolve or merge completely and therefore normally exhibit an interface between one another.

The fierce competition in the fibre reinforced composites (or plastic) market has compelled the manufacturers to be innovative, adopt newer production techniques, utilize cheaper resins and fillers while maintaining performance in terms of strength, temperature resistance, fracture and resilience. Essentially new grades of plastics are developed for existing and newer applications by utilizing different fillers and combinations of fillers/reinforcements. Traditionally, most synthetic fibres, such as carbon, E-glass, boron, aramid, and Kevlar, have been widely used as reinforcing medium in composites. Commonly used resins include polypropylene, nylon, polyphenylene sulphide (PPS), polycarbonate (PC), polyethylene, and polyethylene ethyl ketone (PEEK). Due to the increased pressure from environmental activists and attendant stringency of laws passed by most developed countries, the composite manufacturing industry has to search for plant based natural fibre reinforcements, such as flax, hemp, jute, kenaf, sisal, henequen, pineapple, and banana. Therefore, accelerated development efforts have taken place over the past two decades for natural fibre based composites.

The market for fibre-reinforced plastics has increased in leaps and bounds over the past four decades. Almost 1.0 billion kilograms of reinforced composites were produced worldwide in 2002 and the market is forecast to increase by some 3.5% per annum, with the production reaching about 1.2 billion kilograms, with a value of US$ 6.5 billion in 2007. Figure 1 shows the distribution of the market for fibre – reinforced composites according to application (Business Communication Company, Inc., 2002).

[Insert Figure 1 Here]

Automotive, construction, marine and electronic applications account for the major proportion of composites. Thermoset composites account for about 62% of the total volume produced in 2002 and it is expected to dominate over fibre-reinforced thermoplastic composites despite the popularity of the latter due to their recyclability. Long-fibre thermoplastic composites and nanocomposites are likely to play an increasingly important role in the coming years, as research and development will mature (Business Communications Company, Inc., 2002).

To strike a balance between cost, quality, performance, environmental regulations and supply of natural fibres, such as, flax, hemp, jute, kenaf and sisal, a number of composite manufacturers are developing new facilities for utilizing alternative fibres (Karnani et al, 1997; Marsh, 2003). To augment the resource driven approach and strategy for finding new applications for the available natural fibres, the automotive industry has taken the leadership. The automotive sector requires reasonably durable materials which must biodegrade at the end of their service life. Reinforced composites made from lingo-cellulosic plant materials offer attractive opportunities because of their strength resulting from the strength of fibre bundles. The applications of such bast fibre reinforced composites in load bearing components as opposed to conventional composites based on wood fibre may turn out to be one of the material revolutions of the twenty first century (Rowell, et al, 1998).

The advantages and disadvantages of natural fibre reinforced composites may be listed as follows:

Advantages:

- Reduction in density of products from 10-30% in comparison to conventional metallic parts.
- Acceptable specific strength, toughness and stiffness in comparison to glass fibre reinforced composites.
- Ease of shaping into complex shapes in a single manufacturing process.
- Reduced tool wear.
- Most thermoplastic based natural fibre reinforced composites are recyclable and they are earth friendly as a sustainable renewable raw material is utilized.
- Lower energy consumption from fibre growing to finished composites, in comparison to synthetic and glass fibre based composites. For example, very high thermal energy is required during spinning of synthetic fibres.
- Bast fibres are CO_2 neutral as oxygen is emitted back into the environment during degradation. The possibility of thermal recycling in contrast to the combustion process for glass fibres make them environmentally friendly.

- The manufacturing processes are relatively safe when compared to glass fibre based reinforced composites. The glass fibres emit small airborne glass particles during manufacturing, thus causing the problem of occupational safety.
- Reduced dermal and respiratory irritation.
- Possibility of recycling the cuttings and wastage produced during manufacturing and moulding.
- No emission of toxic fumes when subjected to heat and during incineration.
- The production of natural fibres can be started with a low capital investment and with a lower cost, thus offering great potential to poor and developing nations for the generation of employment.
- Bast fibres exhibit good thermal and acoustic insulation properties.

