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PHYSICAL, CHEMICAL, AND MECHANICAL PROPERTIES OF BAMBOO AND ITS UTILIZATION POTENTIAL FOR FIBERBOARD MANUFACTURING

A Thesis
Submitted to the Graduate Faulty of the
Louisiana State University and
Agriculture and Mechanical College
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

In

The School of Renewable Natural Resources

By
Xiaobo Li

B.S. Beijing Forestry University, 1999
M.S. Chinese Academy of Forestry, 2002
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Table of Contents

List of Tables

List of Figures

Abstract

This study investigated the chemical, physical, and mechanical properties of the bamboo species *Phyllostachys pubescens* and its utilization potential to manufacture medium density fiberboard (MDF). The result showed holocellulose and alpha-cellulose content increased from the base to the top portion. There was no significant variation in Klason lignin content or ash content from the base to the top portion of the bamboo. The outer layer had the highest holocellulose, alpha cellulose, and Klason lignin contents and the lowest extractive and ash contents. The epidermis had the highest extractive and ash contents and the lowest holocellulose and alpha-cellulose content. Specific gravity (SG) and bending properties of bamboo varied with age and vertical height location as well as horizontal layer. All mechanical properties increased from one year old to five year old bamboo. The outer layer had significantly higher SG and bending properties than the inner layer. The SG varied along the culm height. The top portions had consistently higher SG than the base. Bending strength had a strong positive correlation with SG. In order to industrially use bamboo strips efficiently, it is advisable to remove minimal surface material to produce high strength bamboo composites. Compression properties parallel to the longitudinal direction was significantly higher than perpendicular to the longitudinal direction. As expected, at the same panel density level, the strength properties of the fiberboard increased with the increasing of resin content. Age had a significant effect on panel properties. Fiberboard made with one year old bamboo at 8% resin content level had the highest modulus of rupture (MOR) and modulus of elasticity (MOE) among the bamboo panels, which was largely attributed to a higher compaction ratio as well as a higher percentage of larger fiber size. Fiberboard made with five year old bamboo at 8% resin level had the highest internal bond strength.

1. Introduction

1.1 General Introduction

Bamboo is a naturally occurring composite material which grows abundantly in most of the tropical countries. It is considered a composite material because it consists of cellulose fibers imbedded in a lignin matrix. Cellulose fibers are aligned along the length of the bamboo providing maximum tensile flexural strength and rigidity in that direction [Lakkad and Patel 1980]. Over 1200 bamboo species have been identified globally [Wang and Shen 1987]. Bamboo has a very long history with human kind. Bamboo chips were used to record history in ancient China. Bamboo is also one of the oldest building materials used by human kind [Abd.Latif 1990]. It has been used widely for household products and extended to industrial applications due to advances in processing technology and increased market demand. In Asian countries, bamboo has been used for household utilities such as containers, chopsticks, woven mats, fishing poles, cricket boxes, handicrafts, chairs, etc. It has also been widely used in building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters and purlins; it is also used in construction as structural materials for bridges, water-transportation facilities and skyscraper scaffoldings. There are about 35 species now used as raw materials for the pulp and paper industry. Massive plantation of bamboo provides an increasingly important source of raw material for pulp and paper industry in China [Hammett et al. 2001]. Table 1-1 provides a detailed description of diversified bamboo utilization.

There are several differences between bamboo and wood. In bamboo, there are no rays or knots, which give bamboo a far more evenly distributed stresses throughout its length. Bamboo is a hollow tube, sometimes with thin walls, and consequently it is more difficult to join bamboo than pieces of wood. Bamboo does not contain the same chemical extractives as wood, and can therefore be glued very well [Jassen 1995]. Bamboo's diameter, thickness, and internodal length have a macroscopically graded structure while the fiber distribution exhibits a microscopically graded architecture, which lead to favorable properties of bamboo [Amada et al. 1998].

Table 1-1 Various uses of bamboo [Gielis 2002].

Use of bamboo as plant	Use of bamboo as material
Ornamental horticulture	***Local industries***
	Artisanat
	Furniture
Ecology	A variety of utensils
Stabilize of the soil	Houses
Uses on marginal land	***Wood and paper industries***
Hedges and screens	Strand boards
Minimal land use	Medium density fiberboard
	Laminated lumber
	Paper and rayon
Agro-forestry	Parquet
Natural stands	***Nutritional industries***
Plantations	Young shoots for human consumption
Mixed agro-forestry systems	Fodder
	Chemical industries
	Biochemical products
	Pharmaceutical industry
	Energy
	Charcoal
	Pyrolysis
	Gasification

With the continued rapid development of the global economy and constant increase in population, the overall demand for wood and wood based products will likely continue to increase in the future. According to a FAO (Food and Agriculture Organization) global outlook study on the trends of demand for wood products, there will be an increase in demand of the order of 20% by 2010. The current concern is whether this future demand for forest products can be met sustainably [FAO 1997].

As a cheap and fast-grown resource with superior physical and mechanical properties compared to most wood species, bamboo offers great potential as an alternative to wood. Since bamboo species are invasive and spread very fast uncared bamboo species also cause environmental problems. Increased research during the recent years has considerably contributed to the understanding of bamboo as well as to improved processing technologies for broader uses.

The chemistry of bamboo is important in determining its utilization potential. Several studies have investigated the chemical composition of bamboo. But systematic and thorough research on a commercially important bamboo species is needed to determine utilization potential for the products such as medium density fiberboard (MDF). Most of previous studies provide either only general information of several bamboo species or focuses on only one aspect of one species. Chapter 2 presents the effect of age (1, 3, and 5 year old material), horizontal layer (epidermis, outer, middle, and inner layer), and height location (bottom, middle, and top portion) of *Phyllostachys pubescens* in detail.

Physical and mechanical properties of several bamboo species have been studied extensively. Chapter 3 presents the fiber length distribution of *Phyllostachys pubescens* at different age, layer and location. Contact angle of different layers of the bottom portion of three year old bamboo were measured by dynamic contact angle measurement. Specific gravity and bending properties of bamboo at different ages, horizontal layers, and height locations were also determined. Also compressive strength at different ages and height locations were determined.

MDF is the most commonly industrially produced type fiberboard and often has excellent physical mechanical properties, and perfect surface properties. As an ideal board for furniture production and other interior applications, MDF has gained much popularity around the world. Chapter 4 focuses on the utilization of bamboo fibers to MDF. This chapter investigated the effects of age of bamboo fibers and the resin content level on the physical and mechanical properties of the manufactured fiberboards.

1.2 Objectives

The overall objective of this study was to evaluate the physical, chemical, and mechanical properties of the bamboo species *Phyllostachys pubescens*. The effects of plant age, horizontal layer, and vertical height location on physical, chemical, and mechanical properties of bamboo were investigated. The study consisted of the following specific objectives.

1. To determine chemical properties of bamboo, including holocellulose content, alpha-cellulose content, Klason lignin content, hot water extractives content, alcohol-toluene extractives content, and ash content.
2. To ascertain physical, anatomical, and mechanical properties of bamboo, including vascular bundle concentration, fiber length distribution, specific gravity, contact angle, modulus of rupture, modulus of elasticity, and compressive strength.
3. To fabricate bamboo fiberboard and evaluate water soaking, modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) properties of the panels and compare the age effect on the physical and mechanical properties of the fiberboard.

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Chapter 2. Bamboo Chemical Composition

2.1 Introduction

The chemical composition of bamboo is similar to that of wood. Table 2-2 shows the chemical composition of bamboo [Higuchi 1957]. The main constituents of bamboo culms are cellulose, hemi-cellulose and lignin, which amount to over 90% of the total mass. The minor constituents of bamboo are resins, tannins, waxes and inorganic salts. Compared with wood, however, bamboo has higher alkaline extractives, ash and silica contents [Tomalang et al. 1980; Chen et al. 1985].

Yusoff et al. [1992] studied the chemical composition of one, two, and three year old bamboo (*Gigantochloa scortechinii*). The results indicated that the holocellulose content did not vary much among different ages of bamboo. Alpha-cellulose, lignin, extractives, pentosan, ash and silica content increased with increasing age of bamboo.

Bamboo contains other organic composition in addition to cellulose and lignin. It contains about 2-6% starch, 2% deoxidized saccharide, 2-4% fat, and 0.8-6% protein. The carbohydrate content of bamboo plays an important role in its durability and service life. Durability of bamboo against mold, fungal and borers attack is strongly associated with its chemical composition. Bamboo is known to be susceptible to fungal and insect attack. The natural durability of bamboo varies between 1 and 36 months depending on the species and climatic condition [Liese 1980]. The presence of large amounts of starch makes bamboo highly susceptible to attack by staining fungi and powder-post beetles [Mathew and Nair 1988]. It is noteworthy that even in 12 year old culms starch was present in the whole culm, especially in the longitudinal cells of the ground parenchyma [Liese and Weiner 1997]. Higher benzene-ethanol extractives of some bamboo species could be an advantage for decay resistance [Feng et al. 2002].

The ash content of bamboo is made up of inorganic minerals, primarily silica, calcium, and potassium. Manganese and magnesium are two other common minerals. Silica content is the highest in the epidermis, with very little in the nodes and is absent in the internodes. Higher ash content in some bamboo species can adversely affect the processing machinery.

The internode of solid bamboo has significantly higher ash, 1% NaOH, alcohol-toluene and hot water solubles than the nodes [Mabilangan et al. 2002]. However, differences between the major chemical composition of node and internode fraction of bamboo are small [Scurlock 2000]; neither the number of nodes nor the length of internode segments would be critical to the utilization of bamboo for energy conversion, chemical production, or as a building material.

Fujji et al. [1993] investigated the chemistry of the immature culm of a moso-bamboo (*Phyllostachys pubescens Mazel*). The results indicated that the contents of cellulose, hemicellulose and lignin in immature bamboo increased while proceeding downward of the culm. The increase of cellulose in the lower position was also accompanied by an increase in crystallinity.

The culm of the bamboo is covered by its hard epidermis and inner wax layer. It also lacks ray cells as radial pathways. Several results have revealed that bamboo is difficult to treat with preservatives [Liese 1998; Lee 2001]. An oil-bath treatment can successfully protect against fungal attack, but severe losses in strength have to be expected [Leithoff and Peek 2001].

Since the amount of each chemical composition of bamboo varies with age, height, and layer, the chemical compositions of bamboo are correlated with its physical and mechanical properties. Such variation can lead to obvious physical and mechanical properties changes during the growth and maturation of bamboo. This chapter concentrates on a detailed analysis of chemical composition at different age, height, and horizontal layer of bamboo in order to have a better understanding of the effect of these factors on the chemical composition of bamboo. It can also provide chemical composition data for the pulp and paper industry which may have interest to better utilize bamboo.

2.2 Materials and Methods

The bamboos for this study were collected on June, 2003 from the Kisatchie National Forest, Pineville, La. Two representative bamboo culms for each age group (one, three, and five years of age) were harvested. The internodes of each height location and age group for chemical analysis were cut into small strips with razor blade. The strips were small enough to be placed in a Wiley Mill. All of this material was ground in

the Wiley Mill. The material was then placed in a shaker with sieves to pass through a No. 40 mesh sieve (425-µm) yet retained on a No. 60 mesh sieve (250-µm). The resulting material was placed in glass jars labeled with appropriate code for chemical analysis.

Table 2-1 Chemical analysis of bamboo [Higuchi 1955].

Species	(%) ash	(%) Ethanol-toluene extractives	(%) lignin	(%) cellulose	(%) pentosan
Phyllostachys heterocycla	1.3	4.6	26.1	49.1	27.7
Phyllostachys nigra	2.0	3.4	23.8	42.3	24.1
Phyllostachys reticulata	1.9	3.4	25.3	25.3	26.5

To prepare the samples of different horizontal layers of bamboo, bottom portion of three year old bamboo was used. The epidermis of the strips was first removed with a fine blade. The epidermis was kept for chemical analysis and the rest of the strips were divided evenly based on volume into inner, middle and outer layers along the radial direction by a fine blade. The grinding process was the same as above described.

All tests were conducted under the standards of American Society for Testing and Materials (ASTM) except for alcohol-toluene solubility of bamboo. There was a minor modification for extractive content test. Instead of benzene solutions, toluene solution was used. The exact standard that was followed for each chemical property performed is presented in Table 2-2.

Table 2-2. Standards followed for chemical analysis

Property	**Standard**
Alcohol-toluene solubility *	ASTM D 1107-56 (Reapproved 1972)
Hot-water solubility	ASTM 1110-56 (Reapproved 1977)
Klason lignin	ASTM D 1106-56 (Reapproved 1977)
Holocellulose	ASTM D 1104-56 (Reapproved 1978)
Alpha-cellulose	ASTM D 1103-60 (Reapproved 1978)
Ash Content	ASTM D 1102-84 (Reapproved 1990)

Each test was conducted using 3 replications. It was necessary to conduct additional experimentation when analyzing for alcohol-toluene extractive content and holocellulose content. The alcohol-toluene test is the starting material for many of the other experiments. Both the lignin and holocellulose content test are performed with extractive-free bamboo that is derived from the alcohol-toluene extractive test. Additionally, holocellulose is a necessary preparatory stage in order to determine the alpha-cellulose content.

Alcohol-toluene Solubility of Bamboo

The extraction apparatus consisted of a soxhlet extraction tube connected on the top end of a reflux condenser and joined at the bottom to a boiling flask. A two-gram oven-dried sample was placed into a cellulose extraction thimble. The thimble was plugged with a small amount of cotton and placed in a soxhlet extraction tube. The boiling flasks contained a 2:1 solution of 95 percent ethyl alcohol and distilled toluene respectively and were placed on a heating mantle. The extraction was conducted for eight hours at the rate of approximately six siphonings per hour.

When the extraction was completed, all of the remaining solution was transferred to the boiling flask which was heated on a heating mantle until the solution was evaporated. The flasks were oven-dried at 103±2^{o}C, cooled in a desiccator, and weighed until a constant weight was obtained.

The following formula was used to obtain the alcohol-toluene solubility content of bamboo:

$$\text{Alcohol-toluene solubles (percent)} = \frac{W_2}{W_1} \times 100 \qquad [1]$$

where,

W_1=weight of oven-dry test specimen (grams).

W_2=weight of oven-dry extraction residue (grams).

A minor change was made since it was necessary to conduct additional experiments in order to provide sufficient extractive-free bamboo for other chemical

property experiments. Therefore, the sample size was increased to 20 grams and the extraction time to forty-eight hours.

Hot-water Solubility of Bamboo

A two-gram sample was oven-dried and placed into a 250 mL Erlenmeyer flask with 100 mL of distilled water. A reflux condenser was attached to the flask and the apparatus was placed in a gently boiling water bath for three hours. Special attention was given to insure that the level of the solution in the flask remained below that of the boiling water. Samples were then removed from the water bath and filtered by vacuum suction into a fritted glass crucible of known weight. The residue was washed with hot tap water before the crucibles were oven-dried at 103±2°C. Crucibles were then cooled in a desiccator and weighed until a constant weight was obtained.

The following formula was used to obtain the hot-water solubility of bamboo:

$$\text{Hot-water solubles (percent)} = \frac{W_1 - W_2}{W_1} \times 100 \qquad [2]$$

where,

W_1=weight of oven-dry test specimen (grams).

W_2=weight of oven-dry specimen after extraction with hot water (grams).

Klason Lignin in Bamboo

A one-gram, oven-dried sample of extractive-free bamboo was placed in a 150 mL beaker. Fifteen mL of cold sulfuric acid (72 percent) was added slowly while stirring and mixed well. The reaction proceeded for two hours with frequent stirring in a water bath maintained at 20 °C. When the two hours had expired, the specimen was transferred by washing it with 560 mL of distilled water into a 1,000 mL flask, diluting the concentration of the sulfuric acid to three percent.

An allihn condenser was attached to the flask. The apparatus was placed in a boiling water bath for four hours. The flasks were then removed from the water bath and the insoluble material was allowed to settle. The contents of the flasks were filtered by vacuum suction into a fritted-glass crucible of known weight. The residue was washed

free of acid with 500 mL of hot tap water and then oven-dried at 103±2°C. Crucibles were then cooled in a desiccator and weighed until a constant weight was obtained.

The following formula was used to obtain the lignin content of bamboo:

$$\text{Klason lignin content in bamboo (percent)} = \frac{W_4 - W_3}{100 \times W_2} \times (100 - W_1)$$

where,

W_1=alcohol-toluene extractive content (percent).

W_2=weight of oven-dried extractive-free sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

Holocellulose in Bamboo

A two-gram sample of oven-dried extractive-free bamboo was weighed and placed into a 250 mL flask with a small watch glass cover. The specimen was then treated with 150 mL of distilled water, 0.2 mL of cold glacial acetic acid, and one gram of $NaClO_2$ and placed into a water bath maintained between 70 °C -- 80 °C. Every hour for five hours 0.22mL of cold glacial acetic acid and one gram of $NaClO_2$ was added and the contents of the flask were stirred constantly. At the end of five hours, the flasks were placed in an ice water bath until the temperature of the flasks was reduced to 10 °C.

The contents of the flask were filtered into a coarse porosity fritted-glass crucible of known weight. The residue was washed free of ClO_2 with 500 mL of cold distilled water and the residue changed color from yellow to white. The crucibles were then oven-dried at 103 ± 2°C, then cooled in a desiccator, and weighed until a constant weight was reached.

The following formula was used to determine the holocellulose content in bamboo:

$$\text{Holocellulose content in bamboo (percent)} = \frac{W_4 - W_3}{100 \times W_2} \times (100 - W_1) \qquad [4]$$

where,

W_1=alcohol-toluene extractive content (percent).

