Characterization and Factors Effecting Fiber Properties

Roger M. Rowell[1,2], James S. Han[1] and Jeffrey S. Rowell[2]

[1] *Forest Products Laboratory, USDA,*

One Gifford Pinchot Drive, Madison, WI 53705

[2] *Department of Forest Ecology and Management, 1630*

Linden Drive, University of Wisconsin, Madison, WI 53706

Abstract

A single agro-based fiber is a three dimensional, biopolymer composite composed mainly of cellulose, hemicelluloses, and lignin with minor amounts of free sugars, starch, protein, extractives, and inorganics. The performance of a given fiber used in a given application depends on several factors including chemical composition, physical properties, the interaction of a fiber within the composite matrix, and how that fiber or fiber/matrix performs under a given set of environmental conditions. In order to expand the use of agro-fibers for composites, it is essential that information is available on fiber characteristics and the factors which effect performance of that fiber. In order to do this, it is necessary to develop a detailed data base of chemical and physical properties of the vast variety of natural fibers that are potentially available in the world. It is also necessary to understand the factors which effect the performance of a given fiber in a given application. This chapter will deal with the chemical and physical properties of agro-fibers and factors which effect fiber properties.

Introduction

Agro-based resources have played a major role throughout human history. Even the earliest humans learned to use these resources to make shelters, cook food, construct tools, make clothing, keep records, and produce weapons. Collectively, society learned very early the great advantages of a resource that was widely distributed, multi-functional, strong, easy to work, aesthetic, biodegradable, and renewable.

Agro-based resources are renewable, widely distributed, available locally, moldable, anisotropic, hydroscopic, recyclable, versatile, non-abrasive, porous, viscoelastic, easily available in many forms, biodegradable, combustible, compostible, and reactive. Agro-based fiber have a high aspect ratio, high strength to weight ratio, relatively low in energy conversion, and have good insulation properties (sound, electrical and thermal). The fiber structure is hollow, laminated, with molecular layers and an integrated matrix. Some might consider part of these properties as limitations, such as biodegradable and combustible, but these features provide a means of predictable and programmable disposal not easily achieved with other resources. Other properties listed above are factors which effect both fiber properties and performance[13].

As we approach the 21st century, there is a greater awareness of the need for materials in an expanding world population and increasing affluence. At the same time, we have an awareness that our landfills are filling up. our resources are being used up, our planet is being polluted, that non-renewable resources will not last forever, and that we need more environmentally friendly materials.

The traditional source of agro-based fibers has been wood and for many countries, this will continue to be the major source. Wood has a higher density than annual plants so there will be more bulk when using agricultural crop fiber. There are also concerns about the seasonality of annual crops which requires consideration of harvesting, separating, drying, storing, cleaning, handling, and shipping. In the present system of using wood, storage costs can be reduced by letting the tree stand alive until needed. With any annual crop, harvesting must be done at a certain time and storage/drying/cleaning/separating will be required. This will almost certainly increase costs of using agro-based resources over wood depending on land and labor costs, however, in those countries where there is little or no wood resource left or where restrictions are in place to limit the use of wood, alternate sources of fiber are needed if there is to be a natural fiber industry in those countries.

In some cases, agro-based fibers are being used for no other reason than their cost compared to other resources. In these cases, it may not be important to know and understand chemical and physical properties or what factors effect fiber properties. But, in the cases where a specific fiber is being used for its fiber properties, it becomes important to have a data base on that fiber.

Information on chemical and physical properties are scattered in the scientific literature. In many cases, different analytical procedures have been used to collect the data so it is difficult to compare one set of data with any other set. The data presented in this chapter has been collected from different literature sources and, in some cases, from actual experimental data collected at the Forest Products Laboratory. Because of this. the data is presented more to give a qualitative comparison between different agro-fibers rather than an accurate quantitative comparison.

Chemical Properties

The major chemical component of a living tree is water, but on a dry weight basis, all plant cell walls consist mainly of sugar based polymers (carbohydrates) that are combined with lignin with lesser amounts of extractives, protein, starch, and inorganics. The chemical components are distributed through out the cell wall which is composed of primary and secondary wall layers. Chemical composition varies from plant to plant, and within different parts of the same plant. Chemical composition also varies within plants from different geographic locations, ages, climate and soil conditions.

There are hundreds of reports on the chemical composition of plant material. In reviewing this vast amount of data, it becomes apparent that the analytical procedures used, in many cases, are different from lab to lab and a complete description of what procedure was used in the analysis is not clear. For example. many descriptions do not describe if the samples were pre-extracted with some solvents before analysis. Others do not follow a published procedure so comparison of data is not possible.

Carbohydrates

Holocellulose

The carbohydrate portion of the vast majority of plants are composed of cellulose and hemicellulose polymers with minor amounts of other sugar polymers such as starch and pectins. Table 1 shows the chemical analysis of the major components of plant fibers. The combination of cellulose and the hemicelluloses are called holocellulose and usually accounts for 65-70 percent of the plant dry weight. These polymers are made up of simple sugars, mainly, **D**-glucose, **D**-mannose, **D**-galactose, **D**-xylose, **L**-arabinose, **D**-glucuronic acid, and lesser amounts of other sugars such as **L**-rhamnose and **D**-fucose. Table 2 shows the sugar content of different plant holocelluloses. These polymers are rich in hydroxyl groups which are responsible for moisture sorption through hydrogen bonding.

