PERSPECTIVES ON THE PERFORMANCE OF NATURAL PLANT FIBRES

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ABSTRACT

The main characteristics of the most important plant fibres are described in terms of their microscopic features, chemical composition, and physical properties.

Basic properties of plant fibres can be related to the properties of end products, which may in turn be divided into two main groups: 1) mats based on plant fibres for potential use as insulation materials, filters, geotextiles and growth media, and 2) composites for structural or non-structural purposes. The latter can include products manufactured by hot-pressing or alternatively by processes such as extrusion or injection moulding in which the fibres act as reinforcement (e.g., in plastics or cement).

The aim of this presentation is to review basic knowledge of plant fibre properties and to provide a general introduction to the topics that will follow in the rest of this conference.

INTRODUCTION

For thousands of years mankind has been strongly dependent on plant fibres for all kinds of purposes. Fibrous materials such as wood and bamboo have found particular application in construction. Other important uses have included tools, weapons and energy generation. A wide variety of fibres have also been used for production of textiles, pulp and paper and fibreboards.

With the appearance of synthetic materials (e.g., plastics) at the beginning of this century, synthetic-based materials have steadily replaced bio-based products. As a result of this change in raw material utilisation, combined with an enormous increase in energy and chemical demand, the world is now facing an ecological crisis. This crisis will greatly intensify with the expected growth in demand for industrial products in developing countries. It has been estimated that global industrial output will be five to ten times that of world production in 1987 when the world population stabilises some time in the next century (Our common future 1987). Thus, the world community is facing a challenge in having to decrease pollution levels while at the same time significantly increasing industrial output. Such predictions have led to a number of political initiatives, including support for enhanced industrial use of renewable resources (e.g., biomass) at the expense of non-renewable resources (plastic, glass fibres, etc.). Plant fibres may therefore face a renaissance, not only for industrial uses as in the past but also for the manufacture of new types of materials and products. Examples of the latter could include the manufacture of three-dimensional products by hot-pressing of fibre mats or by extrusion or injection moulding of plant fibres in combination with plastic.

An enhanced use of plant fibres for the manufacture of industrial commodities or niche products with minimal environmental impact requires knowledge of the basic properties of plant fibres. Those involved in the chain from growing the plants to the manufacture of fibre-based products must have a basic knowledge of the performance of plant fibres. The aim of this paper is to review some of this basic knowledge and to describe how the conference will provide the target audience of fibre suppliers, industrial users, designers, and researchers with an overview of the opportunities and challenges associated with plant fibre utilisation.

WHAT IS A PLANT FIBRE?

All plant species are built up of cells. When a cell is very long in relation to its width it is called a fibre. For example, wood fibres are mostly 50-100 times as long as they are wide (Table 1). The fibre is like a microscopic tube (i.e., a wall surrounding a central void referred to as the lumen). Moreover, when the cell wall is made up mainly (85% or more) of cellulose, hemicellulose and lignin, we talk about lignocellulosic fibres, and this includes woody species, scrubs and most agricultural crops. Typical lignocellulosic fibres from agriculture are found, for example, in straws, flax, hemp, jute and sisal. Non-lignocellulosic fibres are fibres that do not contain lignin and are found in potatoes, beets and cotton amongst other crops.

The variation in fibre dimension is great (Table 1). Furthermore, the various types of raw material are separated using processes to generate fibres suitable for specific end products, e.g., bast or stem fibres are mainly used in the textile or rope industries because both require fibres that are as long as possible. Bast straw, for example, is not separated into single fibres but into fibre bundles, which may contain thousands of single fibres; in contrast, wood is usually separated into single fibres or very small fibre bundles suiting the particular needs of the pulp, paper or board industries. Thus, in selecting fibres for new materials, there are a great number of opportunities for selecting fibres of different dimensions (Table 1).