W_2=weight of oven-dried extractive-free sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

Alpha-cellulose in Bamboo

A three gram oven-dried sample of holocellulose was placed in a 250 mL Erlenmeyer flask with a small watch glass cover. The flasks were placed into water bath that was maintained at 20 ^{o}C. The sample was then treated with 50 mL of 17.5 percent NaOH and thoroughly mixed for one minute. After the specimen was allowed to react with the solution for 29 minutes, 50 mL of distilled water was added and mixed well for another minute. The reaction continued for five more minutes.

The contents of the flask were filtered by aid of vacuum suction into a fritted-glass crucible of known weight. The residue was washed first with 50 mL of 8.3 percent NaOH, then with 40 mL of 10 percent acetic acid. The residue was washed free of acid with 1,000 mL of hot tap water. The crucible was oven-dried in an oven at 103±2^{o}C, then cooled in a desiccator, and weighed until a constant weight was reached.

The following formula was used to obtain the alpha-cellulose content in bamboo:

$$\text{Alpha-cellulose (percent)} = \frac{W_4 - W_3}{100 \times W_2} \times W_1 \qquad [5]$$

where,

W_1=Holocellulose content (percent).

W_2=weight of oven-dried holocellulose sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

Ash Content in Bamboo

Ignite an empty crucible and cover in the muffle at 600 ^{o}C, cool in a dessicator, and weigh to the nearest 0.1 mg. Put about 2 gram sample of air-dried bamboo in the crucible, determine the weight of crucible plus specimen, and place in the drying oven at 103±2^{o}C with the crucible cover removed. Cool in a desiccator and weigh until the weight is constant. Place the crucible and contents in the muffle furnace and ignite until all the carbon is eliminated. Heat slowly at the start to avoid flaming and protect the crucible from strong drafts at all times to avoid mechanical loss of test specimen. The temperature of final ignition is 580 ^{o}C to 600^{o}C. Remove the crucible with its contents to a dessiccator, replace the cover loosely, cool and weigh accurately. Repeat the heating for 30 min periods until the weight after cooling is constant to within 0.2 mg.

The following formula was used to obtain the ash content in bamboo:

$$\text{Ash content (percent)} = \frac{W_2}{W_1} \times 100 \qquad [6]$$

where,

W_1=weight of ash (grams).

W_2=weight of oven-dried sample (grams).

The effects of age, height, layer on bamboo chemistry were evaluated by analysis of variance at the 0.05 level of significance.

2.3 Results and Discussion

The results of the bamboo chemistry testing are listed in Table 2-3. For specific chemical component the result is discussed in detail in the following. Table 2-4 shows the results of analysis of variance and Table 2-5 shows the Tukey comparison results.

2.3.1 Alcohol-toluene and Hot Water Extractives

The alcohol-toluene extractives of bamboo consists of the soluble materials not generally considered part of the bamboo substance, which are primarily the waxes, fats, resins, and some gums, as well as some water-soluble substances. The alcohol-toluene extractive content of different age and height locations is presented in Figure 2-1. Age

had a significant effect on alcohol-toluene extractive content. With the increase of age, alcohol-toluene extractive content increases steadily. Five year old bamboo had the highest extractive content. There was some variation among vertical sampling locations. The top portion had the highest extractive content. The bottom and middle had not significantly different in alcohol-toluene extractive content.

Table 2-3. Chemical composition of bamboo

Age	Location	Ash	Hot Water Solubles	Alcohol-toluene Solubles	Lignin	Holo-cellulose	α-cellulose
		%	%	%	%	%	%
One	Bottom	1.82	5.83	3.32	21.98	68.92	46.52
	Middle	1.94	5.07	2.86	22.11	70.84	47.30
	Top	1.95	5.14	3.48	21.26	71.95	47.51
Three	Bottom	1.30	6.33	4.17	23.21	68.58	46.21
	Middle	1.36	6.91	4.38	23.95	72.69	46.82
	Top	1.41	7.43	5.21	23.71	73.82	46.99
Five	Bottom	1.26	4.89	6.61	22.93	69.94	46.08
	Middle	1.30	5.19	6.81	22.97	72.50	47.65
	Top	1.35	5.84	7.34	23.02	73.65	47.91
Three[1]	Epidermis	4.09	9.19	5.99	22.41	63.14	41.71
	Outer	0.54	5.26	3.15	24.30	69.94	49.02
	Middle	0.65	7.25	4.25	21.79	65.84	45.08
	Inner	0.88	9.33	5.78	22.57	64.54	42.84

[1] The bottom portion of three year old bamboo was used to determine the effect of horizontal layer on the chemical composition of bamboo.

Table 2-4. Analysis of variance table for bamboo chemical composition.

Source	DF	Pr>F					
		Ash	Hot Water Solubles	Alcohol-toluene Solubles	Lignin	Holo-cellulose	α-cellulose
Year	2	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.025
Height	2	0.001	<0.0001	<0.0001	0.3760	<0.0001	<0.0001
Year*Height	4	0.700	<0.0001	0.0105	0.3379	0.0493	0.1625
Layer	3	<0.0001	<0.0001	<0.0001	0.0029	<0.0001	<0.0001

Table 2-5. Tukey comparison table for bamboo chemical composition.

Source	Location	Ash	Hot Water Solubles	Alcohol-toluene Solubles	Lignin	Holo-cellulose	α-cellulose
Year	1	A	C	C	B	B	AB
	3	B	A	B	A	A	B
	5	B	B	A	A	A	A
Height	Bottom	B	B	B	A	C	C
	Middle	A	B	B	A	B	B
	Top	A	A	A	A	A	A
Layer	Outer	B	C	C	A	A	A
	Middle	B	B	B	B	B	B
	Inner	B	A	A	B	C	C
	Epidermis	A	A	A	B	C	C

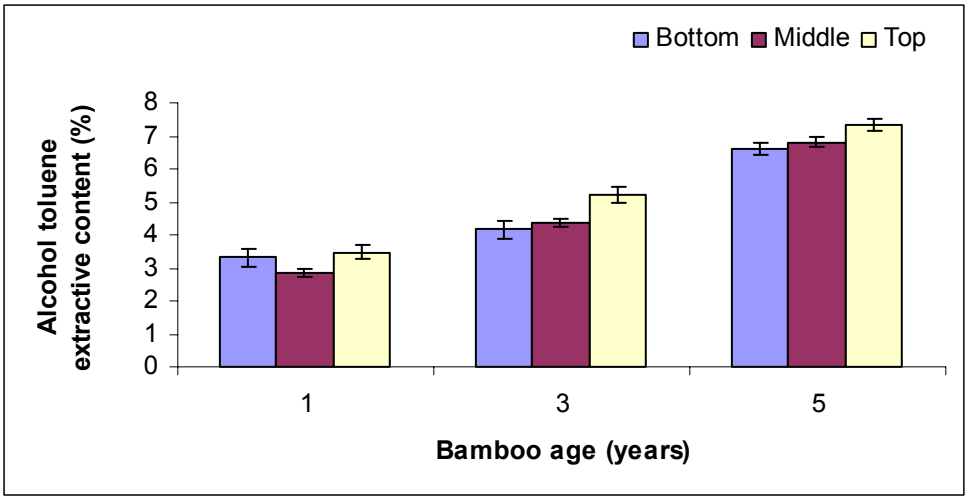

Figure 2-1. Alcohol-toluene extractive content of bamboo at different age and location.

The alcohol-toluene extractive content of different horizontal layers of the bottom portion of three year old bamboo was presented in Figure 2-2. Epidermis and inner layer had significant higher alcohol-toluene extractive content. The outer layer had the lowest alcohol-toluene extractive content.

The epidermis of bamboo has an attractive green color due to the chlorophyll in its epidermis. After extraction with alcohol-toluene, the color of the extraction solution turned to a dark green color due to the extraction of chlorophyll. Also several studies have revealed that the chlorophyll in the epidermis is very easily degraded and thus

treatment with inorganic salts such as chromates, nickel salts, and copper salts have been used to conserve the green color of bamboo surfaces [Chang et al. 1998, 2001; Wu 2002]. Wax material attached to the inner layer also contributed to the higher alcohol-toluene extractive content relative to the middle and outer layers.

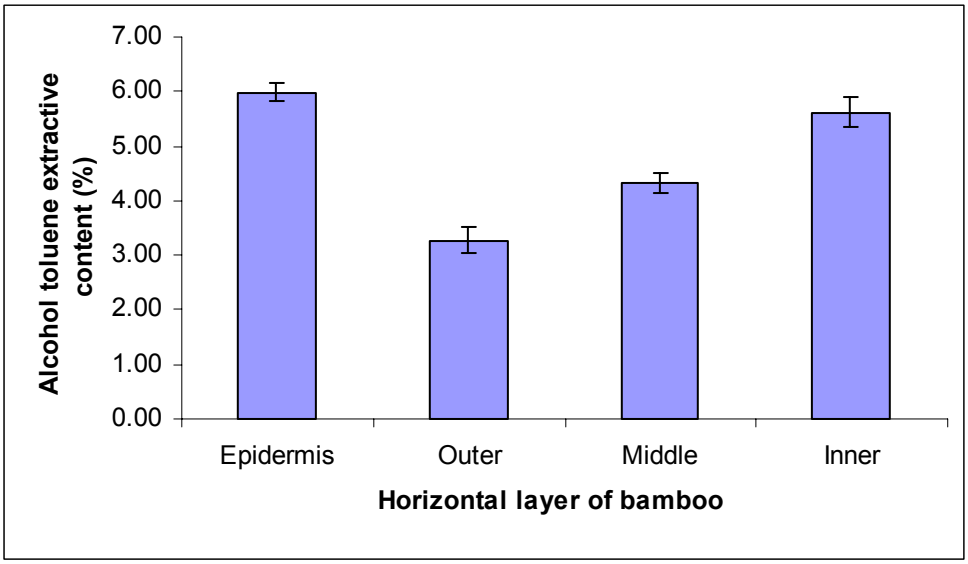

Figure 2-2. Alcohol-toluene extractive content of three years old bamboo of different horizontal layers.

Hot water extractives in the bamboo include tannins, gums, sugars, coloring matter, and starches.

Age had some effect on hot water extractive content of bamboo. Three year old bamboo had the highest hot water extractive content. There was no significant difference between one and five year old bamboo. This indicates that hot water extractive increased from year one to year three and then decreased gradually.

Height also had some effect on the variation of hot water extractive content. Bamboo top portions had a significantly higher hot water extractive content than middle and bottom portions. There was no significant difference between the middle and bottom portion.

The hot water extractive content in each layer showed a similar trend as that of alcohol-toluene extractive content. The outer layer had the lowest hot water extractive

content. The epidermis and inner layer had significantly higher extractive content, which can be explained similarly as was detailed for alcohol-toluene extractives.

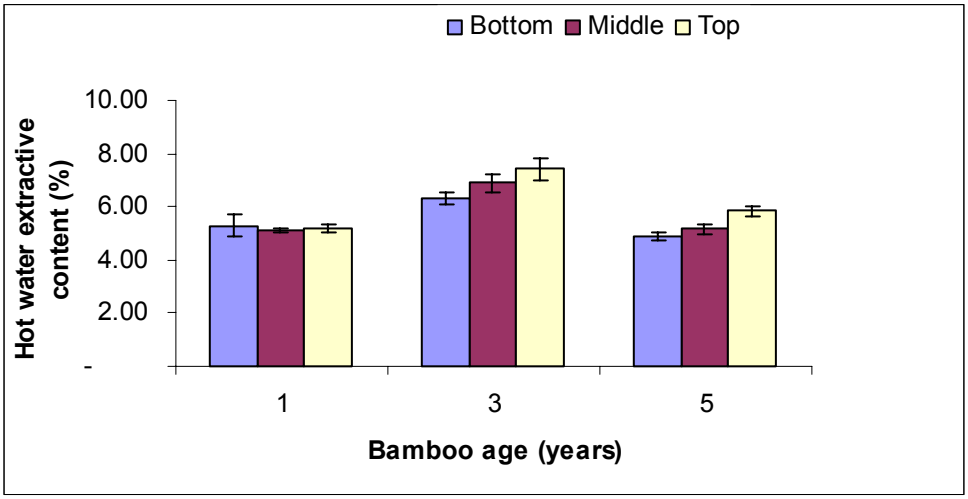

Figure 2-3. Hot water extractive content of bamboo at different age and height location.

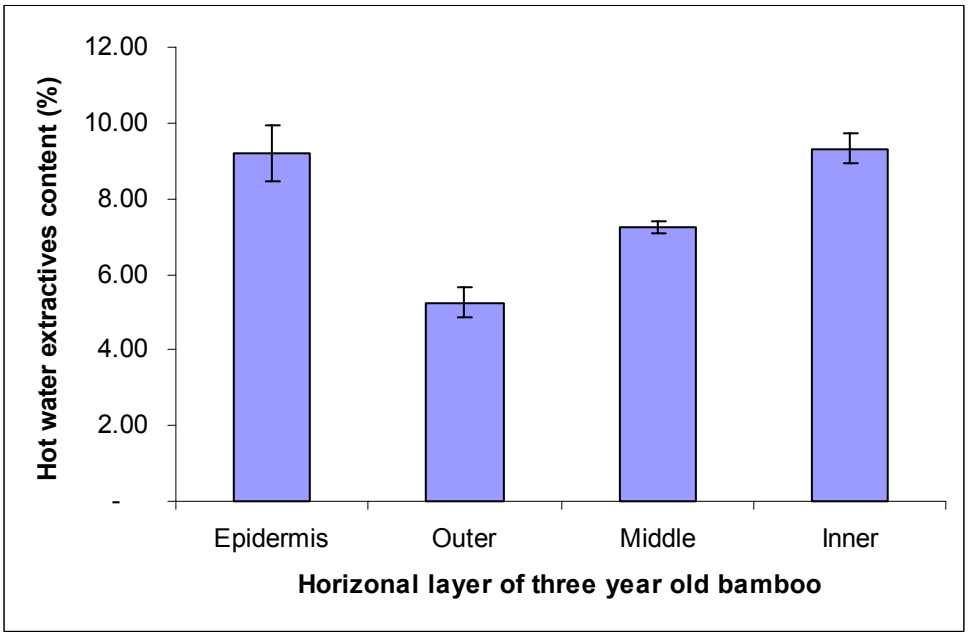

Figure 2-4. Hot water extractive content of bamboo of different horizontal layers.

2.3.2 Holocellulose Content and Alpha-cellulose Content

Holocellulose include alpha-cellulose and hemicellulose. Alpha-cellulose is the main constituent of bamboo. Approximately 40-55% of the dry substance in bamboo is

alpha-cellulose. Cellulose is a homopolysaccharide composed of β-D-glucopyranose units which are linked together by (1→4)-glycosidic bonds. Cellulose molecules are completely linear and have a strong tendency to form intra- and intermolecular hydrogen bonds. Bundles of cellulose molecules are thus aggregated together in the form of microfibrils, in which crystalline regions alternate with amorphous regions. Hemicelluloses are heterogeneous polysaccharides, like cellulose, most hemicelluloses function as supporting materials in the cell walls [Sjostrom 1981]. Alpha-cellulose is the main source of the mechanical properties of bamboo and wood [Janssen 1981].

Figure 2-5 presents the holocellulose content of bamboo at different ages and locations. There is no significant difference between three and five year old bamboo in holocellulose content. One year old bamboo had relatively lower holocellulose content.

Height had a significant effect on holocellulose content. Top portion had the highest holocellulose content; bottom portion had the lowest holocellulose content.

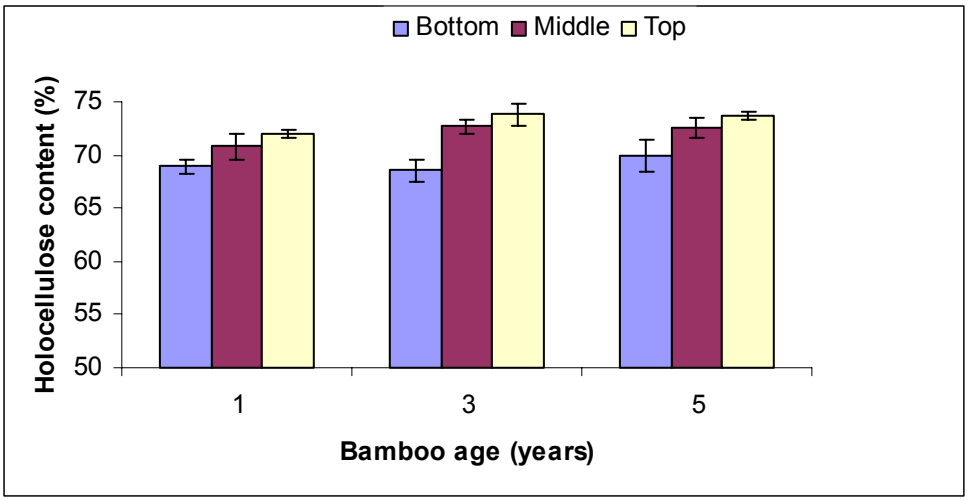

Figure 2-5. Holocellulose content of bamboo at different ages and heights.

Holocellulose content of different layers of the bottom portion of three year old bamboo is presented in Figure 2-6. Outer layer had the highest holocellulose content, and the epidermis had the lowest. Although holocellulose content seems to decrease from the outer layer to the inner layer, it was not significantly different between the middle and inner layers. Low holocellulose content in the epidermis is partly due to its high

extractive and ash contents. Previous research has shown that the epidermis wall consisted of an outer and inner layer; the inner layer appears to be highly lignified. The cutinized layer is composed of cellulose and petin [Liese and Hamburg 1987]. Since the outer layer had a significantly higher extractive content and ash content, it seriously reduced the holocellulose content in bamboo epidermis.