Cellulose

Cellulose is the most abundant natural polymer in the world. It is estimated that 830 million tons of cellulose are produced each year through photosynthesis”. If the average plant (on a dry weight basis) contains 40% cellulose, the annual agro-based resource would be approximately 2000 million dry tons. This compares to 225 x 10^9 tons which is the estimated world reserve of petroleum and natural gas.

Table 1. Chemical composition of some common fibers.

Type of Fiber	Cellulose	Lignin	Pentosan	Ash	Silica
Stalk fiber					
Straw					
Rice	28-48	12-16	23-28	15-20	9-14
Wheat	29-51	16-21	26-32	4.5-9	3-7
Barley	31-45	14-15	24-29	5-7	3-6
Oat	31-48	16-19	27-38	6-8	4-6.5
Rye	33-50	16-19	27-30	2-5	0.5-4
Cane fiber					
Bagasse	32-48	19-24	27-32	1.5-5	0.7-3.5
Bamboo	26-43	21-31	15-26	1.7-5	0.7
Grass fiber					
Esparto	33-38	17-19	27-32	6-8	--
Sabai	--	22	24	6	--
Reed fiber					
Phragmites Communis	44-46	22-24	20	3	2
Bast fiber					
Seed flax	43-47	21-23	24-26	5	--
Kenaf	44-57	15-19	22-23	2-5	--
Jute	45-63	21-26	18-21	0.5-2	--
Hemp	57-77	9-13	14-17	0.8	--
Ramie	87-91	--	5-8	--	--
Core fiber					
Kenaf	37-49	15-21	18-24	2-4	--
Jute	41-48	21-24	18-22	0.8	--
Leaf fiber					
Abaca (Manila)	56-63	7-9	15-17	1-3	--
Sisal					
(agave)	43-62	7-9	21-24	0.6-1	--
Seed hull fiber					
Cotton	85-96	0.7- 1.6	1-3	0.8-2	--
Wood fiber					
Coniferous	40-45	26-34	7-14	< 1	--
Deciduous	38-49	23-30	19-26	< 1	--

Table 2. Sugar analysis of some agro-fibers by Order of Decreasing Lignin Content.

	Chemical composition (% total)[a]							
Fiber type	Lignin	Ash	Glu	Ara	Gal	Rha	Xyl	Man
Peat moss	45.90	1.10	19.16	0.25	2.54	1.19	2.77	2.35
Coconut shell	35.72	--	25.91	0.29	0.32	0.21	23.93	0
Coconut fiber	33.50	--	34.87	0.05	0.36	0.16	16.98	0.12
Sheet moss	30.20	11.50	18.46	1.37	5.44	1.24	1.34	7.27
Flax shive Acacia	27.80	--	34.89	0.28	0.73	0.32	18.50	1.9
	26.00	--	41.99	1.37	0.49	0.28	15.46	1.72
Jute core	24.77	0	39.09	0.11	0.41	0.38	17.35	0.91
Flax	22.90	--	31.21	1.17	1.77	0.62	12.29	1.13
Sunn hemp	core	22.74	0	41.46	0.26	0.73	0.27	17.08
Rice hull	21.40	16.30	33.89	1.52	0.85	0.05	13.95	0.16
Bagasse	19.87	0.25	43.10	1.93	0.55	0	24.19	0.18
Velvet leaf core	19.61	0	40.61	0.29	0.73	0.49	18.33	0.75
Spanish moss	19.50	1.90	29.54	4.61	4.86	0.23	15.04	0.72
Kudzu bark	19.30	--	36.55	2.93	2.04	0.54	4.95	1.09
Purple top	18.86	2.77	31.96	2.85	1.13	0.72	20.25	0.18
Little bluestem	18.79	2.41	35.05	3.03	1.18	0.12	18.19	0
Kenaf core	18.30	--	33.45	0.49	0.83	0.29	14.24	1.01
Big bluestem	18.17	2.48	34.19	2.88	1.20	0.27	19.57	0.20
Sphagnum moss	16.60	1.90	29.54	4.61	4.86	0.23	15.04	0.72
Tobacco	16.46	0.53	33.16	0.63	0.80	0.42	12.40	0.92
Kudzu	15.70	--	39.40	1.81	1.67	0.57	11.36	0.69
Lechugilla	15.21	0	41.84	0.45	1.03	0.14	17.33	0
Loofa	13.60	--	56.38	0.24	0.36	0.15	14.89	0.17
Jute fiber	13.73	0.14	56.87	0.11	0.49	0.16	12.17	0.50
Hibiscus	12.60	--	55.98	0.58	0.70	0.29	9.01	0.29
Abaca	12.66	0.19	52.69	1.83	1.03	0.16	12.81	0.89
Banana pinzota	11.10	1.20	43.24	3.85	1.47	0.34	10.66	1.82
Sunn hemp	bast	11.14	0.23	56.38	1.08	2.05	0.29	1.97
Kenaf	9.88	--	43.32	2.04	0.46	1.25	10.80	1.25
Tobacco bark	9.69	0	27.42	1.46	1.33	0.62	8.42	0.90
Velvet leaf	9.03	0.12	34.37	1.89	1.67	0.77	8.95	0.98
Agave	6.80	0.23	55.79	0.42	1.24	0.46	12.83	0.82
Pineapple	4.60	0.10	64.35	0.90	0.71	0.06	12.04	0.20
Hemp	Chinese	3.00	0.40	83.81	1.34	2.11	0.79	1.92

[a] L-arabinose (Ara), **L**-rhamnose (Rha), **L**-galactose (Gal), **D**-mannose (Man), D-glucose (Glu), **D**-xylose (Xyl).