Disadvantages:

- Lack of consistency of fibre quality, high level of variability in fibre properties depending upon source and cultivars.
- Preparation of fibre is labour intensive and time consuming.
- Poor compatibility between the fibres and matrix which requires surface treatment of fibres.
- Lower impact strength of bast fibre reinforced composites.
- High moisture absorption which brings about dimensional changes in composite materials.
- Poor fire resistance which restricts applications where risk due to fire is possible. Fire retardants have to be bonded to the fibre cell wall to improve the fire resistance of the composites.

- The availability of suitable fibres is uncertain and supply is rather irregular. The uncertain of supply is sometimes influenced by national agricultural policy and politics.
- Low density of bast fibres can be disadvantageous during composite processing application because fibres tend to migrate to the surface rather than getting mixed with the matrix.
- Fluctuation in price depending upon the global demand and production.
- Problem of storing raw material for extended time due to possibility of degradation, biological attack of fungi and mildew, loss in colour, and foul odour development.
- Lower resistance to ultra violet radiation, which causes the structural degradation of the composites.

FIBRES FOR COMPOSITES

The compatibility between polymers, fibre surface, and composite manufacturing processes employed will determine the properties of composite materials. Important natural plant materials used in composite materials is classified in Figure 2.

[Insert Figure 2 Here]

Wood fibres have been traditionally utilized in some composite applications as they are uniform, inexpensive and abundant; nevertheless, they are very short which limits their reinforcing ability. Bast fibres alone account for some 4 million tons of global fibre production and represent a vast and sustainable raw material source. Other natural fibres from leaf (sisal, banana, palm, pineapple) and seed (cotton, coir, kapok) of plants are also utilized as reinforcement in composite materials; however, they are out of the scope of the present paper. The physical, mechanical and chemical properties of major bast fibres, as well as the widely used E-glass fibre, are compared in Table 1.

[Insert Table 1 Here]

The bast consists of a woody core surrounded by a stem. The stem consists of a number of fibre bundles, each containing individual fibre cells or filament like fibres. Chemically, the fibres are made of cellulose and hemicellulose and they are bonded together by a matrix containing lignin or pectin. The pectin surrounds the bundle of fibres and bonds it to the stem. The pectin is removed during the retting process which enables the separation of fibre bundles from the rest of the stem.

From Table 1 it is evident that the density of glass fibres is higher than all the bast fibres. The tensile strength of all bast fibres is lower than that of glass fibre, nevertheless, the elastic modulus, E, of hemp and flax fibres is comparable to that of glass fibre. Due to the lower density of bast fibres, their specific strengths are comparable to that of glass fibre. The dimensional properties of bast fibres are highly variable due to their natural origin, retting process and fibre separation techniques employed. The moisture absorption of bast fibres is far higher than that of glass fibre which is somewhat disadvantageous in certain composite manufacturing processes. Special pre-treatments are required to control the moisture during the composite manufacturing processes.

COMPOSITE PROCESSES

The applications of bast fibres in composites include particle boards, automotive components, electronic circuit boards, household appliances and packaging products. Most of these applications involve compression moulding technology in which usually medium to long bast fibres in the form of nonwoven mat or felt are used. Compression moulding was specifically developed with a view to replace metal components with composite parts. The moulding process can be carried out with either thermosets or thermoplastics. However, most applications today use thermoset polymers and in fact, compression moulding is the most common method of processing thermosets.

As natural fibres do not possess thermoforming properties the addition of polymer as binder is necessary. The composite can be formed by coating, impregnating or compounding the bast fibres with polymer and then setting/curing the matrix to form a solid material which can be moulded into the desired shape. The process employed is dependent upon the type and characteristics of the polymer. Thermoplastic polymers, such as polypropylene, polyester and their bi-components are used for thermoforming the natural fibres. In the thermoset process, the natural fibre mat or fabric is coated or impregnated with epoxy resins or polyurethane. It is then moulded into the desired finished products. All bast fibres, such as flax, hemp, jute and kenaf, can be used to produce thermoset or thermoplastic moulded components using compression moulding techniques.