Alpha-cellulose content of bamboo at different age and height is presented in Figure 2-7. Analysis of variance showed that age had no significant effect on alpha-cellulose content. There was a significant difference in alpha-cellulose content along the height of the bamboo culm. It increased gradually from the bottom to the top portion.

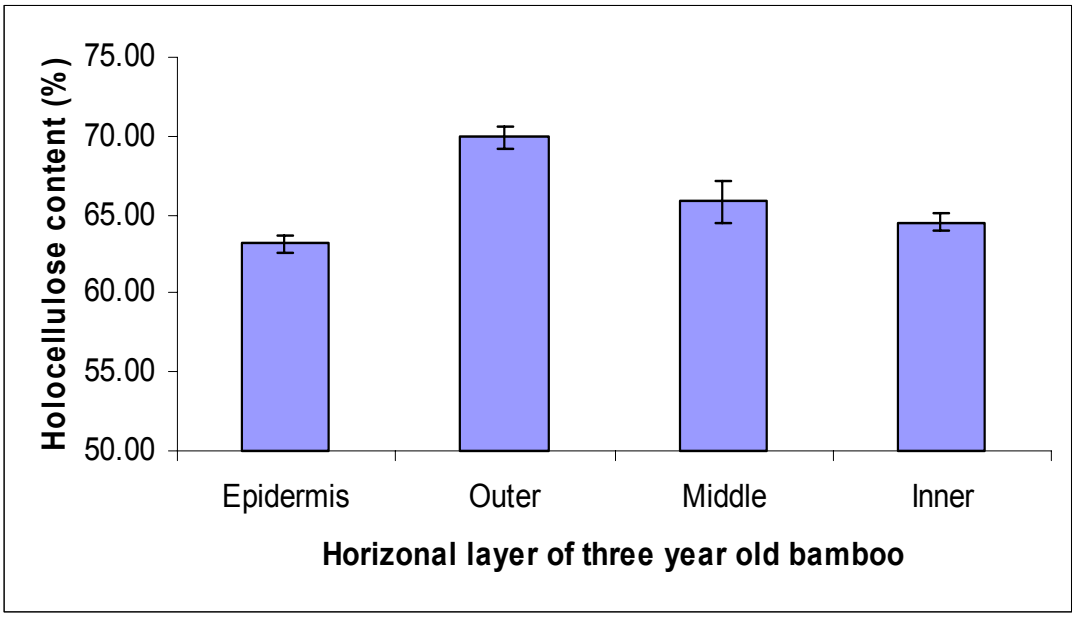

Figure 2-6. Holocellulose content of three years old bamboo of different horizontal layers.

Alpha-cellulose content had a significant difference across the bamboo culm of the bottom portion of three year old bamboo (Figure 2-8). It consistently decreased from the outer layer to the inner layer. The epidermis of bamboo had the lowest alpha-cellulose content.

In general, the alpha-cellulose content in bamboo is 40-50%, which is compatible to the reported cellulose content of softwoods (40-52%) and hardwoods (38-

56%). Cellulose contents in this range make bamboo a suitable raw material for the paper and pulp industry.

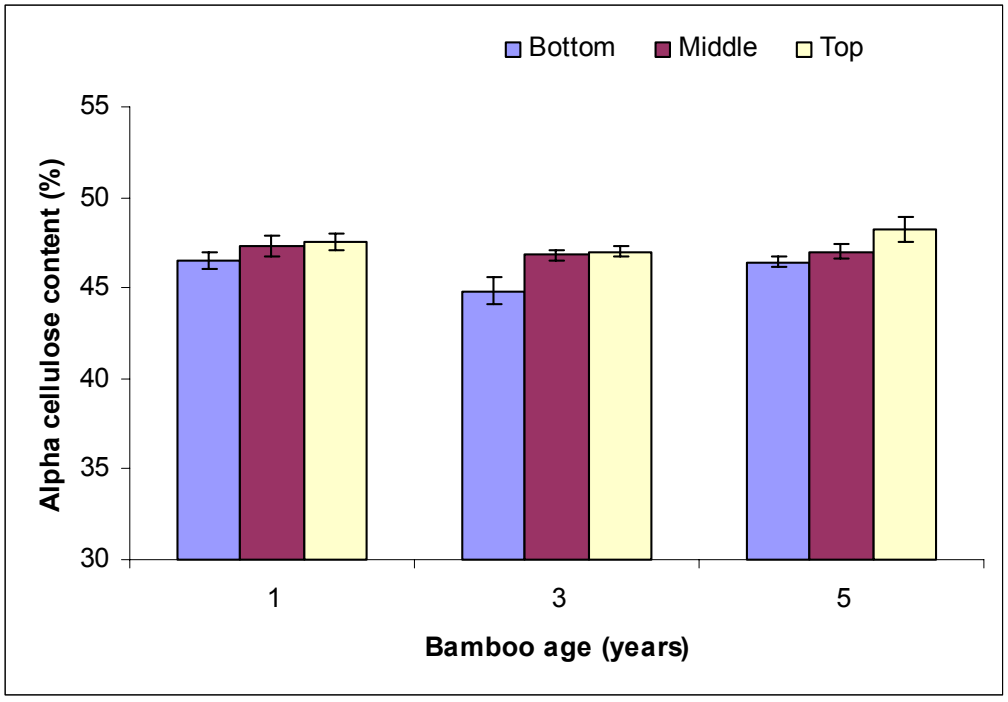

Figure 2-7. Alpha-cellulose content of bamboo at different age and height location.

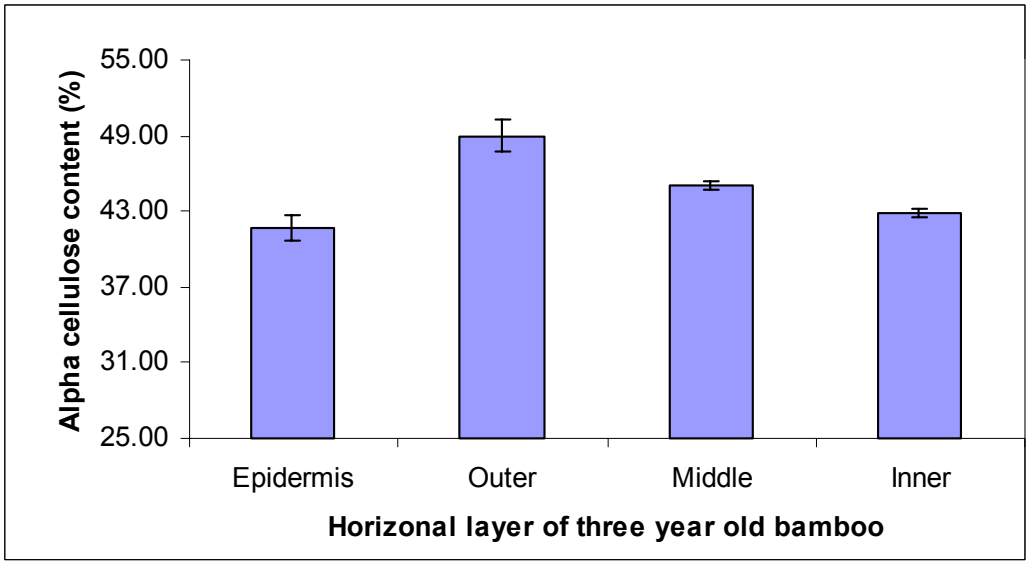

Figure 2-8 Alpha-cellulose content of three years old bamboo of different horizontal layers.

2.3.3 Klason Lignin Content

Lignin is polymer of phenylpropane units. Many aspects in the chemistry of lignin still remain unclear. Lignin can be isolated from extractive free wood as an insoluble residue after hydrolytic removal of the polysaccharides. Klason lignin is obtained after removing the polysaccharides from extracted (resin free) wood by hydrolysis with 72% sulfuric acid [Sjostrom 1981]. Bamboo lignin is built up from three phenyl-propane units, p-coumaryl, coniferyl and sinapyl alcohols interconnected through biosynthetic pathways [Liese 1987].

The lignin present in bamboos is unique. The lignification process undergoes changes during the elongation of the culm, the full lignification of the bamboo culm is completed within one growing season, showing no further ageing effect [Itoh and Shimaji 1981].

The lignin content of one year old bamboo is significantly lower than that of three and five year old bamboo (Figure 2-9). Three year old bamboo seems to have higher lignin content than five year old bamboo, but the magnitude of the difference is not statistically significant.

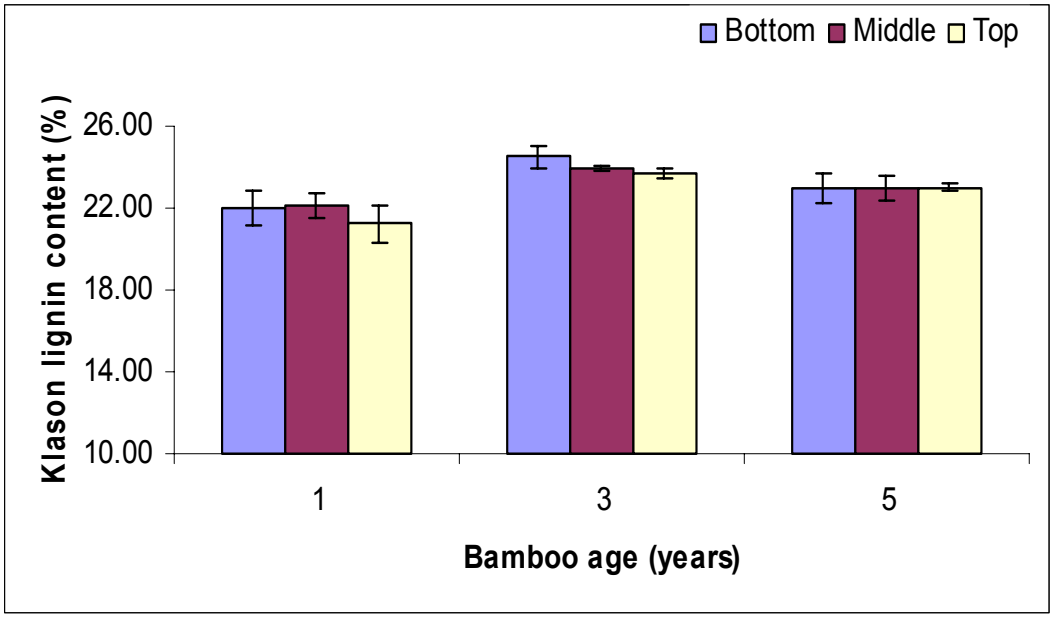

Figure 2-9. Klason Lignin content of bamboo at different age and height locations.

The Klason lignin content of the different layers of the bottom portion of three year old bamboo was presented in Figure 2-10. The outer layer had the highest lignin content. There was no significant difference among epidermis, inner layer and middle layer of bamboo. The higher lignin content contributes greatly to the higher strength properties of the outer layer.

The lignin values of 20-26% place bamboo at the high end of the normal range or 11-27% reported for non-woody biomass [Bagby 1971] and closely resemble the ranges reported for softwoods (24-37%) and hardwoods (17-30%) [Fengel 1984; Dence 1992]. The high lignin content of bamboo contributes to its high heating value of bamboo, and its structural rigidity makes it a valuable building material [Scurlock 2000].

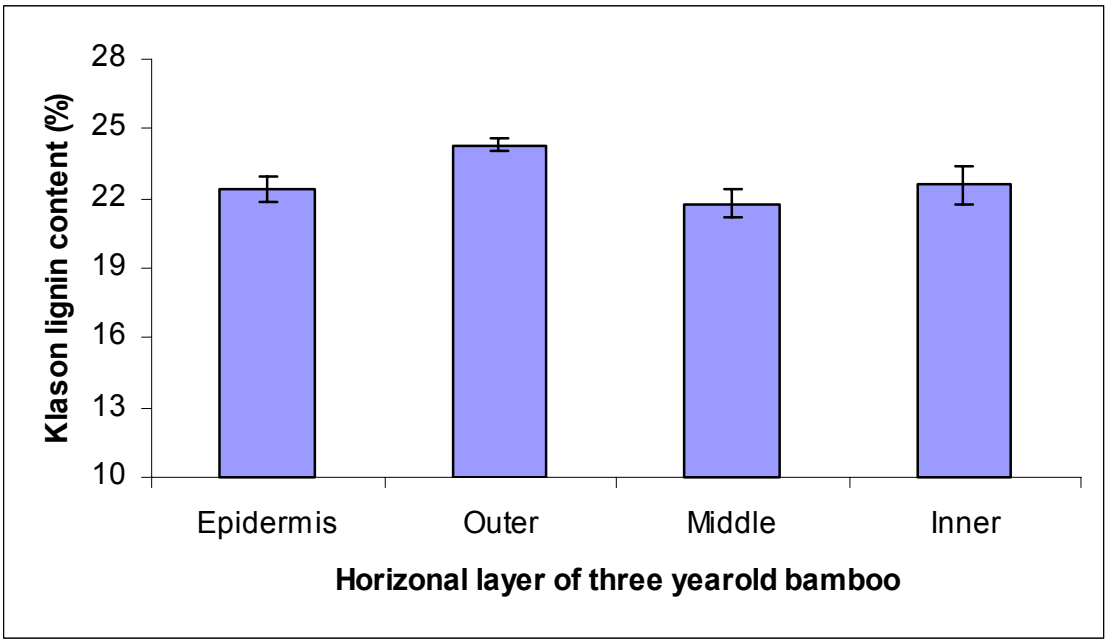

Figure 2-10. Klason lignin content of three years old bamboo of different horizontal layers.

2.3.4 Ash content

Ash is a term generally used to refer to inorganic substances such as silicates, sulfates, carbonates, or metal ions [Rydholm 1965].

The ash content of bamboo at different age and height is presented in Figure 2-11. The ash content of one year old bamboo was significantly higher than that of three and five

year old bamboo. Three and five year old bamboo had no significant difference in ash content. Analysis of variance also showed there was no difference between top and middle portions for ash content; the ash content in the bottom portion of the culm was the lowest.

Figure 2-12 showed the ash content at different layers. We can see that the epidermis had significantly higher ash content, which is three times of other three layers. It has been suggested that the higher ash content in the epidermis is mainly due to the fact that almost all the entire silica is located in the epidermis layers, with hardly any silica in the rest of the wall [Satish et al. 1994]. Table 2-7 also shows the ash content data for several common wood species. It is clear that bamboo has significantly higher ash content than these common woods but generally lower than that of bark of most wood species.

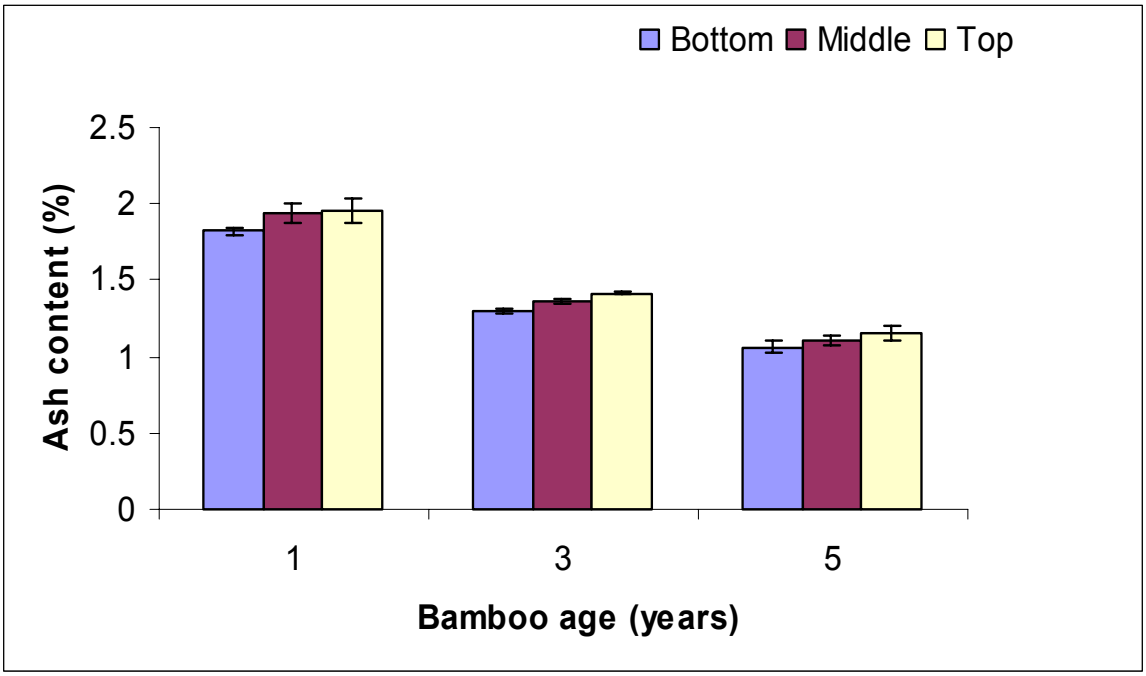

Figure 2-11. Ash content of bamboo at different age and height location.

