

Potential and Structural Variation of Some Selected Cultivated Bamboo Species in Peninsular Malaysia

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Received: August 10, 2011 Accepted: September 13, 2011 Online Published: June 26, 2012

doi:10.5539/ijb.v4n3p102

URL: <http://dx.doi.org/10.5539/ijb.v4n3p102>

Abstract

Screening of different cultivated bamboo species to find out potential variety of bamboo is most important. Structural variations in term of anatomy, physical and strength properties of 3 year-old cultivated *Gigantochloa brang*, *G. levis*, *G. scotechinii* and *G. wrayi* were investigated for screening purposes. The culms of these bamboos were selected, harvested and processed for subsequent studies. The results show that each species exhibited differences in the anatomy, physical and strength properties. Each species has differences in the fiber characteristics which showed significant differences between species in terms of length, diameter and lumen sizes. The vascular bundle for these genera were between 4-7/4mm² and were dense at the outer position in the cross section of the culm having 8.5 vascular bundle/4mm², middle 4.88 vascular bundle/4mm² and at the inner position having 3.4 vascular bundle per/4mm². The vascular bundle length was between 845-1183 µm and a width of 530-759 µm. The fibre lengths were between (1745.00-2039.98 µm), diameter (17.26-22.75 µm), lumen (3.83-8.66 µm) and wall thickness (1.3 -5.31µm). The moisture content (MC) of the bamboo in green condition ranged between 73-112%, the MC is higher at internodes (95%) compared to nodes (78%). Position at inner layer has MC at 126%, middle at 83% and outer at 41%. Density increases from outer to inner layer which started from 500 kg/m² at inner and increased to more than 820 kg/m² at outer part of bamboo at 12% moisture content. The specific gravity for all species tested was about 0.69 - 0.78, but the inner position is 0.58, middle 0.73 and outer positions is 0.94. Shrinkage at radial, tangential and the volumetric were at 5-9, 7-12, and 10-17% respectively for all species. Position in a higher rate of shrinkage were at inner (8.6, 13.50, 15.44%), follow by middle (6.85, 9.72, 12.57%) and outer (5.04, 6.52, 10.40%) respectively. The tensile strength for the bamboos ranged between 103.38-122.15 MPa. The tensile strength of dried bamboo is 138.87 MPa compared with 89.95 MPa for green bamboo. The tensile of modulus of air dried bamboo is 4003.85 MPa compared with 2786.96 MPa for green bamboo. The modulus of rupture (MOR) for the bamboos ranged between 91.19-132 MPa. The MOR for dried bamboo was 142.21 MPa compared to the green bamboo 99.56 MPa. The modulus of elasticity (MOE) varies between 11961.70-20430.40 MPa. MOE of air dried bamboo was 17610.00 MPa and green bamboo 13777.80 MPa.

Keywords: bamboo *Gigantochloa* species, anatomical, physical characteristics, strength properties

1. Introduction

The timber production from the natural tropical forests will continue to be on the decline in contrast to the population growth and the market demand by the wood-based industry in Malaysia. The timber supply from the plantation could not cope with the growing demand for timbers. Bamboo a fast growing plant on earth is an important material that has great potential to replace timber in the coming future. From materials that were used mainly in temporary application, bamboo has immersed as material for structural and heavy duty application. Once the bamboos have been turned into the laminated boards or composites material, their application are unlimited.

The physical and mechanical properties of bamboo have been widely studied by many researchers all over the world. However, information on the relationship between the anatomical, physical and strength properties of some species in genera *Gigantochloa* is still limited. In this study, four species in genera *Gigantochloa* that had potential for commercialization were studied. Assessment of bamboo physical properties such as moisture content, specific gravity, maximum shrinkage (tangential, radial and volumetric, roughness and wet ability has been conducted. Tension (tensile) parallel to grain, the static bending and compression roller shear test for small size specimens were carried out.

Advancement in the application of bamboo in modern era requires further understanding of the material such as properties of the anatomy, physical and strength at different location and position in the bamboo culms.

2. Materials and Methods

Samples of the four bamboo species from genera *Gigantachloa* namely *G.brang*, *G.levis*, *G.scortechinii* and *G.wrayi* were harvested from The Bambusetum Plot, Forest Research Institute Malaysia (FRIM), Kepong, Selangor, Malaysia. Culms of 3-year-old were selected for the study as the culms of this age was found to be most suitable as material for industrial uses. The bamboos had their age verified from the tags and had been monitored since the sprouting stage. The plants were harvested in January 2010. The bamboo culms were cut at about 30 cm above ground level. These culms were taken from randomly selected clumps with diameter range from 8-17 cm diameter, depend on species. Each stem was marked and cut at nodes and internodes 8. An end-coating paint was applied to the cut surfaces before the samples were transported to the laboratory. This was done to minimize evaporation and prevent fungal and insect attacks on the bamboo. The number of specimens taken were 10 culms per species.