Injection moulding is the process in which the polymer matrix is reinforced with short natural fibres in the desired proportion. A hot, molten polymer is injected into a cold mould. A screw apparatus, either a single or twin screw type, is used to inject the polymer into the mould. After the mould cools and solidifies, it is opened and the part is ejected. The short bast fibres are compounded with a polymer, such as polypropylene, and then also extruded into granules for subsequent injection moulding (Karmaker and Youngquist, 1996).

Pultrusion technology for making bast fibre based composite is gaining very wide acceptance these days. Bast fibres can be easily converted into strands and cords due to their spinnability. Pultrusion technology can utilize the thread-like material to form the reinforced composite. Pultrusion is a continuous process for manufacturing composites that have a constant cross-sectional shape. The process consists of pulling a fibre reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured for setting. The primary reinforcement in pultrusion is in the longitudinal fibre direction whereas in filament winding it is in the hoop direction. These materials are generally used in structural applications. Commonly used reinforcements in pultrusion are glass, carbon and aramid fibres. The matrix material must cure quickly, not only because of the high speed of material production but also because it is a continuous process. The technology can be employed for developing high end structural composites from bast fibres as substitutes for man-made fibre based materials (Richardson and Zhang, 2001).

OPPORTUNITIES FOR BAST FIBRES

Bast fibre based composites may offer a profitable return if the selection of raw materials; both fibre grade and polymer, utilisation of the right manufacturing technique in view of the end-use characteristics, and right strategy of value addition through performance improvement features are employed judiciously. The development of new markets by offering products with improved properties, and substituting the existing glass fibre based products by bast fibre based composite can offer opportunities. Major products from bast fibres are summarised here below:

- Particle boards and fibre boards (composite lumber)
- Automotive Components
- Housing and infrastructure products
- Bio-composites

Particleboards and Fibreboards:

Particle and fibre boards constitute major applications of bast fibre based composite materials. In conventional wood based boards, the waste wood or wood chips mixed with saw dust are mixed with phenolic resins and then pressed between two hot plates. Subsequently they are subjected to grinding and polishing for finished products. Low, medium and high density fibre boards are made depending upon the end-use requirement. Hemp, flax, kenaf, either alone, or with other cellulosic waste, such as wood chips and dust, are most widely used with the appropriate binders. Traditionally, isocynate and melamine are the best and the most cost-effective binders for bast fibres and woody matters which provide adequate strength and performance for most exterior applications. Since isocynate releases no formaldehyde during manufacturing and use, which makes it safe. Considerable recent research on binder, the use of inexpensive core of bast as substrate and the improved adhesion with substrate due to pre-treatments, has reduced the cost to make them economically attractive and thus viable.

However, such composite boards are susceptible to destruction due to fire and therefore their use can be limited particularly in public and high-rise buildings. The application of special fire retardant coatings is required to make them non-ignitable. A number of studies have been reported in which fire retardant chemicals, mineral particles as fillers and non-flammable binders are added during the production process (Kozlowski et al, 1999). In this research, a three-layer non-flammable composite particle board, based on lignocellulosic particles and mineral filler, was used with urea – formaldehyde resin as a binder (Kozlowsky et al, 1999). These authors have reported production technologies for making such boards and have produced non-flammable boards with sufficient strength and durability. The technique can be used for raw materials, such as wooden particles, bast fibres and shives (Kozlowski et al, 1999).

The use of alternative binders stems from the need to reduce the cost and comply with newer environment laws. Lignin, a natural binder in plant materials, is also offering potential in developing completely bio-based fibre boards. However, this approach has achieved limited success to date. Other bio-based binders, such as soybeans based adhesives and resins derived from natural source, are under study currently.

