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RESEARCH ARTICLE

THE EFFECTS OF ANATOMY AND PHYSICAL PROPERTIES ON THE STRENGTH OF CULTIVATED FOUR-YEAR-OLD *BAMBUSA VULGARIS*

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ABSTRACT

The anatomy and physical properties of cultivated four (4) years-old bamboo *Bambusa vulgaris* were studied in order to determine their strength. The matured 4 year-old culms of the bamboo were randomly selected and harvested from the Bambusetum Plot located in the Forest Research Institute Malaysia (FRIM) in Kepong. The anatomy study focussed on the vascular bundles and fibres found at the internodes and nodes eight at the outer, middle and inner cross-section of the bamboo. The sizes of the vascular bundle's length, width, fiber length, diameter, fiber lumens diameter, fiber walls thickness and fiber Runkle's ratio were measured for internodes, nodes, located in the cross-section of the bamboo culms. The physical study focussed on the moisture content, basic density and dimension stability. The strength study focused on the tensile parallel to the grain and shear tests. All studies on the anatomical, physical and strength were conducted on internodes and nodes eight of the *B. vulgaris*.

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INTRODUCTION

Bamboo is a fast-growing species and can matured within 3 - 4 years after cultivating. Bamboo can be expected to provide material to replace wood in the coming future. This plant may be an alternative raw material and timber-based industries in the future. The wide exploitation of timbers either from forests of plantation would not be able to sustain for a long duration due to high demand. Research and development appertaining to all aspects of bamboo silviculture, propagation, processing, properties and utilization of wild grown have been augmented. However, a study on cultivated bamboo only confined to certain selected species (Azmy *et al*., 2007). Data on the properties such as anatomical and structural properties were scanty. The properties of the physical and mechanical of bamboo have been studied all over the world. The information on the relationship between the anatomical, physical and strength properties of this species is incomplete. *B. vulgaris* possesses an excellent physical and strength properties.

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The bamboo physical properties such as moisture content, specific gravity, maximum shrinkage (tangential, radial and volumetric), roughness and wet ability have been studied. The tension parallel to grain, the static bending and compression roller shear test for small size specimens also were carried out. The strength and durability are dependent on the anatomical features and physical properties of the bamboo (Abd. Latif and Tamizi, 1993; Liese, 1985; Razak, 1998). Razak *et al*. (2010) in their studies on the anatomical and physical properties of cultivated bamboo support this statement. Information on the anatomical features of bamboo can be used to determine their possible proper utilization. Traditional bamboo crafts such as handicraft, basketry, and high-value-added products of panels, parquets, furniture and low technology construction materials are utilized extensively in the rural areas. *B. vulgaris* is the most popular tropical bamboo species and are easy to cultivate. This bamboo possesses thick culms walls and has uniform sizes between the nodes and internodes. These properties make them suitable as materials for industrial usage. The application of bamboo as potential replacement for wood requires an understanding of this material such as the anatomy, physical and strength properties at different location and position along the bamboo culms. The objectives of the study were to determine the relationship between the anatomy features, physical and strength properties of four (4) year-old bamboo culm of the *B. vulgaris*.

MATERIALS AND METHOD

Culms of the cultivated four (4) year-old bamboo *B. vulgaris* were harvested from a Bambusetum research plot in FRIM, Kepong, Selangor, Malaysia. The culms of this age were found suitable for industrial uses (Abd. Latif and Tamizi, 1993; Razak *et al*., 2010). The culms had their age verified according to their planting tags. The culms cut at about 30 cm above ground level. These culms took randomly selected clumps with a diameter ranging from 8-12 cm measured in diameter at breast height. Each culm marked and cut at internodes 8in order, to minimize sap evaporation; prevent fungal and insect attacks on the bamboo. An end-coating paint was applied to the cut surfaces before the samples were transported to the laboratory. TEN (10) bamboo culms in total were sampled for this study.

- **Culms Preparation:** The culms were divided based on location in the culms wall (outer, middle, and inner layers). The intended samples for anatomical investigations were immediately immersed in formalin-acetic-acid (FAA) after cutting and kept in bottles. Solution of FAA consists of 90% ethanol (conc. 70%), 4% glacial acetic acid and 6% formaldehyde (conc. 37-48%) (Razak, 1998).
- **Anatomy Assessment:** The assessment followed a technique developed by Abd. Latif and Tamizi (1993) with some changes made in the measurement and counting the distribution of the vascular bundles on the bamboo cross-section surfaces. The anatomical study of the bamboo with two locations (node and internode) and three (3) positions (outer, middle and inner layers) were studied. The sizes of the vascular bundles were measured by the scanning electron microscope (SEM) images through it measuring tools.