2.1 Sample Preparation for Anatomy

Bamboo culms were divided according to species, and further sub-divided into node and internodes, position in the bamboo culms wall (outer layer, middle layer and inner layer). Specimen blocks intended for anatomical investigations and were fixed in formalin-acetic acid (FAA) immediately after felling and kept in closed bottles. The mixture of FAA consists of 90% ethanol (conc. 70%), 4% glacial acetic acid and 6% formaldehyde (conc. 37-48%) (Razak, 1998). Each culm was consistently cross cut into position with and without nodes with the sampling preparation protocol for each respective investigation.

2.1.1 Anatomy Assessment

The technique used by Latif and Tamizi (1993) was used with some modification in measuring and counting in the distribution of the vascular bundles on the bamboo surface at the cross section. The anatomical characteristic of the four (4) bamboo species with two locations (node and internode) and three (3) positions (outer, middle and inner layers) of the bamboo culm were studied.

2.1.1.1 Vascular Bundles

Method of measuring the vascular bundles distribution and fibre dimensions was adopted from the technique used by Razak et al. (2007, 2009) and Latif and Tamizi (1993).

2.1.1.2 Vascular Bundle Size

The sizes of the vascular bundles were measured by the scanning electron microscope (SEM) images through it measuring tools.

2.1.2 Determination of Fiber Morphology

2.1.2.1 Bamboo Maceration

The bamboo splits of size 20 mm x 10 mm x thickness were cut tangentially and divided into 3 equal portions (inner, middle and outer layers). Each portion were splits radials into match stick sizes using a sharp knife. Macerates were prepared from match-stick sizes bamboo by placing them in solution containing glacial acetic acid (M=60.05g/mol) and hydrogen peroxide (30% and M=34.01 g/mol) at ratio 1:1. The bamboo in the solution were heated over a water bath inside a fume chamber for 2-3 hrs until it become soft and white. One or two drops of sodium hydrogen carbonate crystals were added to neutralize the acid before the mixture was decanted and washed with distilled water. A through shaking of the mixture was done to separate the individual fibers. Safranin was used to colour the extracted fiber to red. One hundred (100) undamaged or unbroken fibers were measured for their length (L), fiber widths (d), lumen diameter (l) and cell wall thickness(w). Quantimeter Image Analyzer equipped with Lecia Microscope and Hipad Digitizer (Quantimet 520, Cambridge Instruments) was used to observed and measured at computer images at 10 x (length), 100 x (diameter) and 100 x (lumen) magnifications.

2.2 Physical Properties

Moisture content (MC) values were determined using the difference between the green sample and the oven drying method described by ASTM D 4442 and ASTM D143 (Determination of MC at green condition) standards. Specific gravity (SG) values were determined by the volumetric measurement method described by ASTM standard D-2395. The shrinkage was determined using ASTM D-143 (ASTM, 1990; 1997).

The weight and volume of each bamboo samples were determined in green condition according to the American Standard Testing Materials D-2395-02 (ASTM, 2003b). All samples were conditioned at 65% of relative humidity and 22 °C of temperature (air-dry condition) and the weight/volume were measured for a second time. Oven-dried weight and volume were measured a third time once the samples were oven-dried (105 °C for 24 hrs). The wood density (D) of the dry condition was calculated as weight divided by volume, while the moisture content was calculated as the difference between green and dry weight and divided by dry weight, both values expressed as percentages. The SG was calculated as the oven dry weight divided by volume in green condition, and air-dry weight divided by volume in green condition. The volume shrinkage was determined as the difference between green and dry volume, and divided by green volume. Moisture content and specific gravity values were averaged per specimen.

2.2.1 Moisture Content of Bamboo

The sample for both species was randomly taken at nodes and internodes location and was divided into 3 layers which is outer, middle and inner position for the study. Then, the samples were cut to 30 x 30 x thickness to determine the moisture content at green condition. The weight of the samples was recorded. Then, samples were placed in the oven with 60°C for 24 hours and continued with 102°C for next 24 hours. The bamboo sample was then removed from the oven and was cooled in desiccators for 30 minutes. The samples were taken out and weighted for the second time and recorded.