Table 1: Dimensions of some selected agricultural and wood fibres (1)

Fibre type	Fibre length, mm Average (range)	Fibre width, mm Average (range)
Cereal straw (wheat, corn, rice)	1.4 (0.4-3.4)	0.015 (0.005-0.030)
Bast fibres		
• Flax (fibre bundles)	(250-1200)	(0.04-0.6)
• Flax (single fibres)	33 (9-70)	0.019 (0.005-0.038)
• Hemp (fibre bundles)	(1000-4000)	(0.5-5)
• Hemp (single fibres)	25 (5-55)	0.025 (0.01- 0.05)
• Jute (fibre strands)	(1500-3600)	-
• Jute (single fibres)	(2-5)	0.020 (0.010-0.025)
Seed hair, cotton (single fibres)	18 (10-40)	0.020 (0.012-0.038)
Other grass fibres		
• Sugarcane bagasse	1.7 (0.8-2.8)	0.034
• Bamboo	2.7 (1.5-4.4)	0.014 (0.007-0.027)
Deciduous wood	1.0 (0.3-2.5)	0.020 (0.010-0.045)
Coniferous wood	3.3 (1.0-9.0)	0.033 (0.015-0.060)

(1) These figures are qualified guesstimates based on earlier publications (Ilvessalo-Pfäffli, 1995; Rowell et al.,1997).

The chemical composition of some selected fibres is given in Table 2. The data, which are selected from various publications (Fengel and Wegener, 1984; Lignocelluloseudvalgets Rapport, 1990; Olesen, 1997; Robson et al., 1993; Rowell, 1995; Rowell et al., 1997), vary largely because of the different analytical methods used to calculate chemical composition.

Table 2: Chemical composition of some selected agricultural and wood fibres (1)

Fibre	Cellulose	Hemi-	Lignin	Silica	Pectin	Ash

		cellulose				
Cereal straw (Wheat)	40-45	20-31	15-20	3-7	8	2-5
Bast fibres						
• Flax, hemp	68-85	10-17	3-5	-	5-10	1-2
• Jute	70-75	12-15	10-15	-	1	-
Seed hair, cotton	89-99	3-6				
Deciduous wood	38-45	24-39	22-28	-	-	0.5
Coniferous wood	39-45	30-33	26-34	-	-	0.5

(1) These figures are qualified guesstimates from the published data.

THE CELL WALL STRUCTURE

The cell wall of a fibre is made up of a number of layers: the so-called primary wall (the first layer deposited during cell development) and the secondary wall (S), which again is made up of three layers (S_1, S_2 and S_3). In all lignocellulosic fibres these layers contain cellulose, hemicellulose and lignin in varying amounts. The individual fibres are bonded together by a lignin-rich region known as the middle lamella. Cellulose attains its highest concentration in the S_2 layer (about 50%) and lignin is most concentrated in the middle lamella (about 90%) which, in principle, is free of cellulose. The S_2 layer is usually by far the thickest layer and dominates the properties of the fibres.

Cellulose is the basic structural component of all plant fibres. It is the most important organic compound produced by plants and the most abundant in the biosphere. Duchesne and Larson (1989) have estimated that the global standing crop contains 920 billions tons of cellulose and that annual production is about 85 billion tons. The cellulose molecules consist of glucose units linked together in long chains, which in turn are linked together in bundles called microfibrils. The tensile strength of the cellulose microfibrils is enormous, being the strongest known material with a theoretically estimated tensile strength of 7.5 GPa or 1,087,500 pounds per square inch. (Stamm, 1964). In the S_2 layer the microfibrils run almost parallel to the fibre axis. With S_2 representing about 50% of the cell wall, this gives the fibres a very high tensile strength.

Hemicelluloses are also found in all plant fibres. Hemicelluloses are polysaccharides bonded together in relatively short, branching chains. They are intimately associated with the cellulose microfibrils, embedding the cellulose in a matrix. Hemicelluloses are very hydrophilic (i.e., containing many sites to which water can readily bond).

Lignin is a Latin word for wood. Lignin is the compound which gives rigidity to the plant. Without lignin, plants could not attain great heights (e.g., trees) or the rigidity found in some annual crops (e.g., straw). Lignin is a three-dimensional polymer with an amorphous structure and a high molecular weight. Of the three main constituents in fibres, it is expected that lignin would be the one with least affinity for water. Another important feature of lignin is that it is thermoplastic (i.e., at temperatures around 90^0C it starts to soften and at temperatures around 170^0C it starts to flow).