Determination of Fiber Morphology & Maceration

The bamboo of size 20 mm x 10 mm x culm wall thickness was cut tangentially and divided into three (3) similar samples (inner, middle, outer). Each sample was sliced radially into match-stick sizes. Macerates then were prepared from match-stick sizes bamboo by immersing g them in a solution of glacial acetic acid and hydrogen peroxide (30% conc.) at ratio 1:1. The solution then was heated over a water bath inside a fume chamber for 2-3 hrs until the sample became soft and whitish. A few drops of sodium hydrogen carbonate crystals was added to neutralize the acid before the mixture was decanted and washed with distilled water. A thorough shaking of the mixture was done to separate the individual fibers. Safranin was used to color the extracted fiber into the red. One hundred (100) undamaged or unbroken fibers were measured for their length (L), widths (d), lumen diameter (l) and cell wall thickness (w). The Quantimeter Image Analyzer with Lecia Microscope and Hipad Digitizer were used to analyse images.

Physical Properties

Moisture content (MC) was determined by using the difference between the green sample and oven drying method described by ASTM D 4442 standard. Basic density (BD) determined by ASTM standard D-2395. Shrinkage determined by ASTM D-143 (ASTM, 1990; 1997)). The weight and volume of each sample were determined in green condition according to the American Standard Testing Materials D-2395-02 (ASTM, 2003b). Samples were conditioned at 65% of relative humidity and 22°C of temperature (air-dry condition), and the weight/volume measured for the second time. Oven-dried weight and volume measured again once the samples oven-dried (105°C for 24 hrs). The wood density of the dry condition was calculated as weight divided by volume, while the MC was calculated as the difference between weight green and dry, and divided by the dry weight. The BD was calculated as the oven dry weight divided by green volume, and air-dry weight, divided by volume in green condition. The volumetric shrinkage was determined as the difference between green and dry volume and divided by green volume.

Moisture Content

The MC values were determined according to ASTM D143: Determination of MC at the green condition. The sample for both species was randomly taken at node and internode location and divided into three layer which is the outer, middle and inner position of the study. Then, the samples were cut to (30 x 30 x culm wall thickness) mm to determine the MC at the green condition. The weight of the samples recorded. Then, samples placed in an oven set at 60°C for 24 hrs. and later reset at 102°C for 24 hrs. The sample was then removed from the oven and cooled in a desiccator for 30 min. Samples were taken out and weighted for the second time before being recorded.

Basic Density

The basic density (BD) was determined using a density kit equipment. The bamboo samples were cut into a size of (10 x 30 x culm wall thickness) mm. The thickness of sample depended on the culms wall thickness and divided into three positions (outer, middle and inner). Ten replicates were used in the study. The samples were oven dried for 48 h 105±2°C until a constant weight attained. The sample then was weighed to record their dried weight. The samples later were placed into water under a vacuum of 700 mm Hg for 24 hrs. until saturated to attain green volume condition. The volume of fully saturated samples obtained using the water displacement method. The weight displaced was converted to the volume green.

Shrinkage

The volume, radial and tangential shrinkage of bamboo measured based on the ASTM D 143-94 standard of testing small clear specimens of timber.

Ultrastructure Study on Bamboo Cell Walls

Both the scanning electron microscope (SEM) and transmission electron microscope (TEM) were used in analyzing the structure of the bamboo cell walls. The technique used by Mohamad Saiful *et al*., (2016) and Razak *et al*., (2002) were adopted and used here. For SEM analysis, the selected samples cut into a smaller size for the shorter duration of the pre-vacuum process. The surface of the samples was cut using high-speed Microtome blade. The samples underwent through the pre-vacuum process on the thin plate before the Aurum coating process to ensure efficient conductivity for the analysis process. Scanning analysis performed using 'Leica Cambridge S-360', with magnification up to 4000 times. Samples for TEM analysis dehydrated in an ethanol series and embedded in Spurr resin. For cell wall structure of the bamboo fiber, they were chosen according to position and location in bamboo culm and cut into a size 2 mm x 3 mm blocks. They underwent dehydration process in an ethanol series and embedded in Spurr resin (Epon), polymerized for 24 hours at 60°C. Transverse sections (1µm) cut from the implanted material, using the Sorvall ultra-microtome (MT 5000) and stained with Toluidine Blue 1% for lignin distribution determination. This gave a high contrast to lignin-rich structure such as middle lamellas and cell corners. The section was viewed under a polarized microscope (Nikon YS2-H). The thin section (0.1µm) was obtained from implanted samples, stained with uranyl acetate, lead citrate and observed under TEM (energy filter - Zeiss Libra®120).

Strength Properties

Tensile Parallel to the Grain test

Presently, no report on tension strength for the *B. vulgaris*. The tension test parallel to grain was carried out with some modification from the standard testing of small clear specimens timber (ASTM D 143-94). It is not possible to cut similar samples dimensions due to the natural structure of bamboo as suggested in the standard testing procedures. Instron Testing Machine (with 100 kN max. load) used in the tensile test. The samples were prepared with sizes 300 (L) x 20 (W) x 5 mm (T) in accordance with the standard. The tension area of the samples was 3 x 5mm.

Shear Test

The shear test performed by BS EN 314-1:2004 uses the same Instron Testing Machine. The test used rectangular strips with dimensions of 20 mm x 20 mm x culm wall thickness and carried out three times in one sample but at a different position of the layer (this method known as roller shear test). The samples sizes measured and recorded individually. Samples were tested at a crosshead speed of 1.5 mm/min. Dried samples were conditioned at an ambient temperature of 25± 3°C and a relative humidity of 30% (± 2%) before testing. The green samples were tested directly.