The economic viability of bast fibre based particle and fibre board is yet not well established due to their cost of production. The raw material is relatively expensive in comparison to conventional wood based particle boards. The technical feasibility conducted by various researchers on the use of bast fibres, such as kenaf, hemp and flax, in furnishing-based panel and particleboards applications indicate that bast fibres can either supplement or replace conventional wood, provided products are planned to exploit their special properties, such as strength and toughness (Marsh, 2003; Lloyd and Seber, 1996).

Automotive Components:

Automotive components offer unprecedented opportunities for bast fibres. During the past 10 years the use of natural fibre composites in automotive interior components has increased in leaps and bounds. Due to the availability of different manufacturing technologies and the proximity of raw materials in Europe, hemp and flax fibres are utilized in such applications. Jute, grown in sub-tropical regions, such as India and Bangladesh, and Kenaf in USA are also now-a-days utilized in automotive components. Decorticated bast fibres, such as flax, hemp, jute and kenaf, are particularly suitable as reinforcement for polymeric resins, thermoplastic and thermoset composites, most prevalent in automotive components. The rapid increase in bast fibre based composites in automotive industries is also attributed to the production of lighter and fuel efficient cars, the requirement for reduced air pollution and the difficulty associated with recycling glass, carbon, and aramid fibre reinforced composites from polyester, epoxy and similar resins, besides the high level of energy expended in the entire value-addition chain. One ton of natural bast fibres require only 12% of the energy required to produce the equivalent amount of glass fibres (Marsh, 2003).

A logical beginning should be to utilize easily available recyclable resins, such as, polypropylene, polyolefin, polyethylene, polyamide and polyurethane, in combinations with biodegradable plant fibres. Thanks to high production nonwoven technologies that can provide nonwoven mat or felt at relatively low price. The nonwoven mat can be produced by the most prevalent needle-punching or air laying or hydroentanglement technology. The compression moulding technology can be utilized with appropriate binders to make thermoset or thermoplastic composites. Nonwoven mat from hemp fibres as reinforcing medium in phenolic resin have been studied (Richardson and Zhang, 2001). The introduction of two layers of nonwoven fabrics into resin improved the panel flexural strength from 11 MPa to 25 MPa and stiffness by 23%. The impact resistance of phenolic resin without reinforcement is quite low due to its brittleness, the addition of hemp as reinforcement improved it markedly due to transfer of impact force from matrix to fibres. The introduction of bast fibre based mat in also reduces the number and size of voids formed due to curing of thermoset attributed to the hydrophilicity of bast fibres which absorbs moisture produced by the curing (Richardson and Zhang, 2001).

The applications of bast fibre reinforced composites in automobiles is so far limited to interior items, such as door panels, inner trim parts, parcel compartments, shelves, headliners, and roof liners, where conventional glass fibre and synthetic fibre based composites far exceed the strength requirements for such applications. This provides a great opportunity for bast fibres as more and more vehicle manufacturers are recognising their cost-benefit advantage and the need to comply with new recycling legislations.

The major drawback of a bast fibre reinforced composite is its poor impact strength, although the properties of bast fibre reinforced composites from thermoplastic and thermosetting resins have proved to be adequate in non- and semi-structural applications, research aimed at improving their impact strength will be very useful for developing structural applications. This requires research on interfacial properties to improve impact strength. Pre-treatment of bast fibres before the composite making process is a key to improve interlaminar strength. For example, in a recent study a treatment of bast fibres with alkali and diluted resin improved adhesion between fibres and epoxy interlaminar strength almost by 100%. Recent invention specifically overcomes past difficulties involving compounding and injection moulding of composite specimens with bast fibre reinforcements. In one form, ultrasonic energy is applied to decorticated bast fibres to cause fibrillation which improves their adhesion to polymer matrix (Krishnaswamy, US Patent No: 6767634, July 27, 2004).

Housing and Infrastructure Products:

Housing and infrastructure applications require structural composite materials and the use of natural fibres based composites can play an important role in this segment as new emerging materials. The construction industry accounts for almost 32% of the total demand for reinforced composites today. It is important that better and affordable houses are built from ‘green’ materials to reduce the impact of erosion of trees for ecological and climatic conditions. For 21st century housing affordable alternative materials are needed and researchers are focused on biobased structural composite materials. The manufacturing technologies leading to the hybridization of different constituents, such as fibre reinforced composite and biobased plastic, at structural levels can help (Drzal et al., 2001, Riedel and Nickel, 1999).