The combined effect of the three main constituents results in properties which are unique for plant fibres. The most important are:

- *Very good strength properties, especially tensile strength.* In relation to its weight the best bast fibres attain strength similar to that of Kevlar.

- *Very good heat, sound and electrical insulating properties.*

- *Combustibility.* From a waste point of view, combustibility is an advantage. Products can be disposed of through burning at the end of their useful service lives and energy can simultaneously be generated.

- *Biodegradability*. As a result of their tendency to absorb water, fibres will biodegrade under certain circumstances through the actions of fungi and/or bacteria.

- *Dimensional stability.* As a consequence of the hygroscopicity of the fibres, products and materials based on plant fibres are not dimensionally stable under changing moisture conditions. This is the greatest disadvantage in relation to industrial use of plant fibres. However, if necessary, this may be controlled at an extra cost by a number of known treatments (e.g., heat treatments or chemical modification procedures such as acetylation).

- *Reactivity.* The hydroxyl groups present in the cell wall constituents not only provide sites for water absorption but are also available for chemical modification (e.g., to introduce dimensional stability, durability, or improved oil/heavy metal absorption properties).

THE RAW MATERIAL

Today the annual global production of lignocellulosic fibres from man-made crops is about 4 billion tons, of which roughly 60% comes from agricultural crops and 40% from forests. In comparison, annual world production of steel is currently around 0.7 billion tons and plastic production is about 0.1 billion tons (Rowell et al., 1997). Denmark's annual production of lignocellulosic fibres from agriculture is about 7 million tons and from forestry about 1 million tons, based on dry matter (Lignocelluloseudvalgets Rapport, 1990). An insignificant fraction of the agricultural fibres available in Denmark is used industrially at present, in contrast to the high levels of wood fibre utilisation by the forest products industries.

Taking the above figures into consideration, it is apparent that there should be more than sufficient volumes of agricultural fibre available globally for new industrial products. Given the environmental benefits from use of renewable plant fibre resources (including lower energy demand to make products when compared with metals, petrochemical-based plastics, or cement-based materials; the role of natural fibres as carbon sinks; recyclability) and the properties described in the previous section, there should be an increasing role for plant fibre-based products in the future. The extent to which this potential can be realised will depend upon numerous factors, not least of which will be consumer demand, the availability of suitable processing and product handling equipment, and the further development of existing and new technologies.

THE POSSIBILITIES

Industrial use of lignocellulosic fibres, especially wood, for the manufacture of pulp, paper, fibreboards and particleboards is well established. A relatively new industrial breakthrough for the use of plant fibres is the production of inner panels for motor vehicles. In this case a plant fibre-based composite has been able to compete with a glass-fibre-reinforced component as a result of the low price of plant fibres and their beneficial properties (low weight and good thermal and sound insulation). The manufacturing techniques employing fibre mats and moulds for three-dimensional products such as car panels can also, in principle, be extended to other product areas within the building, furniture, transportation and packaging industries.

The renewed interest in industrial use of plant fibres has led to worldwide research into the production of a number of products based on plant fibres. These products may be divided into two main groups: (1) mats and (2) composites.

Mats

Loose fibres are bulky and difficult to handle. Therefore, techniques such as needle punching and air laying have been developed to aggregate fibres into mats. The mats may be made entirely of plant fibres or a mixture of plant fibres, plastic fibres and resins in varying amounts depending on the required properties of the end product. The mats may be the end product in itself or an intermediate product for the manufacture of composites, as discussed in the next section. Mats as an end product have potential for utilisation in a number of ways as described below.

Filters: Their surface chemistry and large surface area should make fibres ideal as filters. Unmodified plant fibres absorb heavy metal ions and chemical modification techniques can potentially be used to enhance both heavy metal and oil absorption properties. Applications could include clean-up of polluted drinking water, industrial run-off water, and various other waste waters. Opportunities also exist for use of plant fibre filters in capturing volatile emissions from industrial processes.