RESULTS AND DISCUSSION

Vascular Bundle Distribution

The result for the vascular bundle's distribution shown in Table 1. The mean number of the vascular bundle for *B. vulgaris* was 6.37 at the nodes and 7.73 bundle/4 mm^2 at the internodes. These were in agreement studies by with Abd. Latif (1991) and Mustafa *et al*., (2011) on *G. scortechinii*. The anatomical features vary within and between the culms of different or even the same bamboo species (Pattanath, 1972; Soeprayitno *et al.*, 1990). The of vascular bundles distributions were higher in the internodes than the nodes. The vascular bundles noted to be numerous and more compacted at the outer layers than those in the inner layers of the bamboo culm. The same conclusions were made by Liese (1992) and Abd. Latif & Tamizi (1993). The number of vascular bundles was noted to be higher in a monopodial bamboo compared to the sympodial bamboo species (Wenyue *et al.,* 1981; Li, 2004).

Table 1. Number of the vascular bundle (*per 4 mm^2*) of *B. vulgaris*

Location	Position	No. of vascular bundle	Vascular bundle length *(µm)*	Vascular bundle width *(µm)*
Internode	Outer	13.24 (±1.75)	625.77 (±232.89)	382.41 (±141.22)
	Middle	6.44 (±1.12)	882.32 (±74.07)	494.11 (±73.87)
	Inner	3.50 (±0.64)	853.60 (±110.02)	627.62 (±101.20)
	Mean	7.73 (±1.17)	787.19 (±138.99)	501.38 (±105.43)
Node	Outer	10.55 (±1.77)	785.40 (±193.88)	478.04 (±46.60)
	Middle	5.80 (±1.40)	999.55 (±157.05)	593.74 (±72.24)
	Inner	2.75 (±1.13)	1449.64 (±172.69)	691.88 (±92.30)
	Mean	6.37 (±1.43)	1078.20 (±174.54)	587.89 (±70.38)

Values in bracket represents the standard deviation

Table 2. The physical properties and the ANOVA between location and position

	Moisture Content (%)	Basic Density (g/cm^3)	Shrinkage (%)		
			Radial (%)	Tangential (%)	Volume (%)
LOCATION					
Internode	94.52a	0.72b	7.02a	9.17b	14.83a
Node	78.68b	0.75a	6.68b	10.66a	10.78b
POSITION					
Outer layer	49.82c	0.96a	5.04c	6.52c	10.40c
Middle layer	83.54b	0.75b	6.85b	9.72b	12.57b
Inner layer	124.29a	0.59c	8.63a	13.45a	15.45a

Means followed by the same letter are not significantly different at 0.05 probability level

Table 3. Analysis of variance for anatomical properties between location & position

		Anatomical Properties		
		No. Vascular bundle	Vascular bundle length	Vascular bundle Width
Location	Internode	6.32a	869.87b	585.42b
	Node	4.93b	1058.94a	630.70a
Position	Outer layer	8.56a	748.54c	467.23c
	Middle layer	4.89b	1013.25b	599.76b
	Inner layer	3.42c	1131.42a	757.19a

Table 4. Analysis of variance for fiber morphology between location & position

		Fibre Length (µm)	Fiber Diameter (µm)	Lumen Diameter (µm)	Wall Thickness (µm)	Runkle's Ration (µm)
Location	Internode	2074.24a	18.23b	4.43b	6.90b	4.17a
	Node	1672.62b	22.04a	6.18a	7.02a	3.68b
Position	Outer layer	1698.52c	18.49c	5.44c	7.03b	4.04b
	Middle layer	2060.41a	22.36a	5.51b	8.43a	4.29a
	Inner layer	1861.35b	19.56b	5.96a	6.80c	3.45c

Values followed by the same letter in a column are not significantly different at 95% probability level.

Liese (1985) found that the bamboo possesses long and small vascular bundle at the outer, but short and big towards the inner regions.

Vascular Bundle Length

The results on the vascular bundle's length are shown in Table 1. The vascular bundle length at internodes was 787.19 µm and at the nodes were 1078.20 µm. The vascular bundle's length at the nodes was longer than at the internodes regions. The vascular bundle lengths at outer layer were 748.54 µm, middle layer 1013.25 µm and for inner layer was 1131.42 µm respectively. The lengths were longer in the middle than at the outer and inner periphery.

Vascular Bundle Width

The results on the vascular bundle's width are shown in Tables 1 and 3. The mean of vascular bundle width at the internodes was 585.42 µm and nodes 630.70 µm. The mean average at different position showed a significant difference between the internodes and nodes. The vascular bundle's width was observed to be higher at the node. The mean average of vascular bundle width for outer layer position was 467.23 µm, middle layer 599.76 µm and for inner layer was 757.19 µm. It shows the significant differences between the vascular bundles in samples position. Vascular bundle width widened at the inner and smaller toward the outer periphery position. This was due to the size of the vascular bundle which was smaller and compact at the outer layer, dense to the inner layer of bamboo culms.