While the agro-based resource is renewable, the petroleum and gas resources are not.

Cellulose is a glucan polymer of **D**-glucopyranose units, which are linked together by β-(1-4)-glucosidic bonds. Actually the building block for cellulose is cellobiose since the repeating unit in cellulose is a two sugar unit. The number of glucose units in a cellulose molecule is referred to as the degree of polymerization (DP) and the average DP for plant cellulose ranges from a low of about 50 for a sulfite pulp to approximately 600 depending on the method used to determine it [Stamm 1964]. This would mean an approximate molecular weight for cellulose ranging from about 10,000 to 150,000. Cellulose molecules are randomly oriented and have a tendency to form intra- and intermolecular hydrogen bonds. As the packing density of cellulose increases, crystalline regions are formed. Most plant derived cellulose is highly crystalline and may contain as much as 80 percent crystalline regions. The remaining portion has a lower packing density and is referred to as amorphous cellulose. Table 1 shows the range of average cellulose contents for a wide variety of plant types'. On a dry weight basis, most plants consist of approximately 4.5 to 50% cellulose. This can vary from a high (cotton) of almost 90% to a low of about 30% for stalk fibers.

Hemicelluloses

In general, the hemicellulose fraction of plants consists of a collection of polysaccharide polymers with a lower DP than cellulose and containing mainly the sugars **D**-xylopyranose, **D**-glucopyranose, **D**-galactopyranose, **L**-arabinofuranose, **D**-mannopyranose, and **D**-glucopyranosyluronic acid with minor amounts of other sugars (Table 2). They usually contain a backbone consisting of one repeating sugar unit linked β-(1-4) with branch points (1-2), (1-3), and/or (1-6).

Hemicelluloses usually consist of more than one type of sugar unit and are sometimes referred to by the sugars they contain (Table 3). For example, galactoglucomanan, arabinoglucuronoxylan, arabinogalactan, glucuronoxylan, glucomannan, etc. The hemicelluloses also contain acetyl and methyl substituted groups.

The hemicelluloses from bamboo consist of a backbone polymer of **D**-xylopyranose linked β-(1-4) with an average of every eight xylose unit containing a side chain of **D**-glucuronic acid attached glycosidically to the 2-position of the xylose sugar [Bhargava 1987]. The hemicelluloses from kenaf also contains a backbone polymer of **D**-xylopyranose with side chains of **D**-galactose and **L**-arabinose[4].

One of the main hemicelluloses from softwoods contain a backbone polymer of **D**-galactose, **D**-glucose, and **D**-mannose[16]. The galactoglucomannan is the principal hemicellulose (ca 20%) with a linear or possibly slightly branched chain with β (1-4) linkages. Glucose and mannose make up the backbone polymer with branches

Table 3. Length and width of selected agro-fibers.

Common name	Fiber length (mm)		Fiber width (mm)	
	Avg	Range	Avg	Range
Ramie	120	60–250	50	11–80
Flax	33	9–70	19	5–38
Hemp	25	5–55	25	10–51
Kapok	19	8–30	19	10–30
Cotton lint	18	10–40	20	12–38
Paper-mulberry	10	6–20	30	2.5–35
Sunn hemp	8	4–12	30	25–50
Abaca	6	2–12	24	16–32
Kenaf	5	2–6	21	14–33
Sisal	3	1–8	20	8–41
Bamboo	2.7	1.5–4.4	14	7–27
Raphia	2.4	—	30	17–46
Sabai	2.1	0.5–4.9	9	4–28
Common reed	2.0	1.0–3.0	16	10–20
Jute	2	2–5	20	10–25
Papyrus	1.8	1.0–4.0	12	8–25
Sugar cane	1.7	0.8–2.8	20	10–34
Corn	1.5	0.5–2.9	18	14–24
Rice	1.4	0.4–3.4	8	4–16
Wheat	1.4	0.4–3.2	15	8–34
Esparto	1.2	0.2–3.3	13	6–22
Albardine	1.1	0.2–3.1	12	6–21

containing galactose. There are two fractions of these polymers differing by their galactose content. The low galactose fraction has a ratio of galactose:glucose:mannose of about 0.1: 1:4 while the high galactose fraction has a ratio of 1: 1:3. The **D**-galactopyranose units are linked as a single-unit side chain by a (1-6) bonds. The 2- and 3-positions of the backbone polymer have acetyl groups substituted on them an average of 3 to 4 hexose units. another major hemicellulose polymer in softwoods (5-10%) is an arabinoglucuronoxylan consisting of a backbone of β (1-4) xylopyranose units with a (1-2) branches of **D**-glucopyranosyluronic acid on the average of every 2 to 10 xylose units and α (1-3) branches of **L**-arabinofuranose on the average of every 1.3 xylose units.