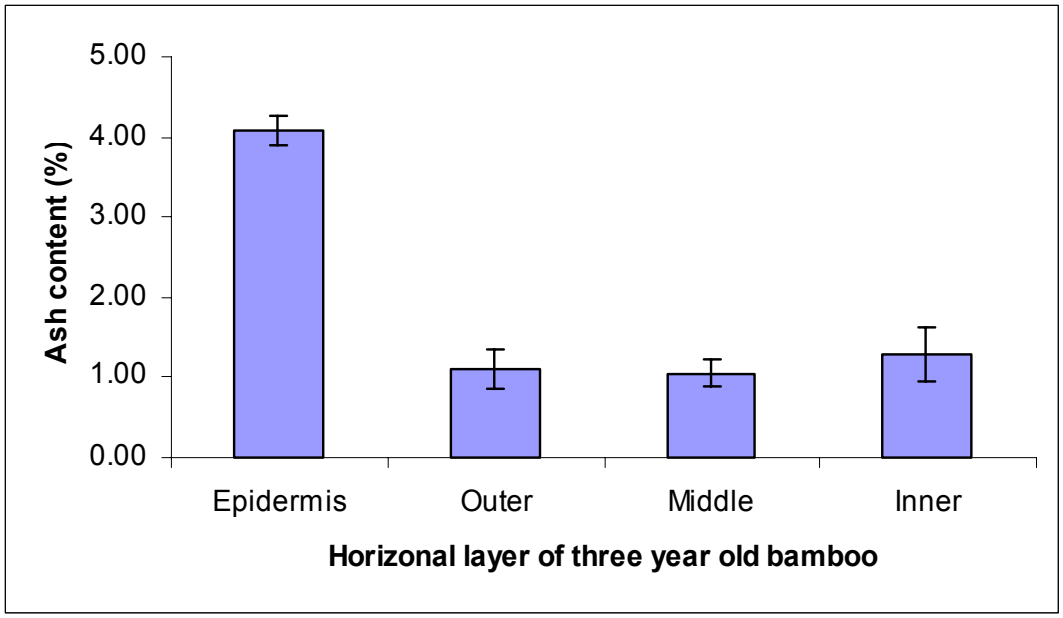

Figure 2-12. Ash content of three years old bamboo of different horizontal layer.

Table 2-6. Low temperature ash content of different wood species [MISRA 1993].

Wood species	Ash content
Aspen	0.43
Yellow poplar	0.45
White oak	0.87
White oak bark	1.64
Douglas-fir bark	1.82

2.4 Summary

The chemical compositions of one, three, and five year old bamboo at different height locations were determined. This study also investigated the chemical composition of different horizontal layers (epidermis, outer, middle and inner layers) of the bottom portion of three year old bamboo.

The results showed that except for one year old bamboo, alcohol-toluene and hot water extractive content increased from the bottom to the top portion. Alcohol-toluene extractive content showed a continuous increase from one year old bamboo to five year old bamboo. Hot water extractives showed an increase from one year old bamboo and then decreased from three year to five year old bamboo.

Holocellulose and alpha-cellulose content increased from the bottom to the top portion. There is no significant variation in lignin content and ash content from the bottom to the top portion of bamboo. Outer layer of bamboo had the highest holocellulose, alpha-cellulose, and Klason lignin content and the lowest extractive content and ash contents. The epidermis had the highest extractive and ash content and had the lowest holocellulose and alpha-cellulose content.

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Chapter 3. Anatomical, Physical and Mechanical Properties of Bamboo

3.1 Introduction

3.1.1 Anatomical Structures

The structure of a bamboo culm transverse section is characterized by numerous vascular bundles embedded in the parenchymatous ground tissue [Grosser and Liese 1971]. The culm tissue consists of two cell types: parenchyma cells and vascular bundles.

The parenchyma cells are mostly thin-walled and connected to each other by numerous simple pits. Pits are located predominantly on the longitudinal walls. The horizontal walls are scarcely pitted.

The size of the vascular bundle is large in the inner and middle layer but smaller and denser in the outer layer as shown in Figure 3-1.

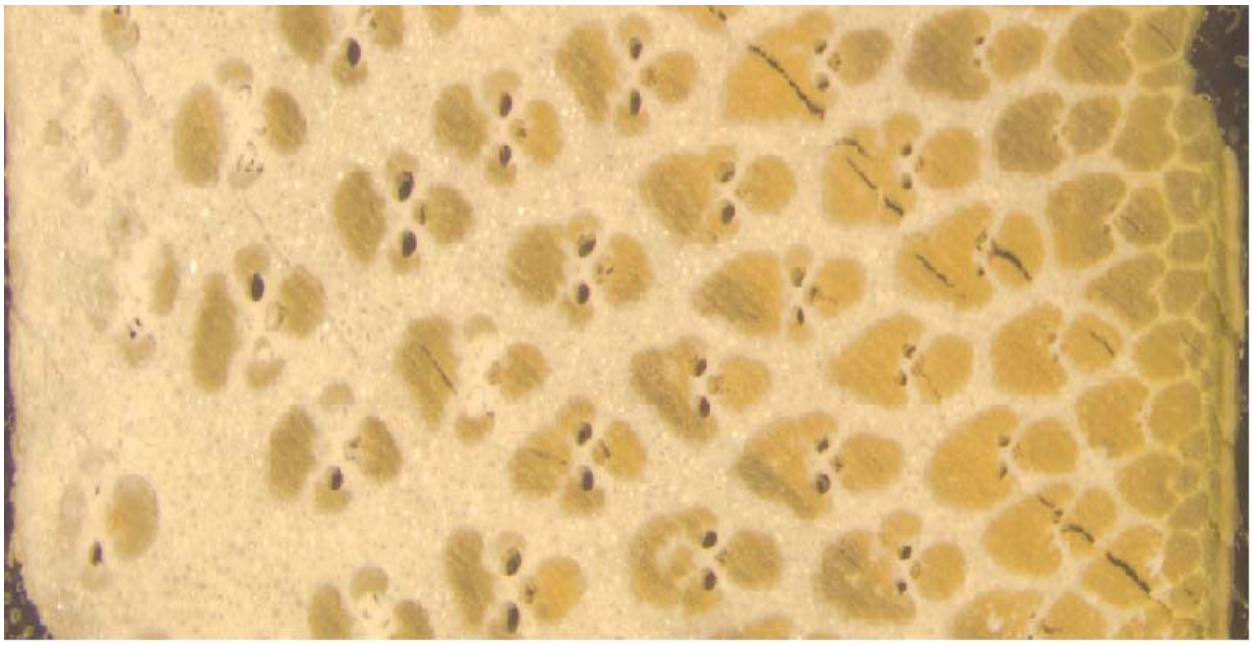

Figure 3-1. Cross section of a bamboo culm (magnification 10X).

3.1.2 Physical and Mechanical Properties

Specific gravity (SG) is a measure of the density of a substance. The specific gravity of a substance is a comparison of its density to that of water. The specific gravity of bamboo varies between 0.4 and 0.8 depending mainly on the anatomical structure. The moisture content of bamboo varies vertically from the bottom to the top portions and horizontally from the outer layer to the inner layers. Bamboo possesses very high moisture content. Green bamboo may have 100% percent moisture (oven-dry weight basis) and can be as high as 155 percent for the innermost layers to 70 percent for the peripheral layers. The vertical variation from the top (82%) to the bottom (110%) is comparatively less. The fiber saturation point of bamboo is around 20-22 percent [Kishen et al. 1956]. The MC range of *Bambusa bluemeana* is 57-97% [Abd.Latif 1993]. Lee [1994] revealed that *Phyllostachys bambusoides* has an average MC of 138% and a green SG of 0.48. Unlike wood, bamboo has no secondary growth; all gains after it reaches its full height are due to the addition of material to cells after the first year.

Wettability is the ability of a liquid to form a coherent film on a surface, owing to the dominance of molecular attraction between the liquid and the surface over the cohesive force of the liquid itself. [Padday 1992]. Wettability of bamboo has a significant influence on adhesion and other related properties. In terms of adhesion theory, bond formation involves wetting, adsorption, and inter-diffusion of the resin with the respect to the adhered substrate [Kaeble 1967]. Adhesive wettability of wood is usually evaluated by contact angle measurement [Shi and Gardner 2001]. Several studies have revealed wettability determined through contact angle measurement is closely associated with gluability of wood and wood based composites [Chen 1970; Hse 1972; Freeman 1959; Herczeg 1965].

The bamboo culm comprises about 50% parenchyma, 40% fibers and 10% vessels and sieve tubes [Liese 1987]. The fibers contribute 60-70% of the weight of the total culm tissue. They are long and tapered at their ends. The ratio of length to width varies between 150:1 and 250:1. Fiber length has showed considerable variation within species. Mean values are: *Bambusa tulda* 3 mm, *B. vlgaris* 2.3 mm, *Dendrocalamus giganteus* 3.2 mm, *Guadua angustifolia* 1.6 mm, *Phyllostachys edulis* 1.5 mm. Generally, the fibers are much longer than those from hardwoods (1-1.5 mm) [Liese

1995]. Fibers in bamboos are grouped in bundles and sheaths around the vessels. The epiderma1 walls consist of an outer and inner layer; the latter of which is highly lignified. Fiber length and fiber width varies within one internode [Liese and Grosser 1972]. Fiber percentage is higher in the outer one- third of the wall and in the upper part of the culm, contributing to its superior slenderness [Grosser and Liese 1971]. The percentage of fibers increases from the bottom to the top of the culm [Seema and Kumar 1992]. Mclaughlin and Tait [1980] studied the mechanism of failure in tension of cellulose-based fibers. They predicted that tensile strength and mean Young's modulus increase with increase cellulose content and decreasing micro-fibril angle.

Bamboo provides an important raw material for the pulp and paper industry in many places, especially in South East Asia [Hammett 2001]. Fiber morphology has an important influence on the physical properties of pulp [Tamolong 1967; Zamuco et al. 1969].

Aging of a bamboo culm influences physical, chemical, and mechanical properties, and consequently its processing and utilization. The physical and mechanical properties of bamboo vary with the age of the bamboo and the height of the culm [Chauhan 2000]. In general, SG and the properties of bamboo drop from the top portion to the bottom. The increase in weight is cumulative and directly related with age. Strength properties are reported to decrease in older culms [Zhou 1981]. Limaye [1948; 1952] found that older culms of *Dendrocalamus strictus* became 40-50 percent stronger and stiffer than young ones. Maximum values were found in 3-6 year old culms. Sekhar et al. [1962] found highest values in 3-4 year old culms of *Bambusa nutans*.

There is also variation in strength properties along the culm height as well. Compressive strength tends to increase with height [Espiloy 1987; Liese 1987; Sattar et al. 1990; Kabir et al. 1991]. The strength increases from the central to the outer part. There is more than 100 percent variation in strength from the inner to the outer layers [Narayanamurti and Bist 1947].

In the United States, interest in bamboo has increased as several studies have been done to evaluate bamboo's physical and mechanical properties and its utilization potential as an alternative to wood resources [Lee et al. 1994; Ahmad 2000; Shupe et al. 2002].

The objectives of this study were to study: (1) vascular bundle concentration at different ages and heights, (2) fiber characteristics, (3) contact angle of different layers, (4) moisture content, SG, and bending properties, along longitudinal and radial directions of one, three, and five year old bamboo and determine the correlation between SG and bending properties, and (5) compressive strength of bamboo at different ages and heights.

3.2 Materials and Methods

The bamboos for this study were collected on June, 2003 from the Kisatchie National Forest, Pineville, La, USA. Two representative bamboo culms for each age group (1, 3, and 5 years of age) were harvested. A procedure has been adopted to classify the bamboo longitudinal location (Figure 3-2). Starting with the second internode from the bottom position to the 31^{st} internode, every 10^{th} internode section was taken. The whole culm was divided into three equal length internode number sections (bottom, middle and top). The second and third internodes in each section were selected for physical and mechanical properties determination. The moisture content of three year old green bamboo was determined soon after the sections were transported to the lab to determine the moisture content variation along the bamboo culm.

3.2.1 Vascular Bundle Concentration

For vascular bundle concentration determination, a 45 micron thick slice of the cross section (transverse section) was cut with a sliding microtome. The slice was dried in the oven at 40 ^{o}C for 8 hours and was viewed at 5 × under a light microscope, and the image was captured using a digital camera. The image was analyzed with Image Pro-plus software. The cross section of each sample was divided evenly into five layers horizontally and the vascular bundle number was counted and the area was measured.

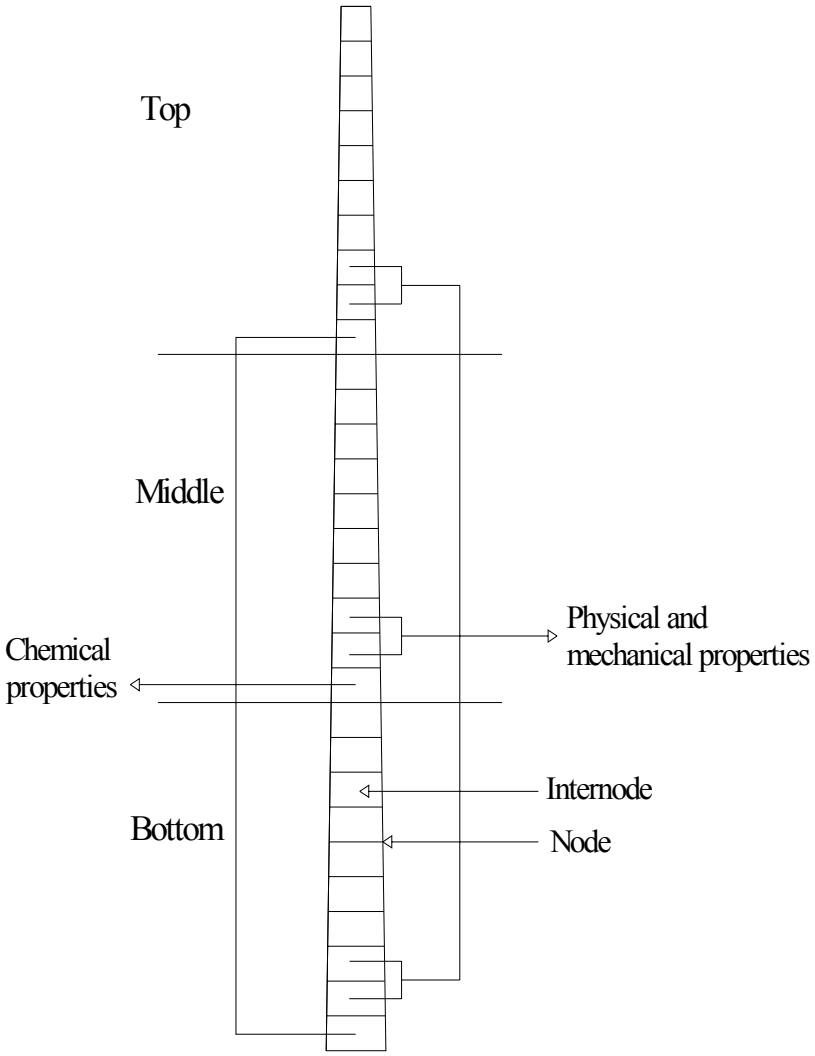

Figure 3-2 .Schematic diagram of sampling technique from bamboo culm.

3.2.2 Contact Angle

The contact angle was measured on the inner and epidermis surface as well as the middle and outer part of the bamboo. Bamboo sections of 1.2 cm width and 2.5 cm length from the bottom were soaked in distilled water for 4 hours. A 60 micron thick section from each layer was cut using a microtone. The fresh layer of bamboo after cutting was kept straight by two slices of glass and dried in an oven of 40 ^{o}C for 24 hours prior to contact angle measurement. A small drop of UF resin liquid (0.1mL) was dropped to the surface of the sample with a 5 mL pipette, As soon as the liquid rested on the surface, the image of the shape of the drop was captured every 30 seconds interval for 180 seconds by a SPOT digital camera connected with a light microscope and a personal computer.

3.2.3 Fiber Characteristics

The strength and durability of bamboo composites are a function of the physical and mechanical properties of the component fibers. Anatomical Analysis of the fibers included the investigation of the fiber's length, width and length/width ratio and specific gravity. Single fibers were also macerated and tested for tensile strength.

The following process was used for bamboo fiber maceration. Bamboo samples from different age materials and height and horizontal locations were cut into 0.25 $\times$0.25 $\times$5 cm toothpick size pieces. Glacial acidic acid, 30% hydrogen peroxide, and distilled water were used as maceration solution and the ratio was: 5:1:4 respectively. The samples were macerated under 60 ^{o}C for 48 hours, unlike most wood for which the normal maceration time is 24 hours. After maceration, the fibers were further separated with a stir rod and were then washed thoroughly with distilled water. The distilled water was drained out by using a vacuum. A small amount of phenol was added as preservative and distilled water was also added to immerse the fibers. The fibers were stored in a jar in a refrigerator for later fiber length and strength determination.

A small amount of fibers from jar were transferred to a small jar. Distilled water was added to dilute the fibers. The small jars were put into a water bath at 50 ^{o}C for twenty minutes and then vibrated in a VWR mini vortexer for 5 minutes to further

separate the fibers. The diluted mixture was then spread evenly on to a transparent glass of 20×20 cm and another piece of glass was placed on top. The glasses with the fibers were then dried in an oven of 50 ^{o}C for 24 hours to evaporate the water. The glass with the fibers was scanned using a HP Precision scanner at 1,200 dpi resolution. The fibers were then randomly selected from the scanned picture, which was magnified in Image pro-plus software and the fiber length on the image was measured. Normally, three to four hundred fibers were selected and measured for each group.

3.2.4 SG, Bending and Compression Properties

To evaluate the effect of SG across the culm on bending properties, the internode was cut with a band saw into strips of 1 cm wide and 16 cm long. The strips were sanded to remove 10%, 25%, or 50 of the outer layer. Some samples had 10% or 25% of the inner layer removed. All removal was on a per weight basis. The specimens were air-dried in the laboratory to equilibrium moisture content of about 10% for 4 week prior to testing. The bending test was performed with some modification of ASTM standard D1037-94 [ASTM 1994] on an Instron machine with the outer layer on the compression side. The span was 12.7 cm and the cross head speed was 0.25 cm/min. After each bending test, a small section of each bending sample was cut for SG measurement using a VM655 AMSLER Volume-meter.