Conventional fibre reinforced plastic, whether from natural or petroleum origin, are not suitable for load bearing housing applications due to their low strength, low bending resistance, low thermal stability and poor dimensional stability. Polyester is the most widely used material in composites for the housing industry. Natural fibres and polyester fibre based nonwoven mats in the proportions of 90% and 10%, respectively, have been tried as reinforcement in unsaturated polyester resin. Blends of unsaturated polyester resin and vegetable oils were also tried as the matrix in a 30% by volume fraction of the reinforcing medium. The mechanical and thermal properties were far superior to conventional petroleum based composite systems (Drzal, 2001). Performance of wood-based or fibre based composites can be improved by suitable chemical modification techniques to modify fibre properties, such as surface characteristics, dimensional stability, resistance to biological and ultraviolet exposure and resistance to chemicals. It can be also treated with conventional fire retardants to improve its fire resistance (Rowell, 1995).

Plant fibres are used as reinforcing medium in the production of cement based composites. The wood fibre reinforced products are widely used as they offer the high tensile strength, impact resistance and workability of wood with the fire resistance, durability, dimensional stability and weather resistance of cement based materials. Research in utilizing alternative fibres and new processes continues to develop cement-based composites with a view to offer balance of performance and aesthetic characteristics at competitive cost for low cost housing (Olesen and Plackett, 2002).

Bio-composites:

The regulatory pressures generated by the recent end-of-life of vehicles (ELV) laws of the European Union require the automotive manufacturers to ensure that all new vehicles are 95% recyclable by 2015. This new regulation has placed serious responsibilities on the automobile manufacturers to be the front-runners in developing new biodegradable composites. Conventional thermoplastic resins, such as polypropylene, polyolefin, polyethylene, polyurethane and polyamide, are the most widely used in fibre reinforced composites; however, they are recyclable but not biodegradable. The composite matrix is very stable and poses considerable problems with respect to reuse or recycling after the product has reached the end of its service life. A simple landfill disposal is becoming unacceptable in view of increasing environmental awareness. To comply with new stringent laws require new strategies for developing composites from natural reinforcing medium and polymeric matrix also derived from natural materials, say plants (Riedel and Nickel, 1999; Drzal, 2001; Marsh, 2002).

Biocomposite products are now commercially produced made from 100% biobased raw materials, both for reinforcement and as polymer. Thermoplastic biopolymers available include polylactic acid (PLA), poly hydroxyl alkanoate, Cellulosic Plastic and Starch Plastic, soybean and corn based polymer resins. Some of these biopolymers have properties similar to petroleum based thermoplastic resins, such as polyester, and they are on their way to full-scale commercialization. New soybean and corn-based polyurethane-type resins are used in making a composite called HarvestForm™[3] having adequate strength, flexibility, corrosion resistance and endurance and being 25% lighter than steel. The composite panels produced by means of this technology are being tested in various agricultural machinery of the company. The research on developing low and high performance polyurethanes from soybeans is continuing and multidisciplinary programme encompassing genetic engineering, composite manufacturing and soy-based liquid moulding is underway at the University of Delaware, USA. Researchers have produced full biocomposites incorporating natural bast fibres. However, the success of these biopolymers in the fibre reinforced composite market will be dependent upon the possibility to achieve their chemical modifications and ease of processing besides their ability to provide the required toughness and strength in the final products.

The success of bast fibre reinforced biocomposites will be dependent upon appropriate processing techniques, modification of fibres to improve the adhesion between fibre and the biopolymer, matrix modification and after treatment to improve performance. Maybe, hybrid biocomposites, containing a high proportion of natural bast fibres and only a small proportion of glass fibres (~ 6%), may offer near term solution while research on 100% biocomposite matures and resolves some of the outstanding problems related to their mechanical properties and dimensional stability (Mishra, 2003).