The major hemicellulose from hardwoods contains a backbone of D-xylose units are linked β (1-4) with acetyl groups at C-2 or C-3 of the xylose units on an average of 7 acetyls per 10 xylose units[17]. The xylan is substituted with side chains of 4-0-methylglucuronic acid units linked to the xylan backbone α (1-2) with an average frequency of approximately 1 uranic acid group per 10 xylose units. This class of hemicelluloses are usually referred to as glucuronoxylans. Hardwoods also contain 2 to 5% of a glucomannan composed of β-**D**-glucopyranose and β-**D**-mannopyranose units linked (1-4). The glucose:mannose ratio varies between 1:2 and 1:1 depending *on* the wood species.

The major hemicellulose from kenaf is similar to a hardwood xylan[5]. It has a backbone of β (1-4) **D**-xylopyranose with side chains of 4-0-methyl glucuronic acid linked α (1-2) with an average frequency of 1 uronic acid group per 13 xylose units. There are terminal rhamnose and arabinose units linked (1-3) but the nature of the glycosidic linkage is unknown. The major hemicellulose from bamboo is composed of a backbone of β (1-4) **D**-xylopyranose residues with an average of every eighth xylose unit containing a side chain of **D**-glucuronic acid attached glycosidically to the 2-position of the xylose unit[3].

The detailed structures of most plant hemicelluloses have not been determined. Only the ratio of sugars these polysaccharides contain have been studied. Table 3 shows the sugar analysis of the two major hemicelluloses from several types of plant stalks[10].

Pentosans

Part of the hemicellulose fraction consists of pentose sugars mainly D-xylose and L-arabinose. The polymers containing these five carbon sugars are referred to as pentosans. Identification of this fraction in a plant material has been important to indicate its potential utilization for furan type chemicals. It is therefore common to see tables of chemical composition data including pentosan content.

Lignin

Lignins are amorphous, highly complex, mainly aromatic, polymers of phenylpropane units. Lignins can be classified in several ways but they are usually divided according to their structural elements[16]. All plant lignins consist mainly of three basic building blocks of guaiacyl, syringyl and *p*-hydroxyphenyl moieties, although other aromatic type units also exist in many different types of plants Figure 1. There is a wide variation of structures within different plant species. The phenylpropane can be substituted at the α, β, and γ positions into various combinations linked together both by ether and carbon to carbon linkages.

Lignins from softwoods are mainly a polymerization product of coniferyl alcohol and are called “guaiacyl lignin”. Hardwood lignins are mainly “syringyl-guaiacyl lignin” as they are a copolymer of coniferyl and sinapyl alcohols. The ratio of these two varies in different lignins from a ration of 4:1 to 1:2.

Lignins found in plants contain significant amounts of constituents other than guaiacyl- and syringylpropane units [Sarkanen and Ludwig 1971]. Lignin from corn contains vanillin and syringaldehyde units along with substantial amounts of *p*-hydroxybenzaldehyde. Bamboo lignin is a mixed dehydration polymer of coniferyl, sinapyl, and *p*-coumaryl alcohols[3]. A recent study showed that the lignin from kenaf contains a very high level of syringyl functionality[12].

Lignin is distributed throughout the secondary cell wall with the highest concentration in the middle lamella. Because of the difference in the volume of middle lamella to secondary cell wall, about 70% of the lignin is located in the secondary wall.

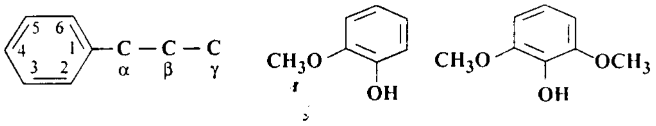
The function of lignin in plants is as an encrusting agent in the cellulose/hemicellulose matrix. It is often referred to as the plant cell wall adhesive. Both lignin and extractives in plants reduce the digestibility of grasses to animals [Jung et al. 1993]. Lignins are also associated with the hemicelluloses forming, in some cases, lignin-carbohydrate complexes that are resistant to hydrolysis even under pulping conditions.

Inorganics

The inorganic content of a plant is usually referred to its ash content which is an approximate measure of the mineral salts and other inorganic matter in the fiber after combustion at a temperature of 575 ± 25 °C. The inorganic content can be quite high in plants containing large amounts of silica.

Protein

Proteins are polymers of amino acids that are normally in high concentration in young growing cells but can also be found in some plants in high concentration



Phenylpropane unit **Guaiacyl** **Syringyl**

Figure 1. Building blocks of lignin.

throughout their life cycle. Proteins include enzymes and toxins as well as those involved in wound responses and pathogen resistance'. Pathogen resistance proteins are related to the structural proteins that are thought to provide the framework, in addition to the microfibrillar phase, onto and around which the various non-cellulosic polysaccharides are arranged.