The samples for compression were made from the internode of different height locations of one, three, and five year old bamboo. The compression test was performed with some modification of ASTM standard D1037-94 [ASTM 1994]. The compression parallel to grain and perpendicular to grain was performed with samples of 1.2 × 1.2 cm using the same Instron machine. The crosshead speed for the Instron machine was 0.12 cm./min..

The effects of age, height, and layer on bending properties were evaluated by analysis of variance at the 0.05 level of significance. Tukey's studentized range test was used for the comparison procedure.

3.3 Results and Discussion

3.3.1 Vascular Bundle Concentration

The concentration of vascular bundles is listed in table 3-1. The vascular bundles are not evenly distributed on the bamboo cross section. Although the total number of vascular bundles decreases with increasing height of a culm, the vascular bundle concentration is the highest on the top portion. The highest vascular bundle concentration was found on the top portion of three year old bamboo with 467 bundles/cm^2. For *Phyllostachys edulis*, 50-80% of the vascular bundles are located in the outer third of the wall, 10-35% in the middle, and only 10-20% in the inner third [Fujji 1985].

Table 3-1. Vascular bundle concentration of bamboo at different age.

Year	Height	Outer [a]	Middle	Inner
One	Bottom	346	174	105
	Middle	344	232	153
	Top	392	297	214
Three	Bottom	292	155	126
	Middle	378	213	135
	Top	467	256	163
Five	Bottom	298	175	117
	Middle	369	193	146
	Top	458	295	148

[a] The unit is bundles/cm^2.

3.3.2 Moisture Content

Moisture content is an important factor in governing the mechanical properties of bamboo. Bending and compression strength have shown significant variation of bamboo for green and air-dry conditions [Lee 1994; Chung and Yu 2002].

Moisture content of bamboo from three year old bamboo is presented in Figure 3-3. Green bamboo had an average MC of 60%. The MC along the longitudinal direction decreased from the bottom to the top portion.

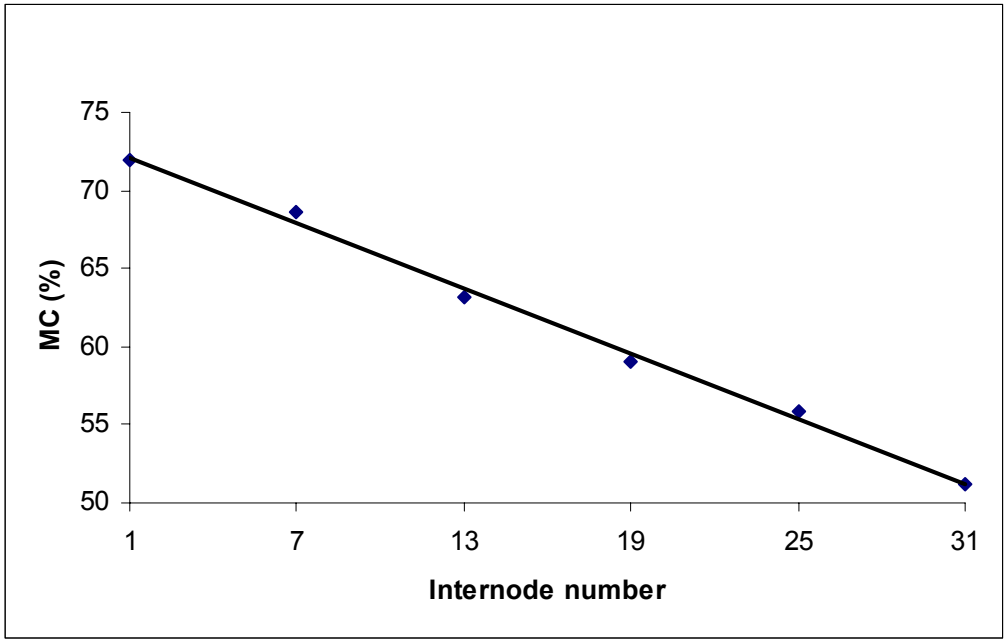

Figure 3-3. Moisture content of three years old bamboo of different internodes.

3.3.3 Fiber Length Characteristics

Figure 3-4 shows the morphology of several macerated bamboo fibers. Figure 3-5 shows the fiber length distribution of one, three, and five year old bamboo. The fiber length range of bamboo was mainly between the ranges of 1.6-3.1 mm. But fiber length as long as 6.4 mm was observed in this study. Comparing to one year old bamboo, three and five year old bamboo had a higher percentage of fibers less than 1.6 mm.

The average fiber length from different horizontal layers of one, three and five year old bamboo is presented in Table 3-2. Outer layer had a significant shorter fiber length than the middle and inner layers. Figure 3-6 also shows bamboo has a large proportion of short fibers in the outer layer.

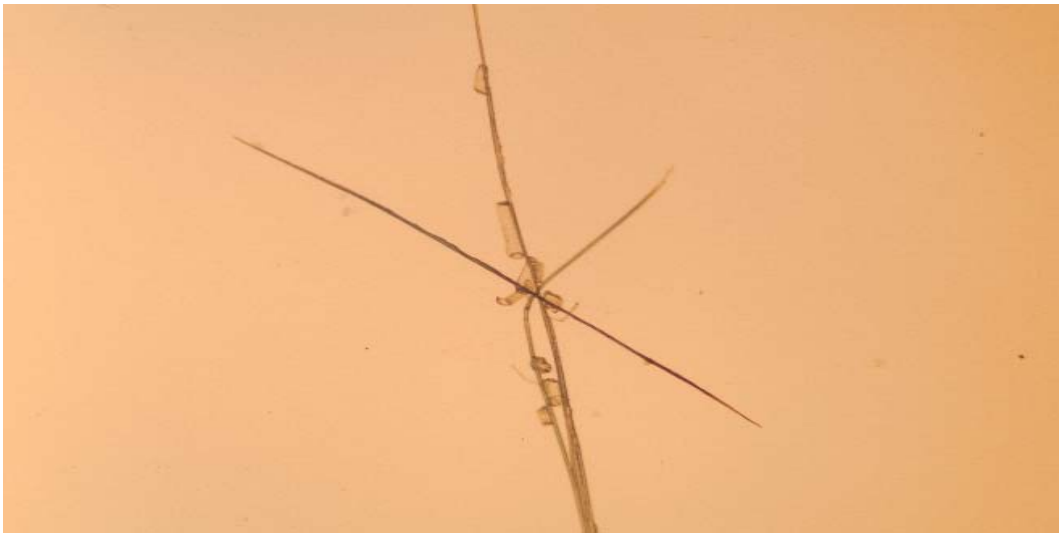

Figure 3-4. A view of the macerated bamboo fibers under microscope (20 × magnified).

Table 3-2. Average fiber length from one, three, and five year old bamboo.

Year	Layer	Fiber Length (mm)	Fiber number measured
One	Outer	2.16	484
	Middle	2.27	401
	Inner	2.19	294
Three	Outer	2.08	321
	Middle	2.32	301
	Inner	2.26	292
Five	Outer	2.03	456
	Middle	2.32	431
	Inner	2.39	307

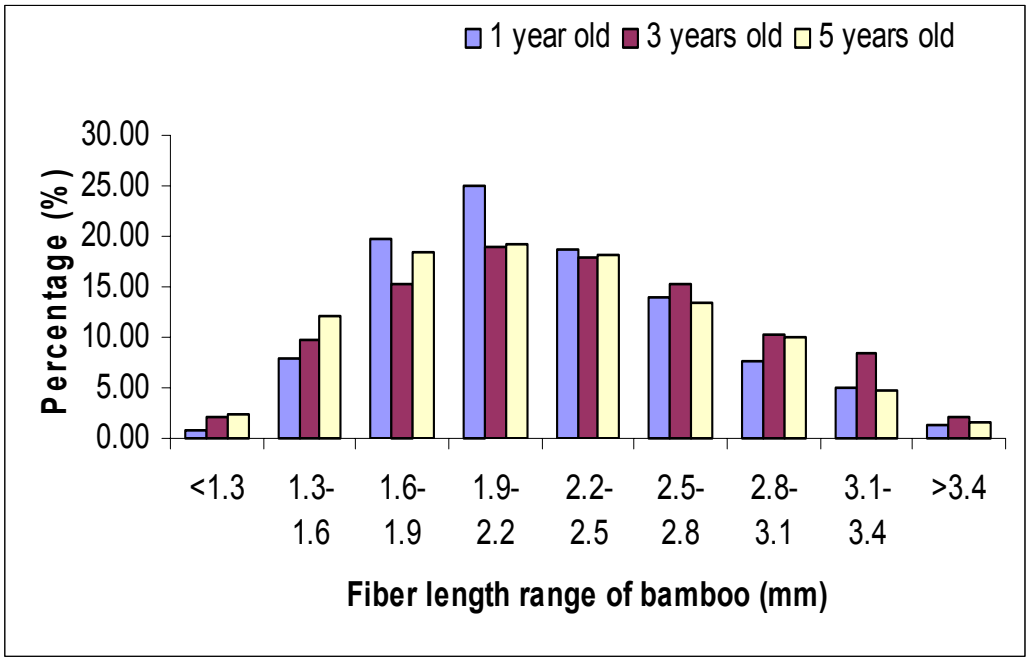

Figure 3-5. Fiber length distribution of different ages of bamboo.

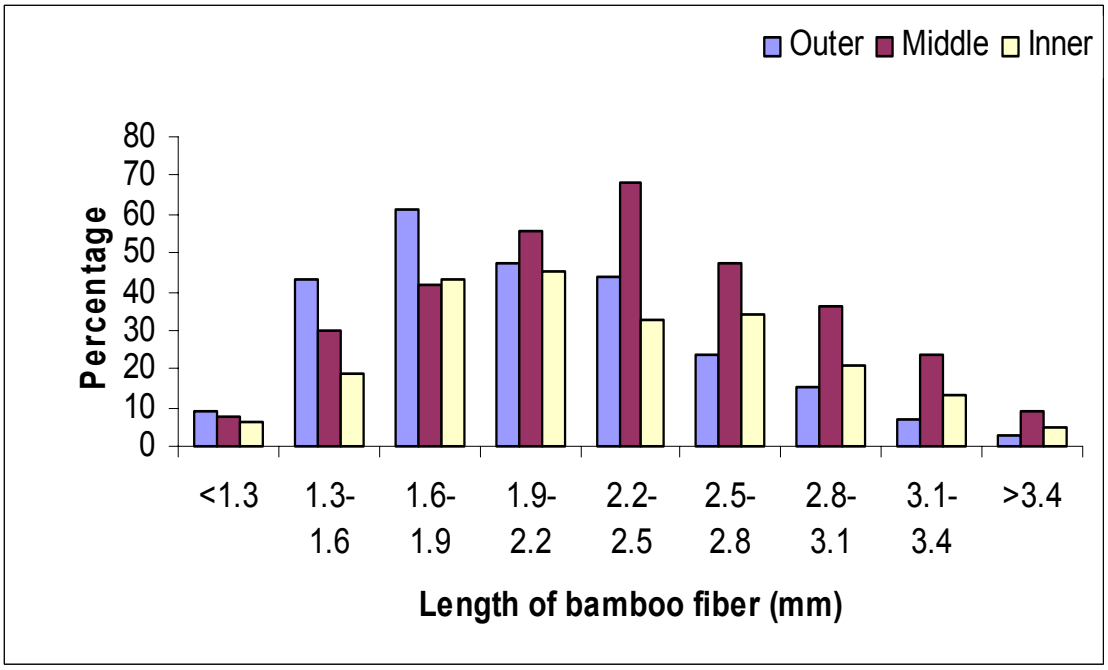

Figure 3-6. Fiber length distribution of different layers of three year old bamboo.

3.3.4 Contact Angle

Contact angle measurements are often the basis for estimations of wetting properties of a material. There are three primary methods applied for contact angle analysis, sessile drop method, Wilhelmy plate or dynamic contact angle method (DCA) and wicking method for powders. In this research, the sessile drop method was used to measure the contact angle of UF resins on the surface of different bamboo layers.

Contact angle of UF resin on the surface of different bamboo horizontal layers was presented in Figure 3-7. The results show that with increasing time after the resin was dropped on the surface of each layer; the contact angle became smaller and then seems to stabilize after it reached equilibrium. The epidermis of bamboo showed the highest contact angle. The inner layer showed the smallest change in contact angle during the 210 second interval. The middle layer of bamboo showed the lowest contact angle.

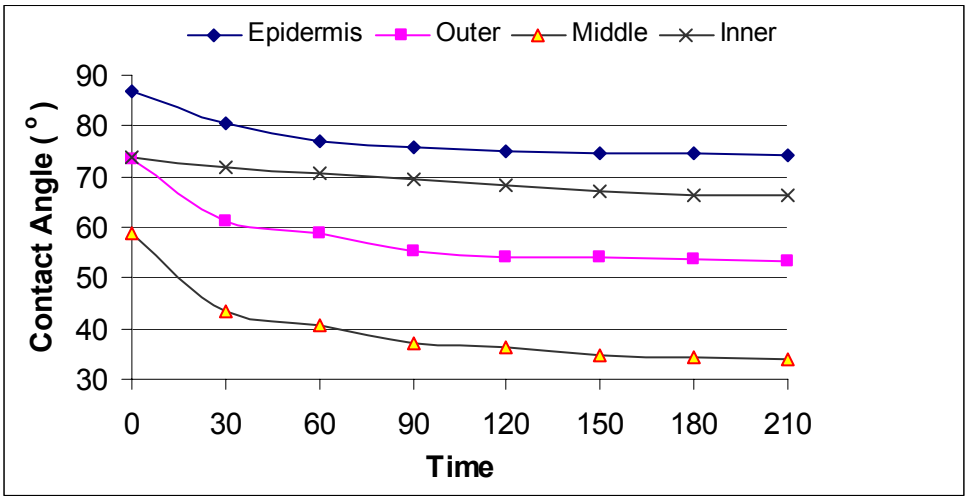

Figure 3-7. Dynamic contact angle of different horizontal layers of bamboo.

3.3.5 Specific gravity

The SG values are listed in Table 3-3. On average, SG of one year old bamboo is significantly lower than that of either year three or five year old culms. But little

difference is shown in SG between year three and year five. It is generally accepted that an increase in density of the culm is mainly due to thickening of the cell wall. Average SG increased about 58% from year one to year three, indicating cell wall thickening occurs mostly in the first two years. The substantial thickening of cell walls up until the second year of growth has been previously reported [Fujii 1985].

Table 3-3. Specific gravity of bamboo [a].

Year	Height	Outer	Middle	Inner
One	Bottom	0.61 (0.05)	0.32 (0.03)	0.29 (0.06)
	Middle	0.63 (0.08)	0.33(0.05)	0.29 (0.04)
	Top	0.63 (0.06)	0.34 (0.02)	0.32 (0.04)
Three	Bottom	0.81 (0.06)	0.60 (0.02)	0.56 (0.02)
	Middle	0.82 (0.04)	0.61 (0.06)	0.55 (0.07)
	Top	0.84 (0.02)	0.60 (0.04)	0.55 (0.04)
Five	Bottom	0.81(0.03)	0.66 (0.02)	0.58 (0.04)
	Middle	0.82 (0.04)	0.66 (0.01)	0.59 (0.03)
	Top	0.84 (0.03)	0.63 (0.02)	0.58 (0.02)

[a] Based on oven dry weight and volume at 12% moisture content.

Height effect was not statistically significant. Nevertheless, the top portions consistently had higher SG than the bottom portion for each age group.

It was interesting to note that substantial difference existed for SG across the cross section of the culms. The SG reduced steadily from the outer to inner layers. The difference is particularly evident on year one. The SG value of outer layers is almost twice that of the inner layer.

3.3.6 Bending properties

The bending and SG data of bamboo is presented in Table 3-4. The effect of vertical sample location along the bamboo culm was not significant while age had a significant effect on the bending strength and stiffness. The bending strength and stiffness of bamboo increased with age. Since the SG varied significantly with age, the specific modulus of rupture (MOR) and modulus of elasticity (MOE) (i.e., MOR/SG, MOE/SG) were calculated. Values for specific MOR were 221, 216, 242 and for specific

MOE 16268, 14346, 17414 respectively for year one, three, and five bamboo, suggesting they had close specific MOR and MOE values. The values indicated that the variation of the bending properties of bamboo is mainly due to the increase in SG during its growth and maturation. The correlation between SG and MOR and MOE of bamboo is plotted in Figure 3-8.

Table 3-4. SG and bending properties of bamboo

Year	Height	SG	MOR (MPa)	MOE (MPa)
One	Bottom	0.49	110.3	7770
	Middle	0.53	119.3	8680
	Top	0.54	117.2	8929
Three	Bottom	0.70	151.0	10039
	Middle	0.71	151.7	10122
	Top	0.72	160.6	10397
Five	Bottom	0.75	186.2	13162
	Middle	0.78	184.8	13410
	Top	0.76	183.4	13307

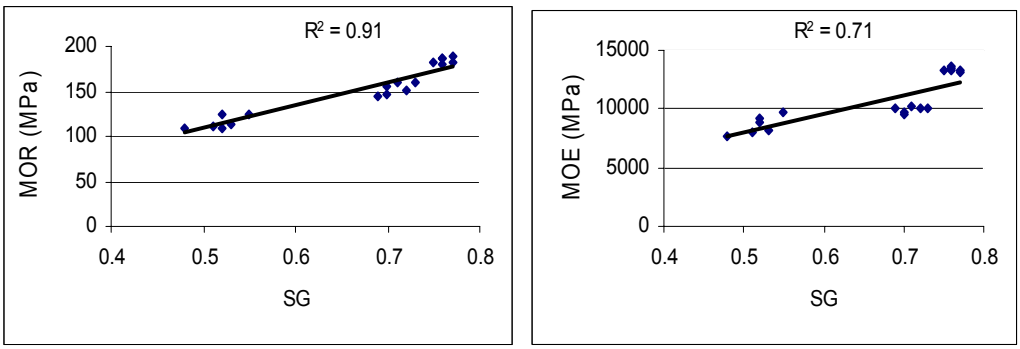

Figure 3-8. Relationship between SG and bending properties.