Future Research Directions:

- Research effort should mainly be directed to the improvement of the interfacial properties between the fibre and the matrix. The surface treatment of fibres can improve adhesion between two different constituents (phases),

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[3] Registered trademark of John Deere and Co.

thereby improving the mechanical properties, fracture and fatigue performance.

- New methods of fibre extraction should provide more elemental and technical fibres for effective embodiment into composite matrix.
- Further exploitation of nonwoven technologies, both in terms of fibre laying and web bonding.
- Composites, resins and adhesives made from renewable resources should be developed. Search for new and improved bioresins to replace standard petroleum based resins should be continued to fully meet with future environmental goals. Multidisciplinary research, involving agricultural, biotechnology, polymer and composite manufacturing aspects should be carried out.
- Composite manufacturing technologies should be refined and made suitable for the new bioresins.
- A paradigm shift with respect to the concept of biodegradability should be thoroughly researched; the research should be directed to ‘triggered’ biodegradability. The biocomposite should start degradation only in the presence of certain triggers to control and initiate the process of biodegradation. This research will have two advantages, namely, preventing the degradation of the product during use, thus preserving essential properties until the end of the product’s useful life and thereafter allow accelerated degradation of the product for quick disposal.
- In the light of the current trend on nanocomposite, research efforts should be directed to derive nanofibres and whiskers from bast fibres and other

lignocellulosic materials. This will help in incorporating natural fibres in nano-clays.

REFERENCES:

Business Communication Company, Inc., RP-178 Composites: Resins, Fillers, Reinforcements, Natural Fibres and Nanocomposites, Report, September 2002.

Centre for Lightweight Structures, TUD - TNO, Netherlands, the Project on Natural Fibre Composites from Upholstery to Structural Components. www.clc.tno.nl

Drzal, L.T., Mohanty, A.K., and Mishra, M. Biocomposites From Engineered Natural Fibres For Housing Panel Applications, National Science Foundation Partnership for Advancing Technologies in Housing (NSF-PATH), 2001. Award No: 0122108.

Drzal, L.T., Mohanty, A.K., Bugueno, and Mishra, M., Biobased Structural Composite for Housing and Infrastructure Applications: Opportunities and Challenges, Pre-publication Communications. Source: www.pathnet.org/si.asp?id=1076

Ellison, G.C., and McNaught, R., The Use of Natural Fibres in Nonwoven Structures for Applications as Automotive Component Substrates, Report Ref. No. NF0309, February 2000, MAFF – Industrial Materials, U.K.

Karmaker, A.C. and Youngquist, J.A., Injection Moulding of Polypropylene Reinforced with Short Jute Fibres, J. Applied Polymer Science, Vo. 62, 1147-1151, 1996.

Karnani, R., Krishnan, M., and Narayan, R., Biofibre-Reinforced Polypropylene Composites, Polymer Engineering and Science, Vol. 37, No. 2, 476-483, 1997.
Lloyd, E.H. and Seber, D., Best Fibres Applications for Composites, BioComposite Solutions, WA, USA.

Kozlowski, R., Mieleniak, B., Helwig, M., and Przepiera, A., Flame Resistant Ligno-cellulosic-mineral composite particleboards, Polymer Degradation and Stability, Vol. 64, 523-528, 1999.

Marsh, G., Next Step for Automotive Materials, Materials Today, Elsevier Science Ltd., April 2003, pp 36-43.

Mishra, S., Mohanty, A.K., Drzal, L.T., Misra, M., Parija, S., Nayak, S.K. , and Tripathy, S.S., Studies on Mechanical Performance of Biofibre/Glass Reinforced Polyester Hybrid Composites, Composite Science and Technology 63: 1377-1385, 2003.

Narayan, R., in Emerging Technologies for Materials and Chemicals from Biomass, Rowell, R.M., Schultz, T.P., and Narayan, R. (Eds.), ACS Symposium Series, 476, 1992.