Growth media: Nurseries use different types of growth media for production of vegetables, flowers and grass mats. For all these purposes mats based on plant fibres appear ideal. At present, mineral wool mats are used over large areas in greenhouses, but not without problems. The water absorption is uneven (too dry on the top and too wet at the bottom), they have to be disinfected after a certain period and, at the end of their service life, they create waste problems since these mats neither burn nor biodegrade.

Insulation: Plant fibre mats may have a promising future as insulation materials within the building industry. One of the major challenges with this application is the provision of fire retardancy. However, this is technically feasible and the first insulation materials based on plant fibre mats are already on the market in France and Germany. The market potential for partial replacement of glass and mineral wool mats for insulation purposes is huge.

Geotextiles: Plant fibre geotextiles are already available as industrial commodities for the control of soil erosion and weeds.

Composites

Composites for structural and non-structural purposes can be manufactured by hot-pressing of mats. The use of mats allows the manufacture of three-dimensional products as referred to in the above example of interior panels for the automotive industry. New technologies for such products allow for high plant fibre contents and relatively short manufacturing cycle times.

Fibre/polymer composites: In addition to hot-pressing of mats in moulds to generate three-dimensional products, fibre-reinforced composites can be manufactured through extrusion or injection moulding of fibre/polymer combinations. Research has shown that use of plant fibres in such processes has advantages in terms of cost, weight, and environmental factors when compared to similar combinations based on glass fibre reinforcement. The wide variety of fibre types, fibre preparation techniques and possibilities for fibre surface modification open up opportunities to tailor such composites to specific end-product requirements.

Fibre/cement composites: Plant fibres have also found application in production of cement-based composites. For example, wood fibre-reinforced cement products are widely available and combine the high tensile strength, impact resistance, and workability of wood with the fire resistance, durability, and dimensional stability of cement-based materials. The result is a range of products offering a unique balance of performance characteristics and aesthetic qualities at competitive cost. Worldwide, research is continuing on the incorporation of alternative fibres and the use of new processes to manufacture such cement-based composites.

Composite product design: With composites, the properties of the final product are determined by a number of plant fibre characteristics. These include surface chemistry (e.g., waxes and inorganics such as silica) and fibre aspect ratio in particular. In addition, other factors such as thickness, fibre percentage, and amount and type of bonding agent (if any) will be important. The existing wood composites industry (e.g., MDF manufacturing) already produces a very wide variety of product lines as a function of product density, thickness, and other characteristics. New composites can similarly be designed to have the required stiffness and strength and other properties depending upon application. The importance of the role of final product design and the involvement of designers with a good understanding of plant fibre-based materials in new product development can not be overstated.

CONFERENCE OVERVIEW

This conference is designed around four topics over the next two days. These topics can essentially be summarised as:

Uses and limitations of plant fibres

The focus here will be on high-performance applications in the automotive and aerospace industries and how plant fibre supply considerations may impact such developments.

New design opportunities

This session will outline current thinking from a number of specialists in the field on the significance of design in new plant fibre product development.

The performance potential of plant fibres

The focus here will be on how future product opportunities may be realised through an understanding of plant fibre properties in relation to processing as well as new advances in process development.

The future

This session will deal with the issues raised earlier in the conference and the next steps required for further development of industries based on plant fibres.

CONCLUSIONS

There is great potential for plant fibres in the production of mats to be used for insulation materials, filters, growth media in nurseries or geotextiles. In addition, mats can serve as intermediates which can subsequently be hot-pressed for the manufacture of products for the building, furniture, transportation, and packaging industries. Plant fibres have already found application in the reinforcement of cement- and plastic-based materials and there is also considerable potential for growth in this field.

Of course, the extent to which plant fibres will be used in industrial and niche products in the future remains to be seen. We do know that many problems will have to be solved and that processing techniques will have to be optimised. However, taking on these challenges will be more than justified if increased plant fibre utilisation can contribute significantly to more environmentally acceptable processes and products. A shared understanding of market demands, process economics and plant fibre technology will be essential if plant fibre utilisation is to reach its full potential.

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