The effect of SG across the culm on bending properties was evaluated by removing various layers of bamboo across the culm. Table 3-5 summarizes the result. In general, bending properties (MOR and MOE) decreased as the percent bamboo layer removed from outer surface increased. These results are largely attributable to the effect

of SG. The significant correlation between SG and bending properties is plotted in Figure 3-9. Since SG decreased across the thickness of culm walls from the outer surface toward the inner layer, removing the outer layer resulted in lower SG, and lower bending properties. Figure 3-10 presents a schematic diagram of the relationship among the layer removal, change in SG, and properties of bamboo. The results indicate that the outer properties of bamboo have much higher bending properties than the inner layer. The results seem to further suggest that overall bamboo properties can be attributable to the small proportion of the outer layer. The decrease of SG and bending properties of bamboo from the outer layer to the inner layer across the cross section of bamboo culm is considered one of the interesting natural structural characteristics of bamboo.

Table 3-5. Bending properties (MPa) of bamboo with various percentages of bamboo removed on a weight basis from outer or inner surfaces.

Sand treatment	One year old			Three year old			Five year old		
	SG	MOR	MOE	SG	MOR	MOE	SG	MOR	MOE
Control	0.52	115.6	8460	0.72	154.4	10057	0.76	184.8	13293
10% outer	0.49	95.1	8173	0.70	146.2	9892	0.75	173.5	13050
25% outer	0.45	82.1	7177	0.66	118.1	9184	0.71	157.0	12397
50% outer	0.41	63.7	5674	0.62	110.6	8347	0.66	121.8	10115
25% inner	0.62	139.5	12031	0.78	210.1	16337	0.84	237.4	19567
10% inner	0.59	121.6	9313	0.73	182.7	12813	0.79	197.6	14831

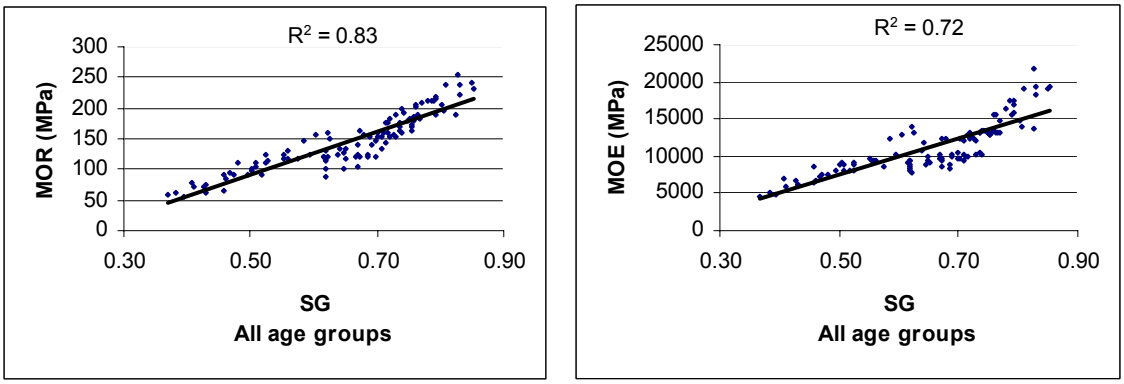

Figure 3-9. Relationship between SG and bending properties.

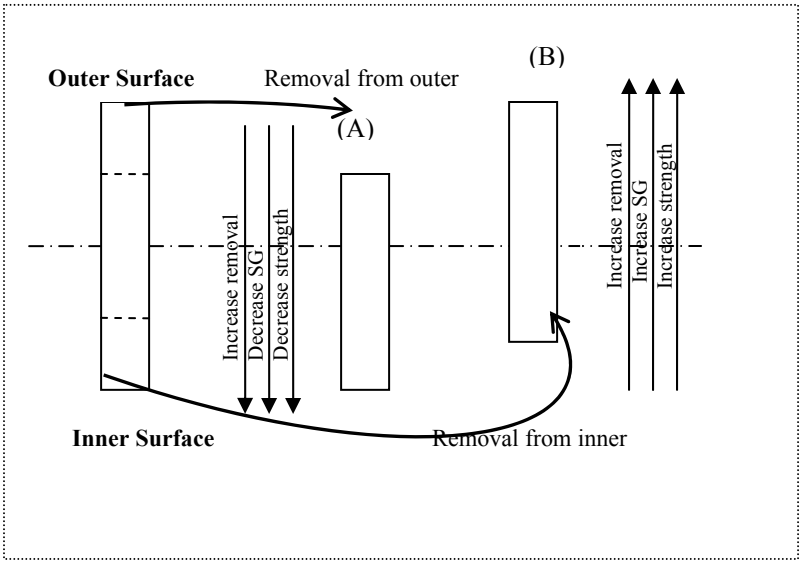

Figure 3-10. Schematic diagram of bamboo cross section showing removal of outer layer (A) and removal of inner layer (B).

3.3.7 Compressive properties

The compressive stress (f_c) and Young's modulus (E_c) strength data parallel and perpendicular to the longitudinal direction of bamboo are presented in Table 3-6.

Table 3-6. Compression strength of bamboo.

Year	Height	SG	Longitudinal		Tangential	
			f_c (MPa)	E_c (MPa)	f_c (MPa)	E_c (MPa)
	Bottom	0.49	47.0 (2.4)	2067 (339)	14.8 (1.1)	277 (61)
One	Middle	0.53	50.9 (3.1)	2776 (362)	16.0 (1.2)	254 (71)
	Top	0.54	55.7 (3.8)	3658 (464)	17.4 (0.5)	359 (75)
	Bottom	0.70	86.8 (1.8)	4426 (491)	33.0 (1.5)	535 (101)
three	Middle	0.71	83.9 (2.8)	4428 (305)	29.8 (3.2)	456 (98)
	Top	0.72	84.0 (3.3)	4660 (451)	33.8 (1.2)	606 (80)
	Bottom	0.75	93.6 (3.6)	4896 (116)	34.1 (2.0)	533 (98)
five	Middle	0.78	86.6 (3.5)	4980 (262)	33.6 (3.0)	527(55)
	Top	0.76	85.8 (5.3)	5185 (330)	35.3 (2.1)	552 (81)

The compressive stress of bamboo perpendicular to the longitudinal direction increased with the increase of bamboo age (Figure 3-11). One year old bamboo had the lowest compressive stress with an average of 16.1 MPa. Five year old bamboo had the highest compressive stress with an average of 34.3 MPa. For the effect of height, the top portion of bamboo had the highest compressive stress. There were no significant difference between bottom and middle portion.

One year old bamboo also had the lowest Young's modulus perpendicular to the longitudinal direction (Figure 3-12). Three year old bamboo had the highest value while the difference between three and five year old bamboo was not statistically significant different. For the effect of height, it is similar to that of compressive stress, the top portion of the bamboo had the highest Young's modulus and there was not a significant difference between bottom and middle portions for Young's modulus.

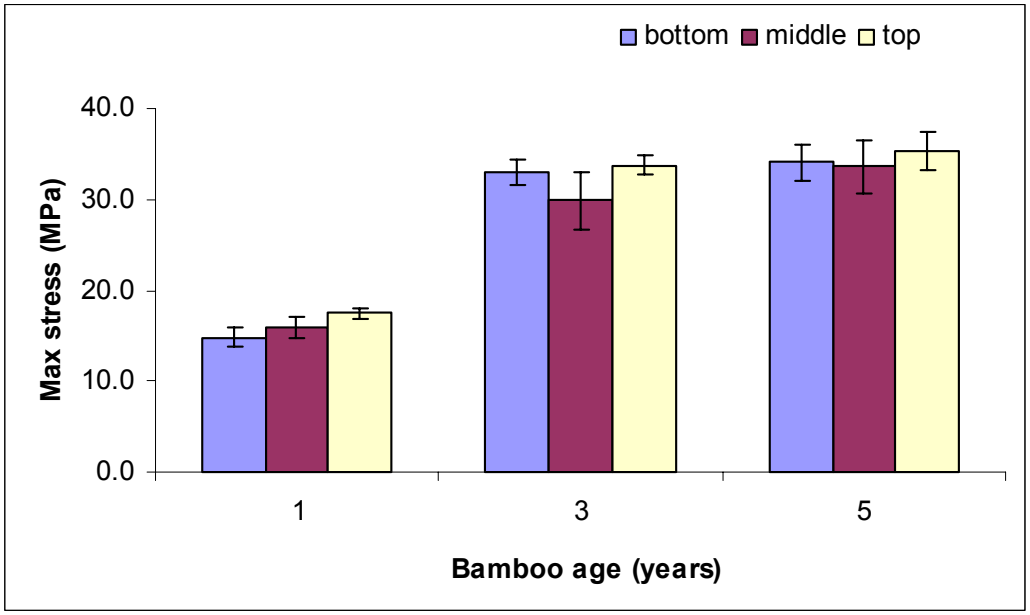

Figure 3-11. Maximum stress perpendicular to the grain of one, three, and five year old bamboo.

Age had a significant effect on maximum compressive stress and Young's modulus parallel to the longitudinal direction. The maximum compressive stress and Young's modulus of one year old bamboo parallel to the longitudinal direction was the lowest with values of 51.2 and 2834 MPa, respectively (Figure 3-13 and Figure 3-14). Analysis of variance also showed that there was no significant difference between different heights of bamboo in maximum compressive stress parallel to the longitudinal direction, while there were significant differences in Young's modulus along the height of bamboo. The top portion of bamboo had a significantly higher Young's modulus than middle and bottom portion. There was no significant difference between middle and bottom portions for Young's modulus.

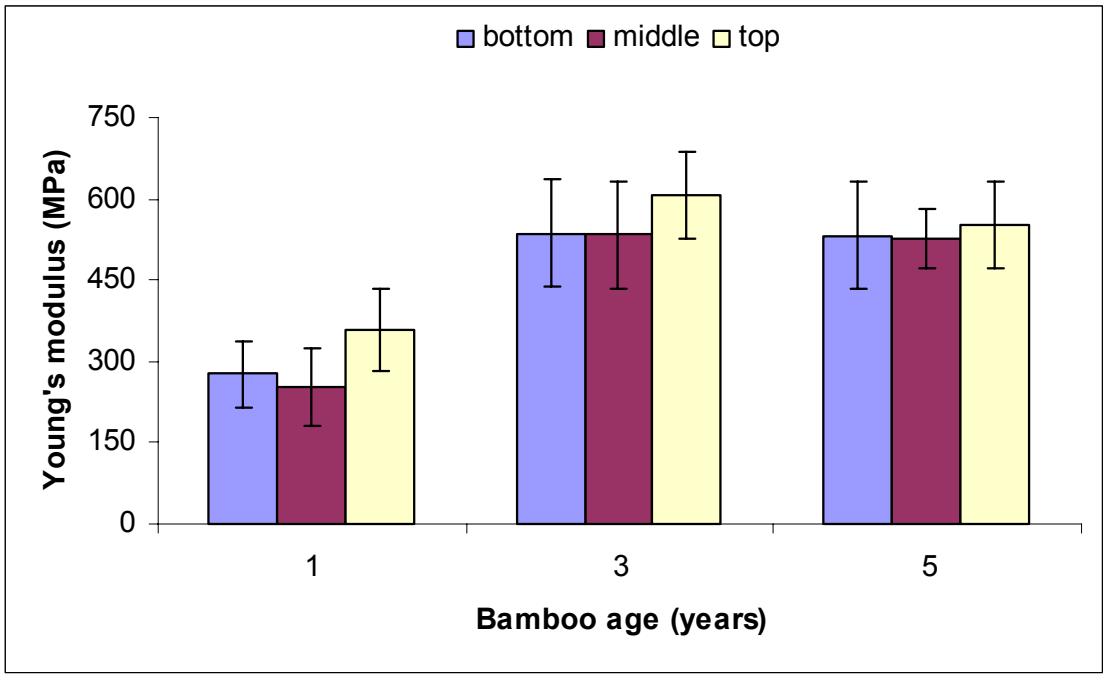

Figure 3-12. Young's modulus perpendicular to the grain of one, three, and five year old bamboo.

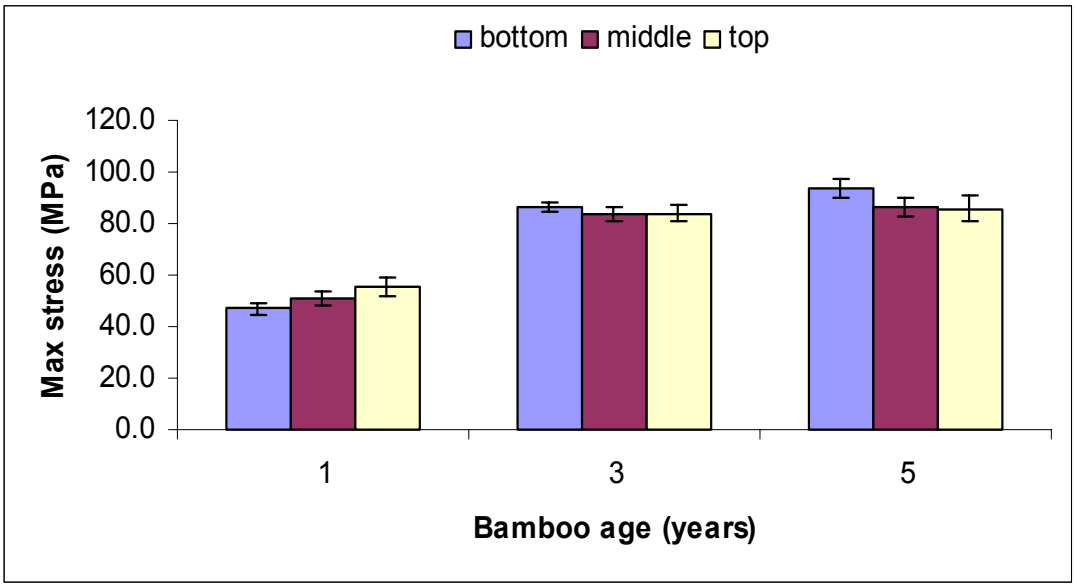

Figure 3-13. Max stress parallel to the longitudinal direction of one, three, and five year old bamboo.

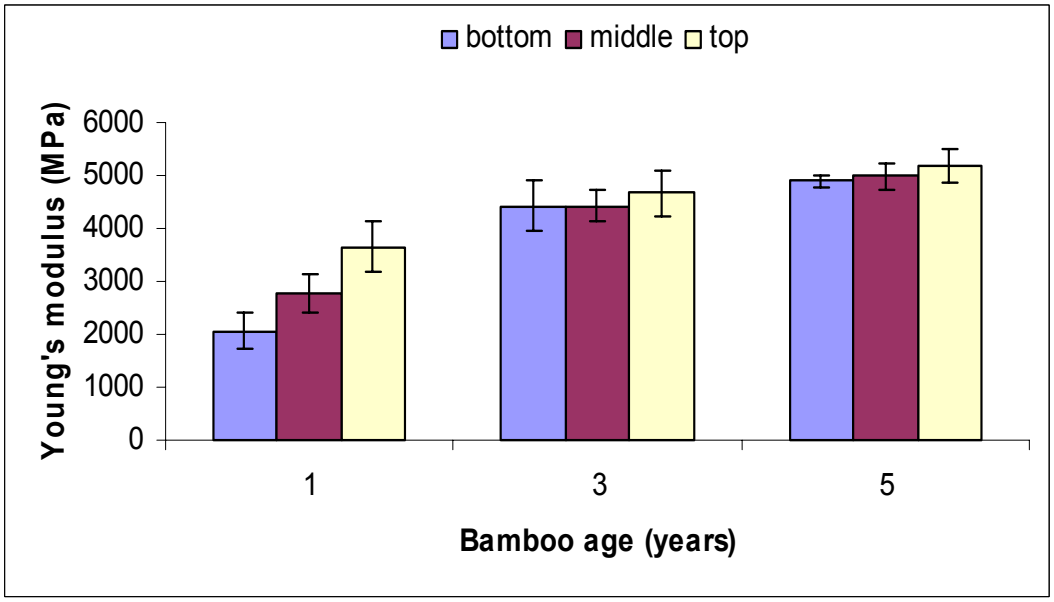

Figure 3-14. Young's modulus parallel to the longitudinal direction of one, three, and five year old bamboo.

Compression properties parallel to the longitudinal direction were significantly higher than that perpendicular to the longitudinal direction. This result clearly showed that bamboo is a material that has directional properties. Also the variability of compression perpendicular to the longitudinal direction was significantly greater due to the weaker bond between fibers and more frequent random break of bond in tangential directions.

3.4 Summary

The vascular bundle distribution had the highest concentration in the outer layer of bamboo. The MC of three year old bamboo in the green condition decreased from the bottom to the top portion. The contact angle of bamboo showed significant differences in each horizontal layer. The outer surface of bamboo had the highest contact angle. The middle layer had the lowest contact angle.