Fiber Morphology

Fiber Length

The results of the fiber lengths study are shown in Table 4. Significant difference observed in the fiber length between the bamboo positions and portions. The fiber length obtained for internodes were 2074.24 µm and nodes 1672.62 µm. The fiber length was higher at the internode compare to the node. At the internode, the anatomy structure was constant, but at the node, it was quite twisted. The anatomical factor may be contributed the different of fiber length between two positions. The mean of the fiber length for outer layer position was 1698.52 µm, middle layer 2060.41 µm and for inner layer was 1861.35 µm. Significant different was observed in the fiber length at the internodes, nodes and between the cross-sectional positions of the bamboo. Similar observations made at the internodes and nodes, which shows that the fiber possesses longer fiber at the middle layer of bamboo. The fiber length shows variations within one culm (Liese & Grosser 1972). The results from this study showed that bamboo fiber length from *B. vulgaris* was longer than the fiber from *P. Pubescens* which growth in large areas of China, Japan, Taiwan and Indochina, The fiber length for this species was about 1300 µm length (Liese, 1992) compared with the genera *Gigantochloa* (1750-2040 µm). Walter Liese (1992) studied the structure of bamboo about its properties and utilization. They reported that the fibers contribute 60-70% by weight of the total culm tissue. Certain species have shorter fibers, such as *Phyllostachys edulis* (1.5 mm), *Ph. pubescent* (1300 µm), other longer ones like *Dendrocalamus giganteus* (3200 µm), *Oxytenanthera nigrocilliata* (3600 µm), *D. membranaceus* (4300 µm). Comparison with the fiber length of the Softwood (3600 µm), The fiber length of *Gigantochloa* (1672 - 2074 µm) genera was shorter but still longer than hardwood (1200 µm). In fact, it is longer than *Eucalyptus spp* (960-1.0400 µm) was popular as a source of short fiber pulp for paper industry (Horn & Setterholm, 1990; Ververis *et al*., 2004).

Fiber Diameter

The fiber diameter at different position showed that the nodes have larger fiber diameter at 22.04 µm and internodes at 18.23 µm (Table 4). Significant different existed between the fiber diameter in position at the internodes and nodes. The fiber diameter at different position showed that the outer layer was 18.49 µm, middle layer 22.36 µm and inner layer 19.56µm. The fiber diameter of the *B. vulgaris* in this study ranged between 18.23 -22.36 µm. Earlier studies on the fiber diameter for *B. vulgaris* were 23-37 µm (Abd. Latif, 1995), while studies on the *Bambusa* genera found that; fiber diameter for *B. blumeana* was 12.0 µm (Ireana, 2009), *B.vulgaris* was 16.9-18.0 µm (Razak, 2010), 20-42 µm (Latif, 1995). This study found that the fiber diameter was smaller than the previous studies. The diameter of the fiber of this study was 17-22.8 µm and is smaller than the Softwood (35 µm) and hardwood (25 µm). The comparison between the fiber diameter in this study indicates that the fibre diameter *Gigantochloa* genera (17-22.8µm) was more prominent than *Eucalyptus spp* (15.5 - 16.3µm).

Fiber Lumen Diameter

The lumen diameter was 4.43 µm at internodes and 6.18 µm at the nodes (Table 4). The diameter at different position showed that the outer layer was 5.44 µm, middle layer 5.51 µm, and inner layer 5.96 µm. Similar results were obtained by Hisham (2006), but smaller than those obtained by Latif (1995). The lumen diameter of *Bambusa* was 1.6 µm for *B. blumeana* (Ireana, 2009), 2.3-2.6 µm for *B. vulgaris* (Razak, 2010). The lumen diameter of *Eucalyptus spp* was 8.5-9.5 µm. The mean average for lumen diameter at different position showed that for the lumen diameter node was 6.18 µm and for the internodes was 4.43µm. The results showed the lumen diameter was larger at the node compared to the internodes. The mean average for lumen diameter at difference position showed that at the outer layer was 5.44 µm, middle layer was 5.51 µm and at the inner layer was 5.96 µm. The result showed the lumen diameter was largest at the inner and smaller toward the outer layer and it was a significant difference.

Fiber Wall Thickness

The mean cell wall thickness was 6.80 µm at internodes and 7.023 µm at the nodes (Table 4). The thickness recorded at 7.03 µm, middle layer 8.43 µm, and inner layer 6.80µm respectively at outer, middle and inner layers. The result showed the wall thickness was thicker at the node as compared to the internodes and significant difference between the two. The average wall thickness at different positions showed the outer layer was 7.03 µm, middle layer 8.43 µm and at the inner layer was 6.80 µm. The result showed the wall thickness decreases from outer to the inner layers. *B. blumeana* which was 5.01 µm (Ireana, 2009), *B. vulgaris* was 7.1-7.6 µm (Razak, 2010), 2.5-13.3 µm (Latif, 1995). The fiber wall thickness of *B. vulgaris* shows an almost similar with fiber wall thickness of *Eucalyptus* spp was 4.3 µm and 3.29-3.86 µm (Viane *at el*., 2009), respectively.