Three classes of structural proteins have been identified and classified on the basis of their repeating amino acid sequences[8]. These three are: hydroxyproline-rich glycoproteins, the glycine-rich proteins, and the proline-rich proteins. The hydroxyproline-rich glycoproteins are usually associated with **L**-arabinose and **D**-galactose. The glycine-rich and the proline-rich proteins lack N-glycosylation sites in their primary sequence.

In wood, the protein content of the cell is usually less than 1 percent but can be much higher in grasses. The protein content is often reported as part of the lignin content if the laboratory personnel are not aware of its presence in the plant tissue when doing a lignin determination since both protein and lignin are isolated in the sulfuric acid procedure.

Extractives

The extractives are a group of cell wall chemicals mainly consisting of fats, fatty acids, fatty alcohols, phenols, terpenes, steroids, resin acids, rosin, waxes and etc. These chemical exist as monomers, dimers, and polymers. They derive their name by being chemicals that are removed by one of several extraction procedures.

Physical Properties

There are several physical properties that are important to know about each agro-fiber before that fiber can be used to reach its highest potential. Fiber dimensions, defects, strength, variability, crystallinity, and structure are some of the important considerations.

Fiber Dimensions

Knowledge about fiber length and width is important for comparing different kinds of agro-fibers. A high aspect ratio (length/width) is very important in agro-based fiber composites as it give an indication of possible strength properties. The length and width of some common agro-fibers are shown in Table 3[9]. In many cases, there is a wide variation in both length and width.

Fiber Strength

The fiber strength can be an important factor in selecting a specific agro-fiber for a specific application. Table 4 gives data on tensile strength of several agro-based fibers. It can be seen that tensile strength varies widely depending on the type of fiber tested.

Fiber Structure

Changes in physical properties can be due to differences in fiber morphology. Scanning electron micrographs of the longitudinal axis and cross section of many different land and water plant fibers are shown in Figures 1 to 10. Different levels of magnification were used to show the major features of the fibers physical structure. The intent here is to show the structure of several different types of plant fibers and not go into details of the cell wall architecture. There are many references in the literature where that type of information can be found.

These figures show just a few of the vast array of fiber structures that exist in the plant kingdom. Major differences in structure (density. cell wall thickness. tracheid length and diameter, for example) do result in differences in physical properties. It is interesting to note that the morphology of the land plants shown are very different from the two examples of water plant fibers (water hyacinth and

Table 4. Tensile strength of some ago-based fibers.

Fiber	Tensile Strength^{+} (GPa)
Kenaf	11.9
Hemp	9.0
Wood	7.5
Sisal	6.1
Cotton	3.5

$^{+}$ all single fiber strength except sisal which is for fiber bundles.

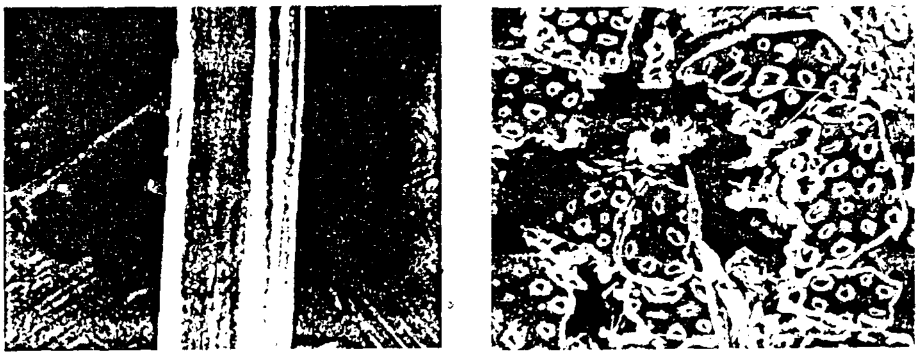


Figure 1. Scanning electron micrograph of jute fiber (longitudinal axis X50, cross section X500).

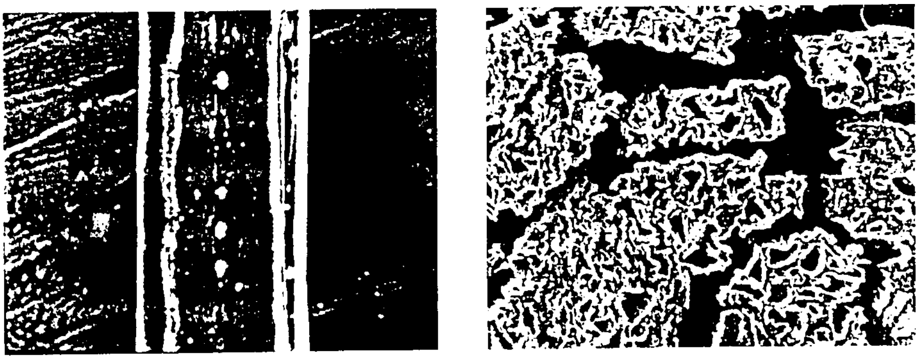


Figure 2. Scanning electron micrograph of mesta fiber (longitudinal axis X50, cross section X100).