Olesen, P.O. and Plackett, D.V., Perspectives on the Performance of Natural Plant Fibres, Plant Fibre Laboratory, Royal Veterinary and Agricultural University, Copenhagen, Denmark, 2002.

Richardson, M. and Zhang, Z., Nonwoven Hemp Reinforced Composites, Reinforced Plastics, Vol. 45, April 2001.

Riedel, U. and Nickel, J., Natural Fibre-reinforced Biopolymers as Construction Materials – New Discoveries, 2nd International Wood and Natural Fibre Composites Symposium, June 28-29, 1999, Kassel, Germany.

Rowell, R.M., and Stout, H.P., Jute and Kenaf, Handbook of Fibre Chemistry, Second Edition, Eds: Lewin, M. and Pearce, E.M., Marcel Dekker, New York, 1998.

Rowell, R.M., Composite Materials from Agricultural Resources, IN: Olesen, O, Rexen, F., and Larsen, J. (eds.), Research in Industrial Application of Non-food Crops, I: plant fibres: Proceedings of a seminar; 1995 May; Copenhagen, Denmark, Lyngby, Denmark Academy of Technical Science: 27-41.

US Patent No: 6,767,634, Krishnaswamy, P., July 27, 2004.

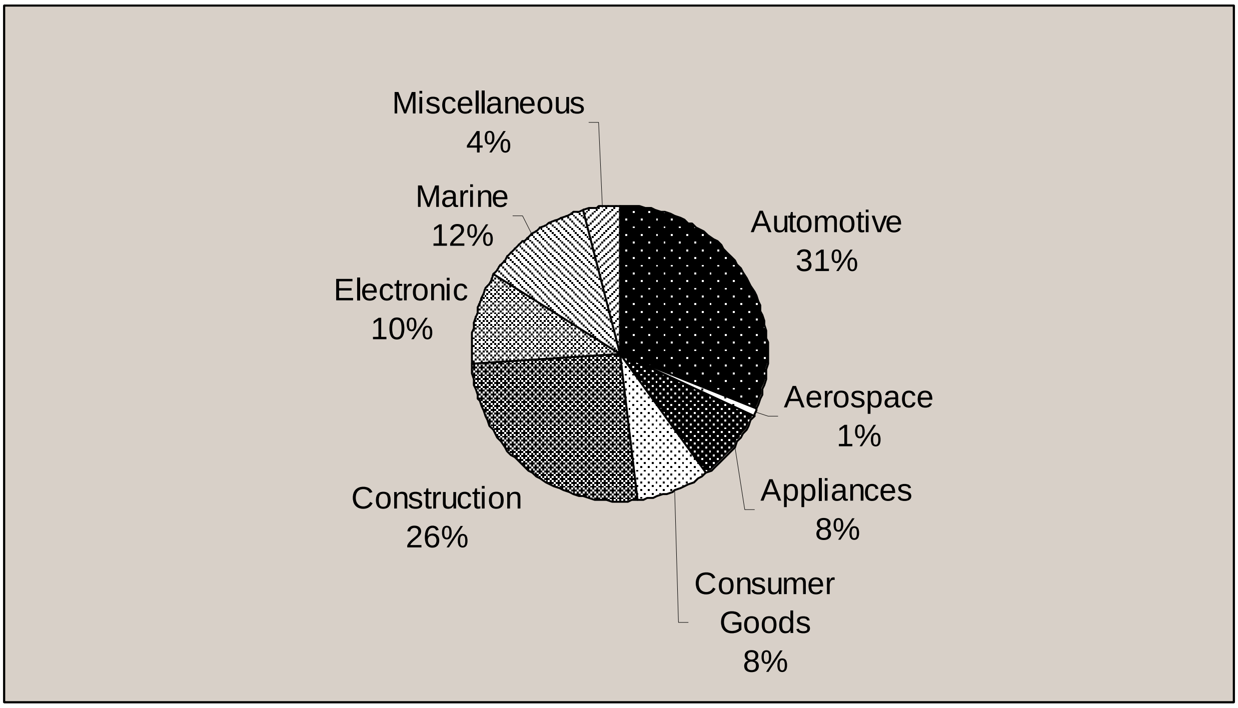

Figure 1: Distribution of fibre-reinforced composites by application (2002).