This demonstrates that *G.scortechinii* could be a source to replace short-fiber pulp that imported from abroad. *Eucalyptus spp*, the Runkle's ratio was less than 1.0, namely 0.7 and 0.8 (Viena *et al*., 2009) was even shorter fiber than *G.scortechinii*. The Runkle's for hardwood and Softwood was 0.4-0.7 and 0.35 respectively. Kenaf has Runkle's ratio of 0.5-0.7 to prove they are good fiber felting power. Runkle's ratio for *G.scortechinii* was lowest than value one, which was 0.97 to prove it can still be used.

Ultrastructure Study

The ultrastructure studies are shown in Figures 1 to 2. Figure 1 shows the ultrastructures of the internodes and nodes focusing on the vascular bundles taken using the SEM. Figure 2 shows the images of the bamboo species taken using TEM concentrate at the fibers cells.

Table 5. Runkle's ratio of *B. vulgaris*

Sample Position	Position	*B. vulgaris*
	Outer	2.16 (±1.50)
Internode	Middle	1.42 (±0.95)
	Inner	0.97 (±0.78)
	Outer	1.71 (±0.96)
Node	Middle	1.06 (±0.64)
	Inner	0.79 (±0.57)

Values in bracket represent the standard deviation.

Table 6. The ANOVA of strength properties at the different condition, location and position in bamboo culms

		Tensile	
	Shear (MPa)	Strength (MPa)	Modulus (MPa)
CONDITION			
Air dry	8.20a	138.87a	4003.85b
Green	5.76b	89.95b	2786.96a
LOCATION			
Internode	6.24b	144.68a	3545.49b
Node	7.72a	84.14b	3245.33a
POSITION			
Outer layer	7.85b	135.93a	4061.64c
Middle layer	9.18a	115.49b	3344.80b
Inner layer	3.90c	91.81c	2779.79a

Means followed by the same letter in a column are not significantly different at 0.05 probability level.

Fiber Runkle's Ratio

The fiber Runkle's ratio was 4.17 at the internode and node was 3.68. It shows there was significantly different from the Fiber Runkle's ratio between a position at the node and internode of the bamboo. The result showed the fiber Runkle's ratio was more prominent at the node as compared to the internodes and it was a significant difference between this two position. Table 5 showed the value of fiber Runkle's ratio at node and internode. The mean average for fiber Runkle's ratio at difference position showed that at the outer layer was 7.03, middle 8.43 and at the inner layer was 6.80. The result showed that the fiber Runkle's ratio was more significant in the middle and thinner toward the inner and outer layer. The considerable difference observed between this three position. Table 6 showed the fiber Runkle's ratio value for every position and position. The Runkle's ratio showed value more than one, this main the fiber properties was hard and difficult to felting during the paper production. The quality of the paper will be compromised and poor bonding if Runkle's ratio value more than one. If the Runkel's ratio is less than one, it indicates the fiber has a thin fiber wall and easily to felting. The quality of the paper would be better, and bonding would be good.

The cells wall of the bamboo fibers shows the presence of more than two layers, which were S1, S2, S3, and Sn. All the four bamboo species shows clear that they belong to bamboo are bamboo in class type. They possess a vascular sheath fiber and one fiber strand. Even though the cells are similar in shape, they are however different in sizes in position at internodes and nodes, and position in the bamboo at either the outer, middle and the inner layers. The distribution of the vascular bundles per 4 mm^2, vascular length, vascular bundle width shown in Tables 1 and 2. The length, diameter, lumen diameters, wall thickness and the Runkle's ratio of the fibers are given in Tables 3, 4 and 5.

Moisture Content

The results of the physical are shown in Table 1 which contain the values of MC, BD, and shrinkage (radial, tangential and volumetric) and the analysis of variance. The MC observed to be higher in the inner layer of the bamboo at 125.90%. The MC at the internodes averaged 94.52% and for the node 78.68%. The MC was higher at the internodes compare to the node (78.68%). The different of MC was due to the anatomical factor between the internodes and nodes.

At the internodes, the metaxylem vessels were more uniform and bigger in sizes, while at the node is metaxylem vessels are smaller and not consistent. The MC at the outer layer was 49.82%, middle layer 83.54% and for the inner layer was 124.29%. The MC was lower at the outer and increases toward inner positions. The area that contents high fiber strand has a small capacity for water storage. Bamboo species can show differences in MC which according to Liese (1985) possibly due to the difference in some inherent factors such as age, anatomical features, and chemical composition. The strength of the bamboo was directly related to the MC as it reduced the strength of the element. Bending and compression strength has shown a significant variation in green and air-dry conditions bamboo (Lee *et al*., 1994; Chung and Yu, 2002). The higher MC at the inner layer could be influenced by the anatomical structure of bamboo. The inner layer contained lower vascular bundles concentration that leads to higher MC as compared to the outer layer.