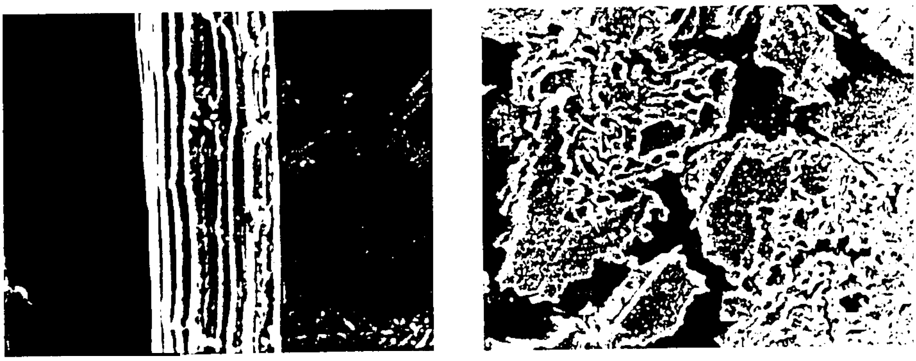


Figure 3. Scanning electron micrograph of pineapple leat fiber (longitudinal axis X50, cross section X100).

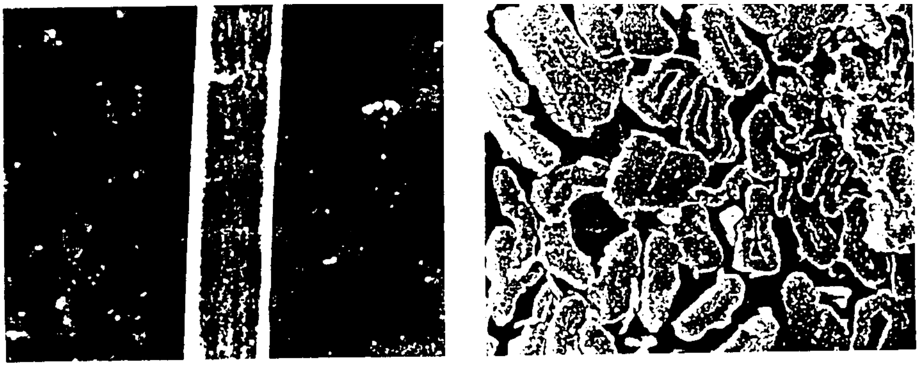


Figure 4. Scanning electron micrograph of ramie fiber (longitudinal axis X50, cross section X100).

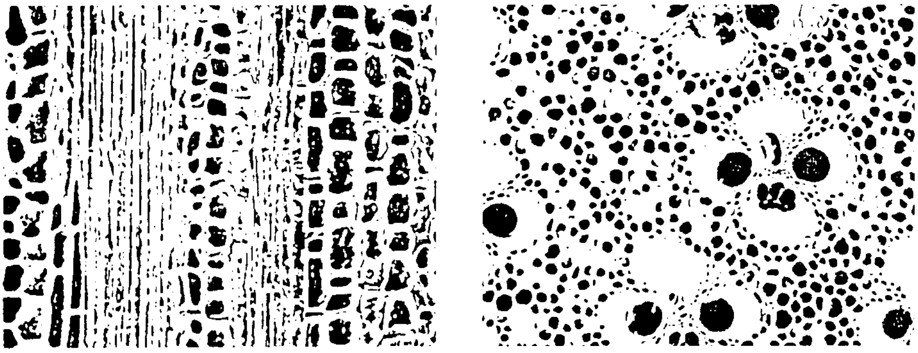


Figure 5. Scanning electron micrograph of bamboo fiber (longitudinal axis X50, cross section x 100).

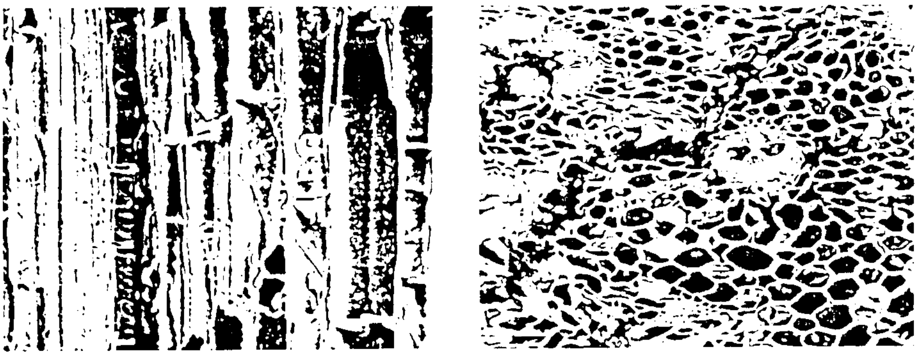


Figure 6. Scanning electron micrograph of sugar cane bagasse fiber (longitudinal axis X100, cross section X100).