Specific gravity and bending properties of bamboo vary with age and height location as well as horizontal layer. They all increase from one year old to five year old culms. The outer layer had significantly higher SG and bending properties than the inner layer. SG varied along the culm height. The top portion had a consistently higher SG than the bottom portion. The outer layer had a more decisive role in supporting bamboo than the inner layer. Bending strength had a strong positive correlation with SG. In order to industrially use bamboo strips efficiently, it is advisable to not remove outer surface material to produce high strength bamboo composites.

Compression properties parallel to the longitudinal direction were significantly higher than perpendicular to the longitudinal direction. The variability of compression perpendicular to the longitudinal direction was significantly higher than parallel to the longitudinal direction.

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Chapter 4. Medium Density Fiberboard from Bamboo

4.1 Introduction

The global demand for wood fiber appears to be never-ending. Therefore, bio-based materials other than wood are receiving increasing attention as possible alternatives to wood to lessen the harvest demand on forests and assist with forest conservation efforts. Bamboo is an inexpensive and fast-grown resource with favorable physical and mechanical properties comparable to some common wood species. Bamboo has great potential as an alternative to wood for many applications [Lakkad and Patel 1981; Jain et al. 1993; Jassen 1995; Shupe et al. 2002].

The utilization of bamboo in construction has been expanded from its traditional way to include its manufacture into various structural composites and as a reinforcement material. Bamboo based composites in particle form [Rowell 1988; Chew et al. 1992; Kasim 2001]; strand form [Lee et al. 1996; Naresworo and Naoto 2001]; fiber form [Chen et al. 1989; Kumiko et al. 2001; Xu et al. 2001] and combined with cement [Rahim 1996], plastics [Chen and Hua 1991], plywood [Chen an Hua 1991; Heng et al. 1998], and new composite panels have been studied extensively.

Bamboo fibers, as a type of cellulose fibers, present many advantages compared to synthetic fibers which make them attractive as reinforcements in composite materials. They come from an abundant and renewable resources at low cost [Gatenholm and Felix 1993], which ensures a continuous fiber supply and a significant material cost saving to the plastics industry [Taib 1998]. Cellulose fibers, despite their low strength, can lead to composites with high specific properties because of their low densities [Sanadi et al. 1996]. As a result, bamboo fibers were frequently used as reinforcement materials in composites. Jindal [1984] reported that bamboo fiber reinforced plastic composites at nearly one eighth the density of mild steel possess strength more or less equal to that of mild steel. Thermogravimetric analysis of *Dendrocalamus strictus* bamboo fibers indicated bamboo fiber is suitable as reinforcement for making composites even with thermoplastic matrix materials whose processing temperature is less than 300 ^{o}C. A previous study revealed the mechanical properties of bamboo-glass reinforced

polypropylene hybrid systems depend on fiber weight ratios, fiber length, and adhesion characteristics between the fibers and the matrix [Thwe and Liao 2000]. High tensile strength was observed in the manufactured bamboo fiber reinforced polymeric composites [Deshpande et al. 2000]. Short bamboo fiber reinforced epoxy composites showed strong resistance capability to both strong acid and base and the composites have the highest tensile load with fiber length of 30 mm [Rajulu et al. 1998]. Surface modification of bamboo fibers with polyesteramide polyol improved the water resistance and mechanical properties of bamboo/epoxy, bamboo/polyester composites [Saxena 2003].

Bamboo/wood composite fiberboards have been manufactured by using bamboo and wood fibers as the raw materials. Increasing the mixing ratio of bamboo fiber improves the MOR, MOE retention ratio, and linear expansion of boards after boiling [Zhang et al. 1995]. It was shown that partial substitution of spruce with bamboo did no affect quality and properties of MDF panels [Van Acker et al. 2000]. Matsumoto et al. [2001] studied the properties of bamboo fiberboard and showed a flat density profile at any density level. The MOE values of the fiberboard were about the same as wood fiberboard, but the MOR was lower. The IB strength was higher than that of wood fiberboard. Also bamboo fiberboard showed lower water absorption and thickness swelling than wood fiberboard. Acetylation of bamboo fiber can produce a more hydrophobic fiber whose equilibrium moisture content is significantly reduced as compared to untreated fiber [Rowell and Norimoto 1987].

The previous chapters presented the difference in chemical composition and mechanical properties of one, three, and five year old bamboo. This chapter will explore the physical and mechanical properties of fiberboards manufactured from different age bamboo fibers. Fiberboard with three levels of UF resin content were manufactured to establish a better understanding of the effect of the resin content on the physical and mechanical properties of bamboo fiberboards. Also, Chinese tallow (*Sapium sebiferum*) tree wood fibers were acquired and tallow wood fiberboards were manufactured to be used to compare with the physical and strength properties of bamboo fiberboards.

4.2 Materials and Methods

Raw Materials

Bamboo species *(Phyllostachys pubescens)* was obtained from the Kisatchie National Forest, Pineville, La, USA. Two representative bamboo culms for each age group were harvested. The nodes were removed before defiberization. No attempt was made to remove the epidermis of the bamboo. The bamboo chips (approximately $0.5 \times 1 \times 2$ cm) were steamed for 30 minutes under atmospheric pressure. The material was then mechanically refined at a disc clearance of 0.254 mm using a Sprout-Waldron model 105-A 305-mm-diameter atmospheric refiner. Tap water was added to the chip feed to improve consistency and to remove furnish from the refiner case. Excess water from the fiber slurry was removed via a laboratory vacuum in a Deckerbock. The fiber mat removed from the deckerbock was broken into small bundles and was then dried at 60 ^{o}C for 24 hours. These dried fiber bundles were then separated into fibers in the refiner again. The fibers were conditioned to a moisture content of 3-4 percent prior to panel assembly.

Fifteen year old tallow trees were harvested in Pineville, La, USA. The average diameter at the breast height was 13 cm. Wood materials were chipped from debarked tallow wood. The tallow chips were then steamed for 5 minutes and then refined by the same processes as that of bamboo fibers.

Table 4-1. General information of bamboo and tallow.

Species/year	Breath height		Total height (m)
	wall thickness (mm)	Diameter (cm)	
Bamboo/one	8.15	7.81	13.15
Bamboo/three	7.87	8.12	12.58
Bamboo/five	7.94	8.46	13.65
Tallow/fifteen	--	13.0	--

A liquid urea formaldehyde resin (Chembond YTT-063-02) was obtained from Dynea Co., Winnfield, La, USA. The solid content of the resin was 60% and Formaldehyde content was 0.1~0.25% by weight. It was used for all of the panels.

Mat forming and Panel Fabrication

To prepare each panel, furnish was weighed and then placed in a rotating drum-type blender. For mixed mats, The UF resin, in an amount equal to 8 percent of the oven-dry weight of the furnish was then weighed and applied by using a pneumatic single spray gun applicator.

After blending, each furnish was carefully felted into a 15.2×15.2 cm box. Neither furnish type was oriented during the forming process. The moisture content of the mat was approximately 8-10% before hot pressing. The mat was transferred to a 60×60 cm single opening hot press with the platen temperature at 177 ^{o}C. Press time was 3.5 minutes after platen closure. Board pressure during closing was 2.76 MPa and was increased to 3.45 MPa after reaching the target thickness. Stops were used to control a target thickness of 0.645 cm. After pressing, all the panels were cooled overnight by hot stacking at room temperature. The panels were later trimmed to a final size of 30×30 cm.

Sampling and Testing

Each panel was conditioned at room temperature for 24 hours before being cut into 3 static bending specimens of 5×25 cm and 2 dimensional stability specimens of 5×20 cm. Specimens were conditioned in a climate chamber of 50% relative humidity and 26 ^{o}C for two weeks before testing.

Three point static bending tests for modulus of rupture (MOR) and modulus of elasticity (MOE), and internal bond strength (IB) test were performed in accordance with ASTM D1037 [ASTM 1994] using an Instron universal testing machine. Four specimens (5×5 cm) for IB testing were cut from each bending specimen. For dimensional stability evaluation, specimens were immersed in water for 24 hours at ambient temperature. Water absorption (WA) and thickness swelling (TS) were performed in accordance with ASTM D1037 [ASTM 1994].

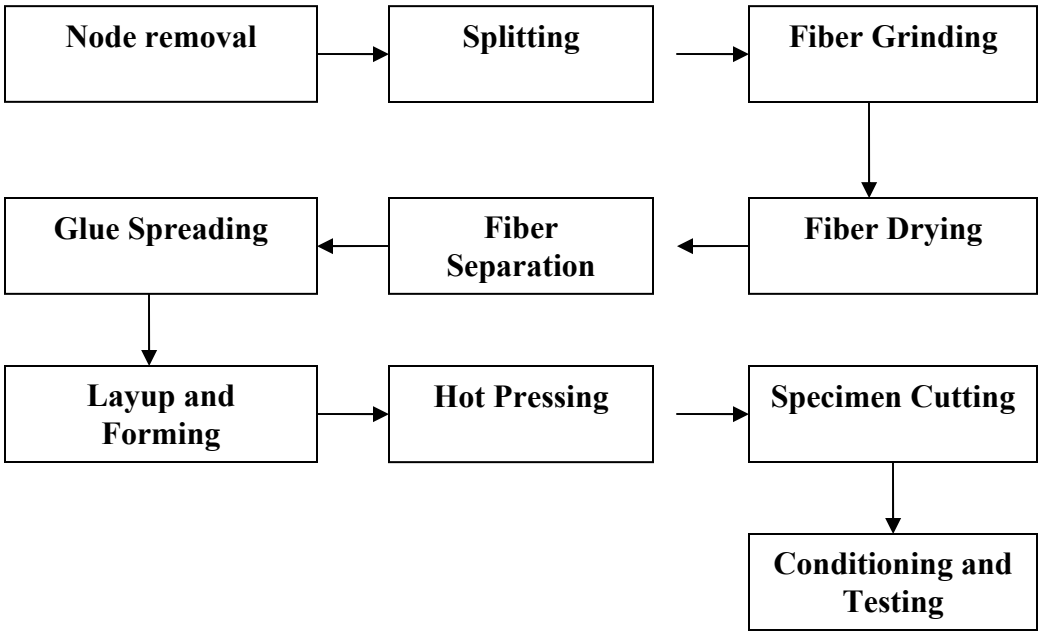

Figure 4-1. Flow chart of the fiberboard manufacturing process.

Fiber size distributions of bamboo fibers were determined on a Bauer-McNett screen system. Three samples of each type, weighing 100 g each, were processed and their results averaged. All size classifications were conducted on air-dry material.

Effects of bamboo age and resin content on the properties of composites were evaluated by analysis of variance at the 0.05 level of significance. Tukey's Studentized Range tests were used to determine significant differences among mean values.

4.3 Results and Discussion

4.3.1 Fiber Size Distribution

The fiber size distribution of one, three, five year old bamboo and tallow wood is shown in Table 4-1 and Figure 4-2. For the effect of age on the fiber size distribution, one year old bamboo showed a significantly higher percentage of fibers retained on No 20 mesh sieves. Three and five year old material had significantly higher percentage of

fibers (14% and 12%, respectively) retained on sieves bigger than 60 mesh than one year old bamboo fibers (6%). The reason for this difference is mainly due to the different machinability properties of bamboo at different age. One year old bamboo had a relatively low SG of about 0.4-0.5. The chemistry study in Chapter 2 also revealed that one year old bamboo has lower lignin content, which acts as bonding agent in strengthen the connection between bamboo components. The SG of three and five year old bamboo (0.65-0.75) was much bigger than one year old bamboo. During the defiberation process, fibers can then be separated more easily and completely than three and five year old bamboo. At the same time, the fibers retained on the No 10 sieve of three year and five year old bamboo were mainly in the form of fiber clumps or aggregates which were caused by incomplete separation during refinement. Such incomplete separation of fibers would adversely affect the uniform adhesive distribution on fibers and thus affect the bonding between fibers and the strength properties of the boards manufactured. It is interesting to note that steaming had a significant effect on the morphology of bamboo fibers.

Compared to bamboo fibers, tallow fibers showed a higher percentage of fibers (15%) retained on sieves larger than 60 mesh. The results also showed that bamboo and tallow had different fiber size distributions.

Table 4-2. Fiber size distribution of bamboo and tallow wood fibers.

Mesh size	Weight percentage (%)			
	Bamboo age			Tallow
	one	three	five	
No10	11.9	2.3	2.4	30.2
No20	39.3	30.9	29.7	21.3
No35	21.2	23.6	31.5	21.4
No60	21.8	27.5	24.9	11.5
No80	1.4	3.7	4.6	5.5
No100	0.7	2.3	2.2	2.3
>100	3.6	9.7	4.7	7.8

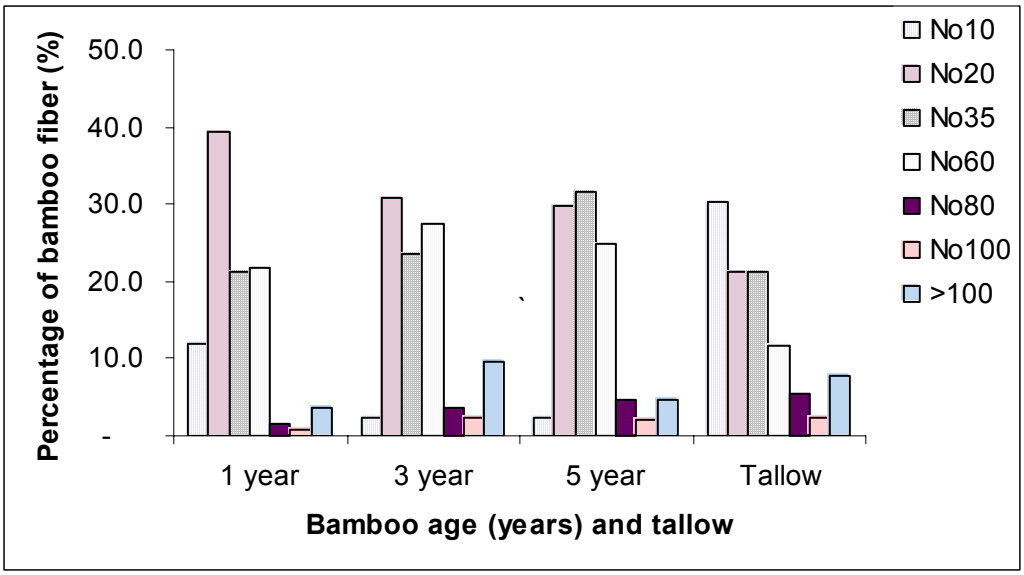

Figure 4-2. Fiber size distribution of one, three, five year old bamboo and tallow wood.

4.3.2 Physical and Mechanical Properties of the Fiberboard

The results of the physical and mechanical properties of one, three, and five year old bamboo and tallow fiberboards are presented in Table 4-2. The target density of the board was 0.75, while all boards made had a density between 0.70-0.74. The density of tallow fiberboard was 0.751. The lower panel density values for the bamboo panels were largely due to the spring back of the bamboo fiberboards after manufacture. Matsumoto et al. [2001] in his study also revealed that the spring back of bamboo fiberboard was greater than that of wood fiberboard. The results show that in general, the physical and mechanical properties of bamboo panels are comparable to those properties of conventional MDF boards.

The analysis of variance result and TUKEY comparison for the physical and mechanical data of bamboo fiberboards are listed in Table 4-4.

Table 4-3. Physical and mechanical properties of bamboo and tallow fiberboards.

Composite Source				MOR	MOE	IB	WA	TS
Fiber tree/ age (years)	Resin content	SG	CR[1]	MPa	GPa	MPa	%	%
Bamboo/one	6%	0.718	1.44	19.0	2.18	0.38	101	43
	7%	0.705	1.41	23.9	2.72	0.85	83	32
	8%	0.714	1.43	27.6	3.07	1.06	77	23
Bamboo/three	6%	0.716	1.02	10.7	1.63	0.48	110	47
	7%	0.727	1.04	17.1	2.50	0.90	78	37
	8%	0.715	1.02	20.0	2.64	1.20	68	29
Bamboo/five	6%	0.731	1.04	21.6	2.19	0.70	105	37
	7%	0.730	1.04	23.6	2.47	1.07	79	30
	8%	0.734	1.05	26.1	2.76	1.16	72	25
Tallow	8%	0.751	1.25	29.6	2.92	0.80	76	19

[1] Compaction ratio=panel density/material density.

Table 4-4. ANOVA table and Tukey comparison for bamboo fiberboards.

		MOR	MOE	IB	WA	TS
Year		<0.0001	0.0053	0.0003	<0.0001	<0.0001
Resin Content		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year× Resin content		0.0909	0.1042	0.2024	0.007	<0.0001
Tukey comparison	1 year	A	A	B	B	B
	3 year	B	B	A	A	A
	5 year	AB	AB	A	A	A
	6% RC	C	C	C	C	C
	7% RC	B	B	B	B	B
	8% RC	A	A	A	A	A

Figure 4-3 and Figure 4-4 show the effect of resin content on the MOR and MOE of bamboo fiberboards. With the increase in the resin content, the bending

properties showed a significant increase. One year old bamboo fiberboard showed higher MOR and MOE. The main factor is the higher compaction ratio of one year old bamboo compared with relatively lower compaction ratios of three and five year old bamboo. Another factor is the more complete separation of bamboo fibers during the defiberation process and a more even distribution of adhesive during adhesive spreading.

The bending strength properties of one year old bamboo fiberboard at 8% resin content was about the same as tallow wood fiberboard at 8% resin content.