Shrinkage

Radial, Tangential and Volumetric Shrinkage

There was a significant difference between the location of nodes (6.68%) and internodes (7.02%) (Table 1). The radial shrinkage was higher at internodes compare to the node. The inner layer was the higher radial shrinkage, and it reduces toward the outer layers. The radial shrinkage of the bamboo ranged from 5.04 to 8.63%. The higher tangential shrinkage was noted at 13.45%. The tangential shrinkage was higher at nodes compare to the internodes. Significant different observed between various samples location in the bamboo culms. The inner layer possessed higher tangential shrinkage and decreased toward the outer layers. The tangential shrinkage ranged from 6.52 to 13.50%. High volumetric shrinkage occurred at 15.45%.

Table 7. Strength Properties of 3-year-old *B. vulgaris*

Sample	Location	Mean Tensile strength (MPa)	Mean Tensile modulus (MPa)	Mean Compression Roller shear (MPa)
(Green sample)	Outer	123.11 (±13.92)	3086 (±327)	4.23 (±0.75)
Internode	Middle	86.62 (±10.78)	1833 (±153)	5.64 (±0.88)
	Inner	79.81 (±9.09)	1672 (±102)	2.90 (±0.86)
	Outer	77.30 (±9.10)	2705 (±288)	5.61 (±1.00)
Node	Middle	69.81 (±5.63)	2205 (±201)	6.14 (±0.48)
	Inner	35.14 (±5.00)	1203 (±109)	1.84 (±0.40)
(Air-dry sample)	Outer	204.92 (±17.13)	5258 (±271)	9.22 (±2.22)
Internode	Middle	219.56 (±14.40)	5036 (±251)	9.92 (±0.91)
	Inner	152.10 (±17.48)	4195 (±385)	4.95 (±1.40)
	Outer	179.11 (±15.68)	5362 (±470)	8.90 (±4.17)
Node	Middle	164.32 (±11.83)	5532 (±456)	12.67 (±1.36)
	Inner	74.08 (±10.55)	3387 (±351)	8.49 (±1.05)

Standard deviations are shown in parentheses

Table 8. Correlation Coefficients of Anatomical Characteristics and Physical Properties with Strength

	Shear Strength (MPa)		**Tensile Strength (MPa)**			
Properties	Air dry Condition	Green Condition	Strength (Air-dry)	Modulus (Air-dry)	Strength (Green)	Modulus (Green)
Moisture Content	-0.34*	-0.56*	-0.44*	-0.52*	-0.40*	-0.63*
Basic Density	0.56*	0.47*	0.50*	0.49*	0.54*	0.70*
Number Vascular bundle	0.38*	0.40*	0.59*	0.64*	0.53*	0.39*
Vascular bundle length	-0.38*	-0.35*	-0.50*	-0.50*	-0.41*	-0.25*
Vascular bundle length	-0.38*	-0.35*	-0.55*	-0.38*	-0.21*	-0.30*
Vascular bundle width	-0.00n	-0.40*	-0.17*	-0.04n	-0.00n	-0.11*
Fibre length	0.00n	0.10*	-0.17*	-0.04n	-0.00n	-0.11*
Fibre diameter	0.29*	0.19*	0.13*	0.01n	-0.06n	-0.18*
Fibre lumen diameter	-0.13*	-0.06n	0.31*	0.23*	0.13*	-0.20*
Fibre wall thickness	0.28*	0.37*	-0.20*	-0.29*	-0.25*	-0.02*

***** significant, ^{n} not significant

Basic Density

The results on BD at different locations and positions in the bamboo culms were shown in Table 1. BD were 0.72 and 0.75 g/cm^3 at the internodes and nodes respectively. The BD values for outer layer was 0.96 g/cm^3, middle layer 0.75 g/cm^{3}and the inner layer was 0.59 g/cm^3. The differences of BD at both the nodes and internodes were due to the fiber wall thickness. In the nodes, fibers have thicker cell walls and the high proportion of fibers in every vascular bundle. There was significantly different between the location of nodes and internodes due to the long and straight vascular bundles at the internodes (Razak 1998). The bamboo BD has a close relation with vascular and ground tissues percentages which according to Janssen (1981); Espiloy (1987); Widjaja and Rashid (1987).

A significant difference existed between nodes and internodes at which volumetric shrinkage was higher at internodes compare to the node. The inner layer showed greater shrinkage compared to middle and outer layer due to the higher amount of parenchyma in the inner layer compared to middle and outer layer. The dimension of bamboo started to change as soon as it starts to lose moisture (Razak *et al*. 2006). Once the bamboo is cut, loss of water took place leading to radial and longitudinal shrinkage. This resulted in the setting up of internal stresses between the fibers. These stresses exceed the cohesion of the fibers leading to warping. The radial shrinkage was 0.5%, and that of longitudinal shrinkage was negligible as in the case of other wood members (Tamizi *et al*. 2011). The dimensional stability shown by bamboo occurred due to the orientation of most of the microfibrils (S2 layer) aligned parallel to the longitudinal axis.