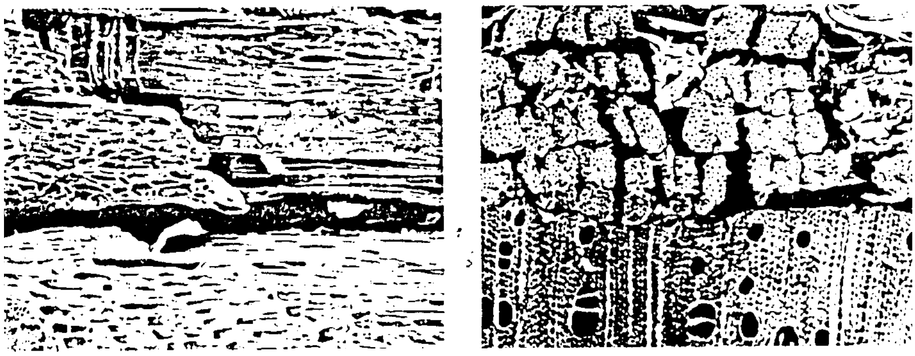


Figure 7. Scanning electron micrograph of kenaf fiber (longitudinal axis X100, cross section X100).

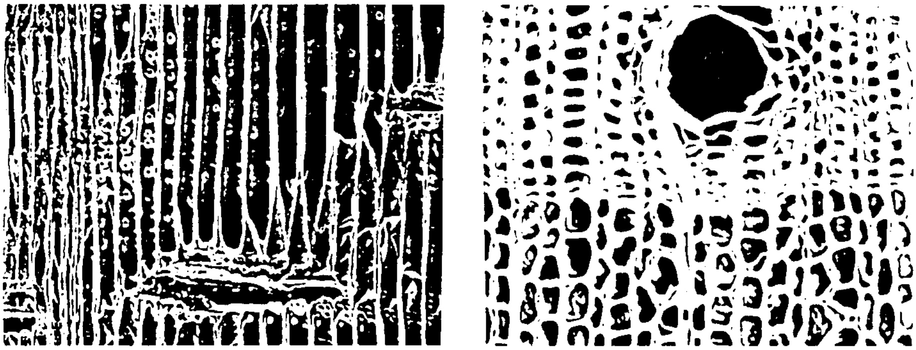


Figure 8. Scanning electron micrograph of southern pine fiber (longitudinal axis X100, cross section X150).

Figure 9. Scanning electron micrograph of pennywort fiber (longitudinal axis X100, cross section X40).

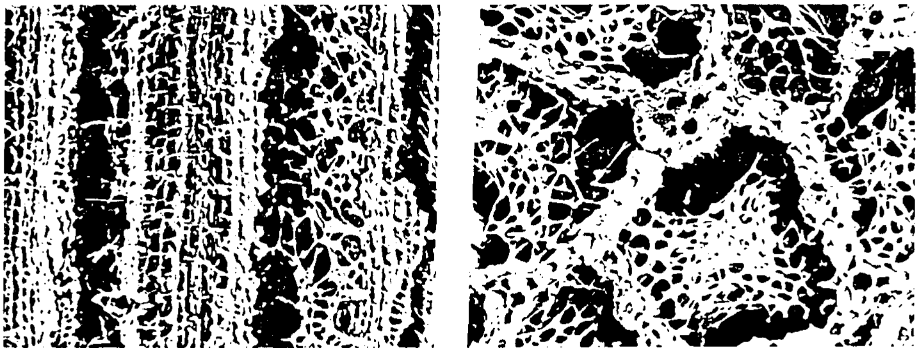


Figure 10. Scanning electron micrograph of water hyacinth fiber (longitudinal axis X50, cross section X200).

pennywort). The fine structure of the water plants may account, in part, for their very high equilibrium moisture content (see Table 7).

Figure 9 shows scanning electron micrographs of crystals found in the longitudinal wall of pennywort. Elemental comparison using SEM-EDXA of these crystals show them to be silica.

Factors Effecting Fiber Properties

There are many factors that effect agro-fiber properties. For example, what part of the plant the fiber came from, the age of the plant when the fiber was harvested, how the fiber was isolated, and permeability and hydroscopicity of the plant cell wall.

It is well known that different parts of a plant have different chemical and physical properties. That is, the chemical composition and fiber properties of plant tissue taken from the roots, stem, trunk, and leaves is different. What is not so well known, is that the chemical composition and fiber properties of plant tissue are also different at different stages of the growing season[14].

Plants have, in general, five stages in their life cycle: germination, growth, flowering, seed formation, and death. Annual plants go through these stages in one growing season. Biennials have a two year cycle where the second year's plant grow from the root system of the first years plant. Perennial plants have the same cycle as annual plants except growth, flowering, and seed formation occur many times before the plant dies.

Variability within a Plant

For wood, the first substance laid down by a tree is known as juvenile wood. It differs both in physical and chemical properties as compared to mature wood. Usually, the percent of juvenile wood is low in a large mature tree but can represent a very large percentage of small young trees. For example, a ten year old Sitka spruce tree may contain up to 90 percent juvenile wood whereas a one hundred year old Sitka spruce tree may contain only one percent juvenile wood at its center.

Juvenile wood usually grows in wider annual rings, has a higher ratio of earlywood (wood substance laid down in the spring and early summer) as compared to latewood (wood substance laid down in the late summer and early fall), lower basic density, and higher moisture content as compared to mature wood Mature wood shrinks very little in the longitudinal (growing) direction whereas juvenile wood can shrink a great deal in the growing direction.

At the ultra structural level, juvenile wood fibers have a larger microfibril angle in the S_2 layer as compared to mature wood which is why juvenile wood shrinks more in the longitudinal direction (0.6%) than mature wood (less than 0.1%).