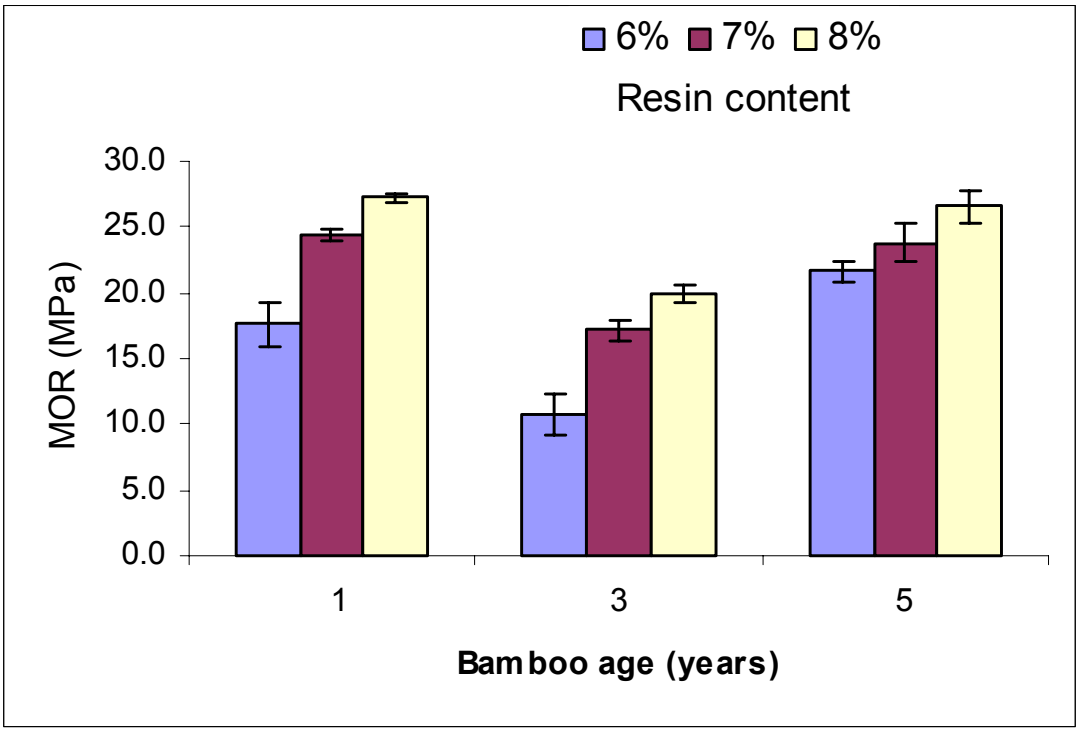

Figure 4-3. MOR of fiberboards manufactured with different resin contents.

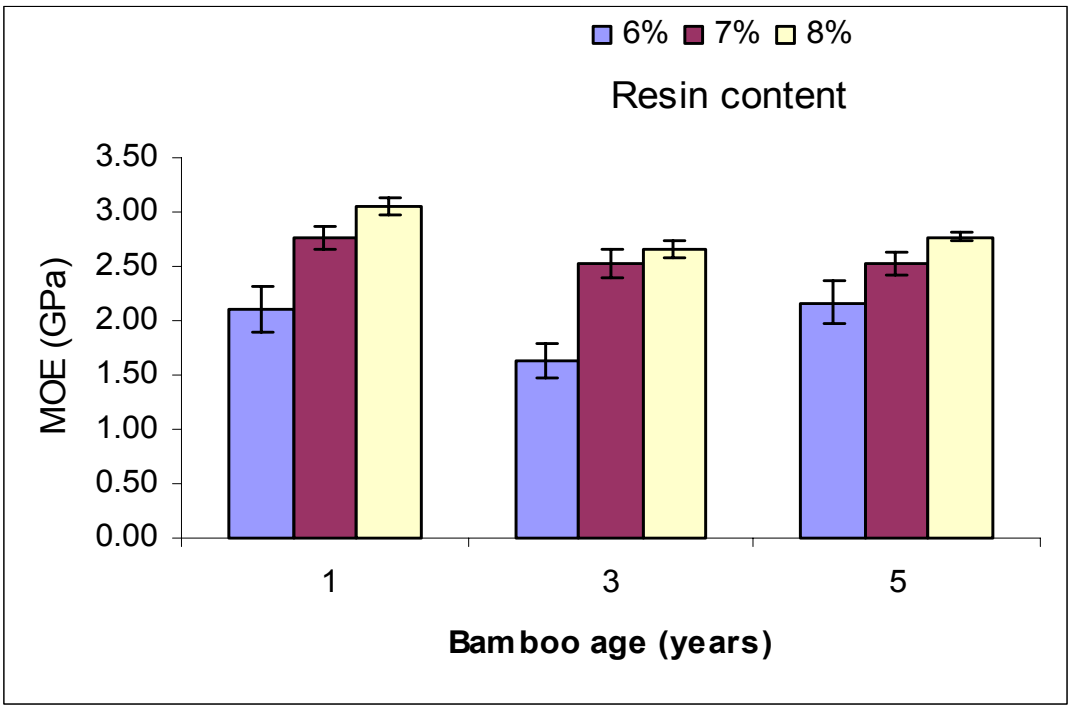

Figure 4-4. MOE of fiberboards manufactured with different resin contents.

The IB strength of one, three, and five year old bamboo fiberboard with different resin contents is presented in Figure 4-5. With the increase in the resin content, the IB strength increase accordingly. The IB strength showed a reverse trend compared to bending properties. Three and five year old bamboo showed significantly higher IB strength than one year old bamboo, which is mainly due to the resin distribution on bamboo fibers. One year bamboo has lower density thus for a certain weight of fibers, one year bamboo has more fibers and thus more surface area. Since the resin content is equal, one year bamboo has less resin amount on the fibers. Another factor might be the strength differences of individual fibers. One year old bamboo fiber likely had much lower tensile strength. With the thickening of bamboo fiber cell wall, the fiber matures and strengthens gradually with age. It is also interesting to note that the IB strength of one year old bamboo at 8% resin content was higher than that of tallow wood fiberboard at the same resin content level.

Dimensional stability of bamboo fiberboards made at all levels of resin application was poor. The water absorption and thickness swelling are presented in Figure 4-6 and Figure 4-7. At higher resin content, the dimensional stability improved to some extent. But even at 8% UF resin level, the result is still not satisfactory. This result indicates wax is needed to improve the dimensional stability of bamboo fiberboards manufactured with UF resin.

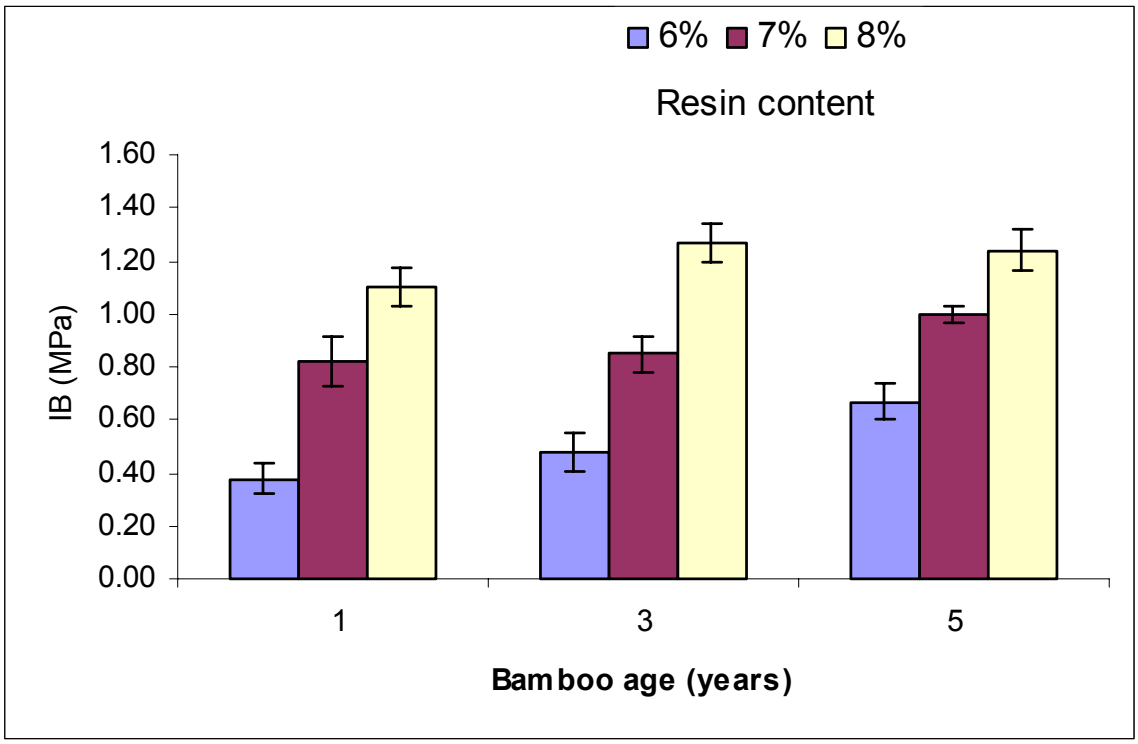

Figure 4-5. IB of fiberboards manufactured with different resin contents.

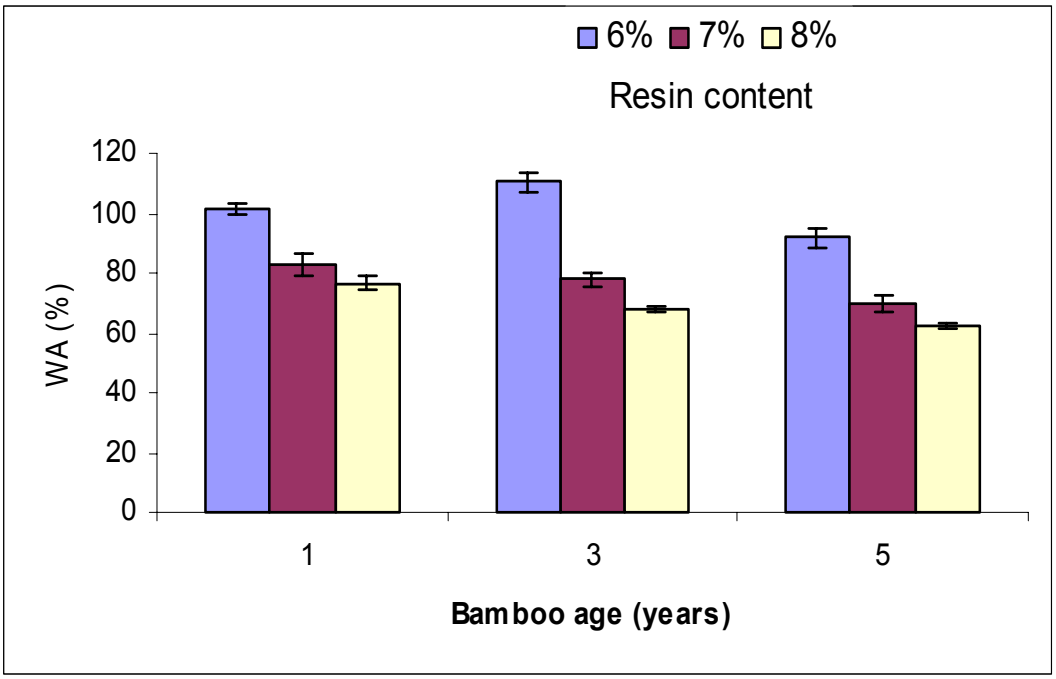

Figure 4-6. WA of fiberboards manufactured with different resin content.

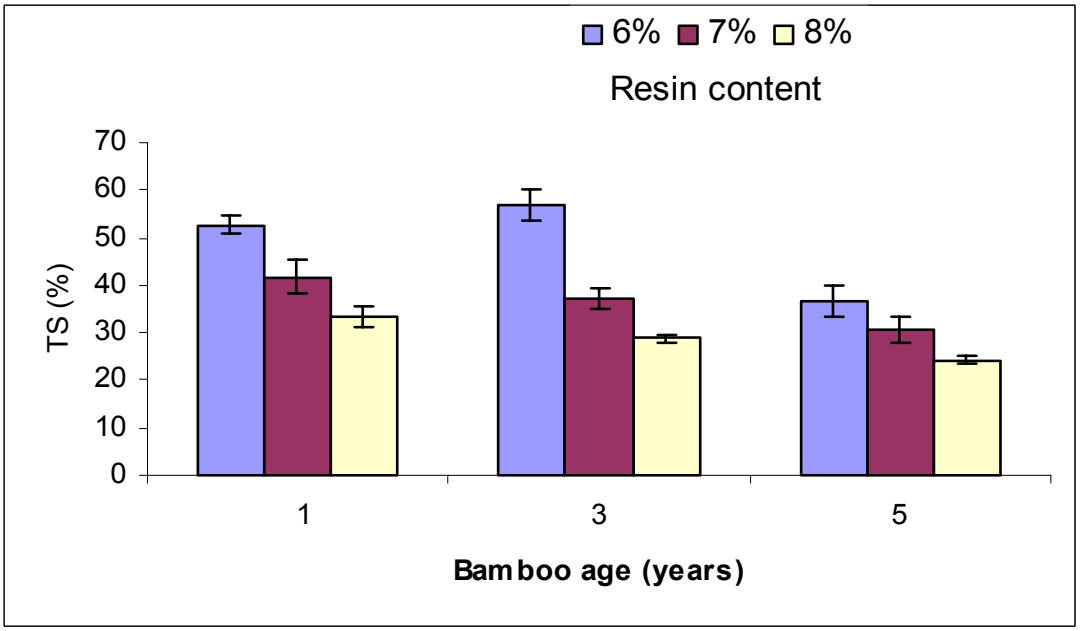

Figure 4-7. TS of fiberboards manufactured with different resin content.

4.4 Summary

The purpose of this study was to investigate the physical and mechanical characteristics of medium density fiberboard from one, three, and five year old bamboo fibers bonded with urea formaldehyde resin. The fiber morphology of one, three, and five year old bamboo acquired under the same treatment process showed significant differences. One year fibers showed a higher percentage of larger fiber size, less percentage of fines, and less lumpy fiber clumps than three and five year old bamboo fibers.

At the same panel density level, the strength properties of manufactured fiberboard increase with greater level of resin content. Culm age had a significant effect on board properties. Fiberboard made with one year old bamboo at 8% resin content level showed the highest MOR and MOE among the bamboo panels, which was largely due to a higher compaction ratio. Fiberboard made with five year old bamboo at 8% resin level had the highest internal bond strength, which was largely attributed to higher resin recovery on the fiber surface compared with one year old bamboo fibers. Three year old bamboo fiberboards showed lower IB compared with five year old bamboo lies in its higher fine percentage.

The MOR and MOE values of the one year old bamboo fiberboard at 8% UF resin content level were about the same as that of tallow fiberboards, but the internal bond strength was higher than that of tallow fiberboard. The dimensional stability of bamboo fiberboard was comparable to that of tallow fiberboard. Wax is needed to improve the dimensional stability of bamboo fiberboards.

Bamboo contains a significant amount of sugar components. Further study should be done to investigate the durability of fiberboard from bamboo fibers.

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Chapter 5. Conclusions

There are several conclusions that can be derived from this study:

1. Except one year old bamboo, alcohol-toluene and hot water extractive contents increased from the bottom to the top portion. Alcohol-toluene extractive content showed a continuous increase from one year old to five year old bamboo. Hot water extractives showed an increase from one year old to three year old bamboo and then decreased from three year old to five year old bamboo.

2. Holocellulose and alpha-cellulose content increased from the bottom to the top portion. There was no significant variation in Klason lignin content and ash content from the bottom to the top portion. Outer layers had the highest holocellulose, alpha-cellulose, and Klason lignin contents but had the lowest extractive and ash contents. The epidermis had the highest extractive and ash contents but had the lowest holocellulose and alpha-cellulose contents.

3. The vascular bundle distribution had the highest concentration in the outer layer. The MC of three year old bamboo in green condition decreased from the bottom to the top portion. The contact angle of bamboo showed a significant difference in each horizontal layer. The outer surface of bamboo had the highest contact angle. The middle layer had the lowest contact angle.

4. Specific gravity and bending properties of bamboo vary with age and height location as well as horizontal layer. They all increase from one year old bamboo to five year old bamboo. The outer layer had significantly higher SG and bending properties than the inner layer. SG varied along the culm height. The top portion had a consistently higher SG than the bottom portion. The outer layer had a more decisive role in supporting bamboo than the inner layer. Bending strength had a strong positive correlation with SG.

5. Compression properties parallel to the longitudinal direction were significantly higher than that of perpendicular to the longitudinal direction.

6. One year old fibers showed a higher percentage of larger fiber size, less percentage of fine fibers retained on sieves higher than 60 meshes, and less lumpy fiber clumps than three and five year old bamboo fibers due to the refinement process.

7. At the same panel density level, the strength properties of fiberboard increased with greater levels of resin content. Age had a significant effect on board properties. Fiberboard made with one year old bamboo at 8% resin content level had the highest MOR and MOE among the bamboo panels, which is largely due to a higher percentage of larger fiber size. Fiberboard made with five year old bamboo at 8% resin level had the highest internal bond strength, which was largely attributed to the higher resin recovery on old bamboo fibers.

8. Bamboo fiberboards showed comparable physical and mechanical properties with tallow wood fiberboards. The dimensional stability of bamboo fiberboard was not satisfactory. Wax was recommended to improve the dimensional stability.

Vita

Xiaobo Li was born on September 16, 1976 in Longtan, Xiangxiang, Hunan, China. He got his Bachelor of Science degree in wood science from Beijing Forestry University in 1999. The author continued his academics as a graduate at Chinese Academy of Forestry (CAF) from 1999 to 2002. He received a Master of Science degree in wood science from CAF in 2002. The author was then joined the wood science and forest products program in Louisiana State University as a master student under the supervision of Dr. Todd F. Shupe in April, 2002. The author's study addressed the physical, chemical and mechanical properties of bamboo and its utilization potential in fiberboard manufacturing.