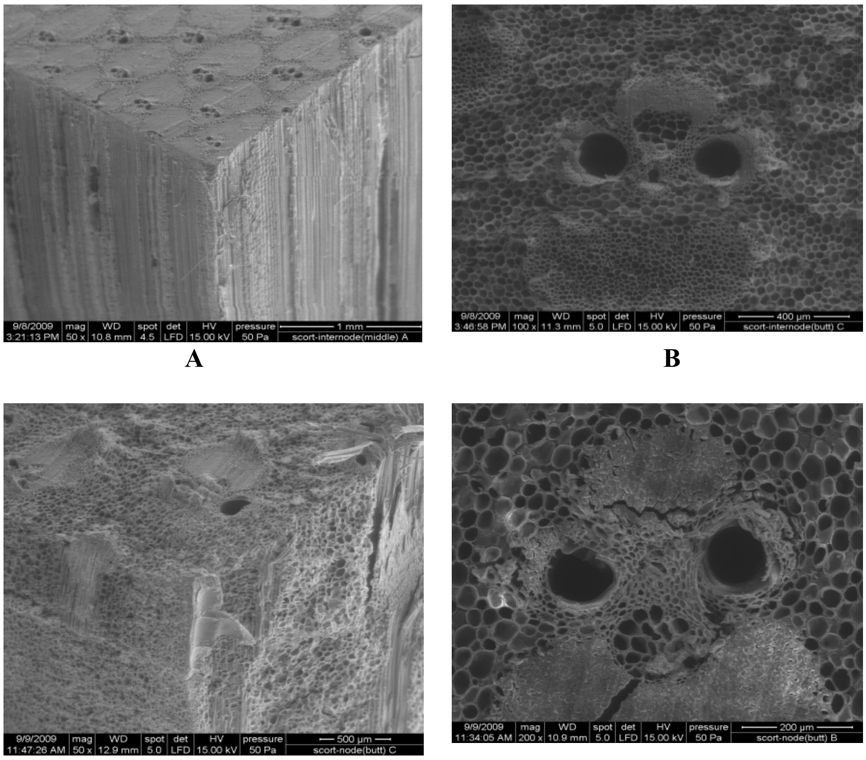

Figure 1. SEM images (A, B) of the vascular bundles at internodes and nodes of the *B. vulgaris*

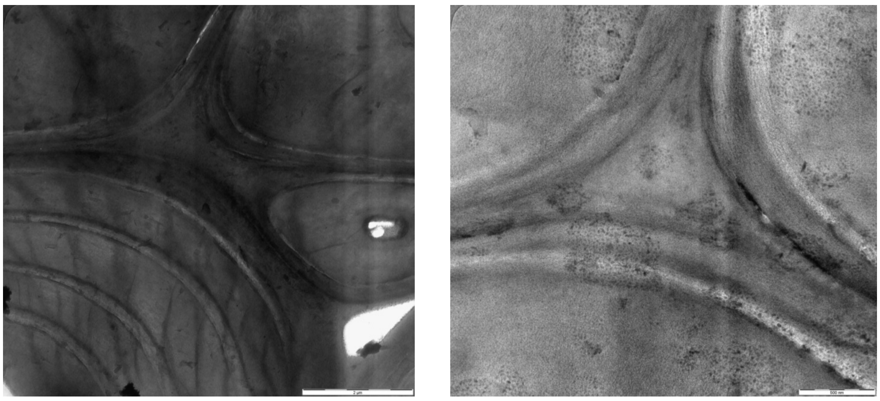

Figure 2. Fibre cells (A) and middle lamella (B) at internodes of the *B. vulgaris*

The explanation of this behavior can also be applied to bamboo. According to the study of the anatomical structure by Parameswaran and Liese (1976), there are two types of microfibril orientation in bamboo, the narrow lamellae showing the fibrillar angle of 80 – 90° to the axis and the broader ones with fibrillar angle almost parallel to the axis. Although the fibers in bamboo demonstrated polylamellate nature (8 lamellae compare to 3 lamellae in wood (S1, S2, and S3)), the thick fibril layer which is parallel to the axis is greater compared to the narrow lamellae. Removal of moisture in the cell wall (the hygroscopic or bound water) causes shrinkage to take place as a result of the contraction of the microfibrillar in proportion to the amount of liquid evaporated (Panshin and De zeeuw, 1970).

Strength Properties

Shear Strength

The results of the ANOVA and the shear strength are tabulated in Table 6. Based on statistical analysis, there was three significant difference group was observed between species at 95% confidence level.

The shear was 6.71 MPa. A significant difference between green and air dry sample were noted. The results for compression roller shears for green was 5.76 MPa and for the air dry was 8,20 MPa. The shear strength of air dry sample was nearly 30% higher than the green sample. The result for the green condition was from 1.29-6.14 MPa.

For the air dry condition, the shear strength increases 4.95-12.67 MPa. The analysis of variance showed a significant difference for the compression roller shears strength between this two locations. This result, irrespective of species and condition of the sample. The shear strength at the nodes was 15 to 20% greater than at the internode. The result of analysis of variance at a different position of the samples on position also showed a significant difference. The compressive strength was noted to increase with the increase the number of the vascular bundles which increased from inner to outer part of the bamboo (Li, 2004; Rafidah *et al*. 2010; Razak *et al*., 2012)). It was also observed that the number of vascular bundle increases from bottom to the top section (Tommy *et al*., 2004).