The fiber length of juvenile wood is much shorter (3.0 mm) than mature wood (4.2 mm) while the lumen size is larger (42.3 µm) in juvenile wood compared to mature wood (32.8 µm). Cell wall thickness is about 3.9 µm for juvenile wood compared to about 8 um for mature wood. Cell diameters are about the same for both (juvenile, 50 µm, mature, 49 µm). The breaking strength of mature wood is about 30% higher and the compression strength parallel to the grain is about 20% higher than juvenile wood.

In general, juvenile wood from both hardwoods and softwoods have less cellulose, (lower pulp yields) more lignin and hemicellulose content than mature wood. There is little difference between the types and amounts of hemicelluloses in both hardwoods and softwoods in juvenile and mature wood.

The extractives can be very different in juvenile wood as compared to mature wood. Extractives from juvenile wood are often more toxic and are in higher concentration. This may account for the decreased digestibility of new growth in birch trees. The concentration of phenolic acids in the extractives are higher in juvenile wood just after leafing has started compared to mature wood.

Plant fibers other than wood also vary in chemical composition and physical properties depending on what part of the plant the fiber came from and the age of the plant. Chemical and physical properties vary in fibers from top to bottom of the plant, distance from the pith, and the age of the plant, especially close to and just after flowering. Table 4 shows the variation in the chemical composition of kenaf as a function of plant height. Note that lignin, glucose and xylose contents are always higher in samples taken at the bottom of the plant as compared to the top. The opposite is true for arabinose and galactose composition[6].

Table 4. Chemical composition of kenaf from top to bottom of the plant.

DAP[+]	Stalk	Chemical Composition (Percent of ovendry basis)				
	Part	Lignin	Glucose	Arabinose	Galactose	Xylose
42	Top	5.00	32.7	2.50	1.74	7.04
	Bottom	6.50	36.0	2.75	1.50	8.50
57	Top	5.10	30.6	3.11	1.96	6.87
	Bottom	9.00	38.2	2.49	1.47	8.93
77	Top	4.10	27.5	3.99	2.83	5.90
	Bottom	19.1	36.7	0.34	0.61	17.5

[+] Days after planting

Table 5. Chemical composition of kenaf bast fiber as a function of plant growing time.

DAP[+]	Chemical Composition (Percent of ovendry basis)				
	Lignin	Glucose	Arabinose	Galactose	Xylose
42	6.00	33.2	3.18	0.62	7.31
57	8.32	35.5	2.21	0.55	8.08
77	9.23	40.5	2.05	0.39	9.16
161	10.2	39.2	2.54	0.56	9.75

[+] Days after planting.

Table 6. Changes in fiber properties of kenaf at different stages of plant growth.

	Stage of plant growth - Days After Planting			
Component	90	120	150	180
Bast Fiber				
Length (mm)	3.34	2.28	2.16	2.42
Width (microns)	18.3	14.5	13.6	15.1
Lumen Width (microns)	11.1	5.4	6.8	7.7
Cell Wall Thickness (microns)	3.6	4.6	3.4	3.7
Core Fiber				
Length (mm)	0.55	0.54	0.45	0.36
Width (microns)	36.9	31.2	32	31.6
Lumen Width (microns)	22.7	14.8	18.6	18.7
Cell Wall Thickness (microns)	7.1	8.2	6.7	6.4

Tables 5 shows the variation in chemical composition of kenaf bast fiber as a function of plant age. Lignin, glucose and xylose contents increase as the plant ages while arabinose and galactose contents decrease.

Table 6 shows the changes in kenaf bast and core fibers as a function of plant age. Both bast and core fiber length and width decrease with age as does lumen width. Cell wall thickness stays about the same for both types of fibers during all

Table 7. Equilibrium moisture content of some agro-fibers.

Fiber	Equilibrium Moisture Content at 27° C		
	30%RH	65%RH	90%RH
Bamboo	4.5	8.9	14.7
Bagasse	4.4	8.8	15.8
Jute	4.6	9.9	16.3
Aspen	4.9	11.1	21.5
Southern Pine	5.8	12.0	21.7
Water Hyacinth	6.2	16.7	36.2
Pennywort	6.6	18.3	56.8

stages of plant growth. It has also been shown that fiber length gradually increased from the bottom to the top of the kenaf plant[6,7,14].

Moisture content as a function of plant fiber type

Table 7 shows the equilibrium moisture content of some common agro-plant fibers. Moisture content at a given relative humidity can have a great effect on the biological performance of a composite made of those fibers. For example, a composite made from pennywort fibers would have a much greater moisture content at 90 percent relative humidity than would a composite made from bamboo fibers. The pennywort product would be much more prone to decay as compared to the bamboo product.

Conclusions

The properties and performance of a given agro-based fiber depends on chemical composition and the physical properties. What part of the plant the fiber came from, the age of the plant, and how the fiber was isolated, are some of the factors which effect the performance of those fibers in a composite. Data on chemical and physical properties are, at best, scattered in the literature, and, at worst, not available at all. Even with the data available, it has been collected under different laboratory conditions and, therefore, it is impossible to compare one set of data with another set. This information is critical before agro-based fibers will reach their highest use potential.

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