Source: Business Communication Company, Inc., 2002.

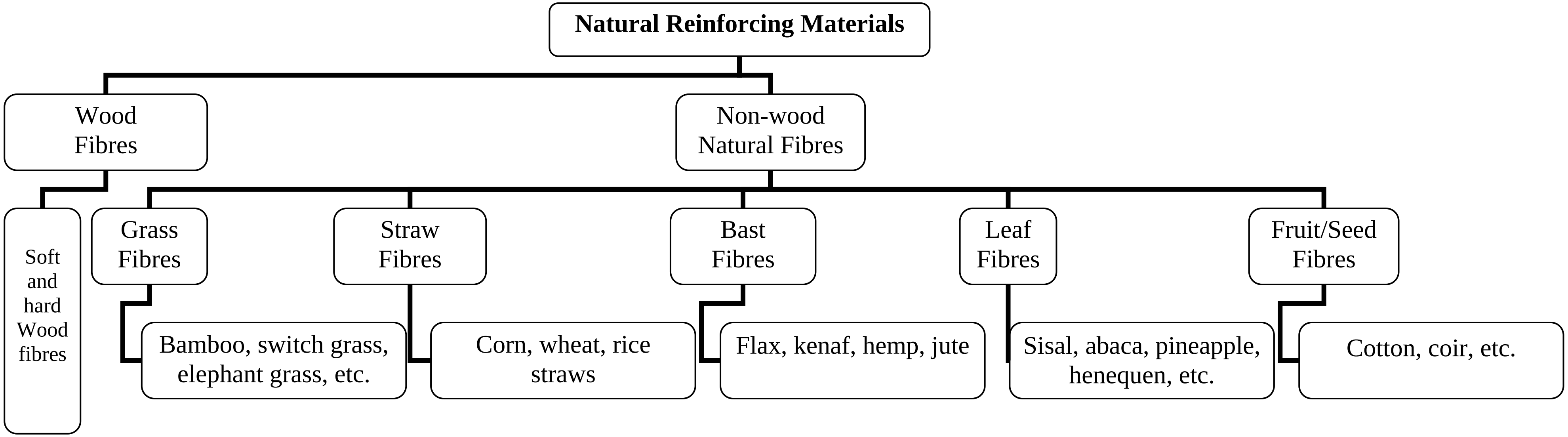

Figure 2: Natural Reinforcing Medium for Composites

Table 1: Physical, mechanical and chemical properties of bast fibres (Source 2-5, Rowell, 1995).

Properties	Flax	Hemp	Jute	Kenaf (bast)	E-Glass Fibre
Single Fibre Length (mm)	10 – 70 (range) 32 (average)	7 – 55 (range) 25 (average)	2-5 (range)	1.4 – 5 (range) 2.6 (average)	-
Bundle Fibre Length (mm)	250-1200	1000-4000	1500-3600	1500 – 4000	-
Mean diameter (µm)	19	25	20	21	
Density (g/cm^3)	1.4	1.48	1.46	1.2	2.55
Moisture Absorption (%)	7	8	12	12	-
Tensile Strength (N/m^2)	800-1500	550-900	400-800	275-450	2400
Young’s Modulus, E (GPa)	60-80	70	10-30	-	73
Specific E/density	26-46	47	7-21`	-	29
Elongation at break (%)	1.2-1.6	1.6	1.8	-	3
Cellulose (%)	78.5	68.1	58-63	60.8	-
Hemi-Cellulose (%)	9.2	15.1	21-24	20.3	-
Lignin (%)	8.5	10.6	12-14	11.0	-
Pectin (%)	2.3	3.6	#	3.2	-
Ash (%)	1.5	2.5	0.5	4.7	-

Note: Properties of natural fibres vary and depend upon the fibre preparation, test specimen, testing method, origin of fibres, agricultural parameters, etc. # no authoritative value available. The table is compiled from various sources.