Tensile Strength and Modulus

The ANOVA on tensile is tabulated in Table 7. The results show that the tensile strength at difference condition (green and air-dry), location (at node and internode) and position (outer, middle and inner layer) of the bamboo taken. Based on statistical analysis, there were two significantly different groups observed between species at a 95% confidence level. The higher group was 122.16 MPa. The significant difference noted between green and air dry sample. The results for tensile strength for green was 89.95 MPa and for the air dry was 138.87 MPa. Table 7 showed the variation of mechanical properties of tensile strength. The result for green condition *B. vulgaris* was recorded from 35.14-123.11Mpa. For the air dry condition, the tensile strength was increased; the result showed that *B. vulgaris* 74.08-208.06 MPa. The air dry samples showed better tensile strength almost 35% compared to green samples. This may be because bamboo behaves similarly to wood whereby the mechanical properties increase with a decrease in moisture content (Hamdan, 2004).

The analysis of variance for tensile strength at a different location in Table 9, showed, there was a significant difference between the internode strips and node strips. The internode possessed a higher tensile strength with 144.68 MPa as compared to the node with 84.36 MPa. This value was recorded without taking an account on species type, condition, and position of strips in the bamboo culm. The difference in tensile strength almost 40% higher in the internode strip compared to the node strips (Internode tensile strength 40% greater than the node. The tensile strength increases from inner to outer part of the bamboo for every bamboo species. Analysis of variance showed that there was a significant difference between the outer, middle and inner strips. The higher was the outer layers which were 135.93 MPa, Middle 115.49 MPa and the lower was the inner layer 91.81 MPa. The difference in tensile strength in this experiment showed that the outer layer has 15% stronger from the middle layer, and the middle layer has 15% stronger than the inner layer. The difference in tensile strength, the outer layer strength was 30% higher than the inner layer. This phenomenon can be related to the presence of numerous vascular bundles in which can lead to the higher density of the outer part and increase the tensile strength of the outer part than the inner part of the bamboo. Li (2004) also stated that tensile strength and mean Young's modulus increase with increase cellulose content and decreasing micro-fibril angle.

Correlation Between Shear, Tensile Strength & Mc, Bd, Anatomy

Initially, moisture content was high, and the strength of the shear roller was lower (see Table 8). The basic density correlated significantly with the shear tests. This shows that at high specific gravity, the roller shear strength was also high.
The basic density plays a direct role in the shear strength test in bamboo. The number of the vascular bundles has a positive relationship with the shear test. This shows that a high number of the vascular bundle influences on the shear strength. The presence of numerous vascular bundle contributed significantly to the strength of the roller shear. Vascular bundle size (for length and width) has a negative relationship with the roller shear tests. The width of vascular bundle does not show a significant correlation with roller shear tests. The correlation between roller shear with fiber morphology was not strong, and some are insignificant. Only fiber wall thickness correlates with roller shear tests. The thicker fiber wall was, the higher of roller shear strength. Table 8 shows the correlation between tensile strength with the moisture content at initial of the bamboo sample. It has a negative and weak correlation. The initial bamboo has a high moisture content but lower the tensile strength. The basic density positively correlated with tensile strength. This means the increase of specific gravity will increase the tensile strength. A number of the vascular bundles has a positive correlation with the tensile strength. Increasing in the number vascular bundle will increase the tensile strength. Vascular bundle size (for length and width) has a negative relationship with the tensile strength. This indicates the larger size of vascular bundle the lower the tensile strength. The correlation between tensile strength with fiber morphology was not strong, and some of them were insignificant. There was no clear relationship of tensile strength with fiber morphology.

CONCLUSION

The morphology fibers showed significant differences between portion and position regarding length, diameter and lumen size. Each species has different characteristics of the fiber. The vascular bundle for this species ranged around 3.50 to 13.24 per 4 mm^2 and it is dense at the outer position which was 10.55 vascular bundle per 4 mm^2, middle 5.80 vascular bundle per 4 mm^2 and at the inner position was 2.75 vascular bundle per 4 mm^2. The vascular bundle length ranged from 785.40 to1449.64 μm and a width from 382.41 to 691.88 μm. The fiber length recorded between 1672.62 to 2074.24 μm, fiber diameter between 18.23 to 22.36 μm, lumen diameter 5.44 to 6.18 μm and fiber wall thickness 6.80 to 8.43μm. The MC in *B. vulgaris* was higher in the internode compared to the node. The inner layer of bamboo possess the highest moisture content than the middle and the outer layers. The basic density were higher at outer position followed bt the middle and the inner positions. The shrinkage were lower at the radial followed by the tangential shrinkage. The inner shrinkage were lower compared to the middle and outer positions at the bamboo cross-sections. The Tensile Strength of dried bamboo were higher than the green bamboo. The Tensile Modulus of air-dried bamboo was 4003.85 MPa as compared to 2786.96 MPa for green bamboo. The shear of dried bamboo was 8.20 MPa compared to the green bamboo 5.76 MPa. The strength of the internodes was 6.24 MPa and the nodes at 7.72 MPa. The strength at outer position was7.85 MPa, while middle was 9.18 MPa and inner 3.90 MPa.

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