2.2.2 Determination of Specific Gravity

The SG was determined by the density equipment with balance and a beaker of water was applied. Each sample block was cut to the size of (10 x 30 x thickness) mm. The thicknesses of sample depend on the culms wall thickness and divided to three positions (outer, middle and inner). 10 replicates were used in the study. The sample blocks were oven dried for 48 h 105±2°C until a constant weight were attained. The sample blocks were then weighed to give the oven dried weight. The sample blocks were placed in water under vacuum of about 700 mm hg for 24 h until fully saturated to attain green volume condition. The volume of fully saturated sample blocks was obtained using the water displacement method. The weight displaced is converted to volume of the sample as a green volume.

2.2.3 Shrinkage

The volumetric, radial and tangential shrinkage of bamboo was carried out with the guidance of the standard methods of testing small clear specimens of timber, ASTM D 143-94.

2.3 Determination of Strength Properties

2.3.1 Tension Parallel to Grain

Tension tests parallel to the grain are seldom investigated for bamboo. There was no report on tension strength for *Gigantochloa species*. However, in order to design bamboo tension members loaded in direct tension, the tension strength value is a fundamental criterion. The tension parallel to grain test carried out was adjusted from the standard methods of testing small clear specimens of timber, ASTM D 143-94. Due to the nature of bamboo, it is impossible to cut similar specimen dimensions suggested in the standard. Instron Testing Machine with 100 kN maximum load was used in the tensile test. The sample were prepared with sized (300 x 20 x 5) mm (length x width x thick) in accordance followed the standard. The speed was 1.0 mm/min and length of span (gauge length) was 30 mm. The tension area of sample was 3 x 5mm.

2.3.2 Compression Roller Shear Test

The shear test was performed according to BS EN 314-1:2004 using an Instron Model 4204 Testing Machine. The shear test was carried out using rectangular strips with dimensions of 20 mm x 20 mm x culm wall thickness. The shear tests were carrying out three times in one sample, but at difference position of layer. So, this method called roller shear test. The weight, lengths, widths and thicknesses of the samples were measured and recorded. Samples were tested at a crosshead speed of 1.5 mm/min. Dried specimens were conditioned at an ambient temperature of 25± 3°C and at a relative humidity of 30% (± 2%) before testing. The green samples were tested directly.

3. Results and Discussion

3.1 Moisture Content

The result on the physical properties conducted on the four *Gigantochloa* species are tabulated in Table 1 and Table 2. These included the moisture content, specific gravity and shrinkage (radial, tangential and volumetric). The analysis of variance was also included in the table. The statistical result between species shows there was three significant different group of moisture content. The higher mean for moisture content was *G.scortechinii* (109.18%) follow by *G.levis* (86.18%) and the lowest was *G.wrayi* (76.23%) and *G.brang* (74.54%) under one group.

Table 1. The physical properties and analysis of variance (ANOVA) between the four *Gigantochloa* species, location and position

	Physical Properties				
	Moisture Content	Specific Gravity	Shrinkage		
			Radial	Tangential	Volume
SPECIES					
<i>G.brang</i>	74.54c	0.77a	6.29b	10.71b	10.72c
<i>G.levis</i>	86.18b	0.75b	5.67c	7.52d	11.08c
<i>G.scortechinii</i>	109.18a	0.71c	8.72a	11.74a	16.83a
<i>G.wrayi</i>	76.23c	0.77a	6.68b	9.68c	12.59b
LOCATION					
Internode	94.45a	0.74b	7.00a	9.17b	14.83a
Node	78.61b	0.77a	6.68b	10.66a	10.78b
POSITION					
Outer layer	49.87c	0.95a	5.04c	6.52c	10.40c
Middle layer	83.82b	0.73b	6.85b	9.72b	12.57b
Inner layer	125.90a	0.58c	8.63a	13.50a	15.45a

Means followed by the same letter is not significant different at 0.05 probability level.

The MC at internode was 94.45% and for the node was 78.61%. It shows there was significant difference between location at internode and node. The MC was higher at the internode compare to the node. The anatomical factor, maybe contribute the different of MC between two location. At the internode, the metaxylem vessel structure was uniform and larger, while at the node is metaxylem vessels are smaller and not uniform. The mean MC at the outer layer was 49.87%, middle layer 83.82% and for the inner layer was 125.90%. MC was higher at the inner layer and reduced to a position outer layer of the bamboo culm. Bamboo species show different moisture values which might be due to difference in some inheret factors such as age, anatomical features and chemical composition (Liese, 1985).

The mechanical properties of bamboo are directly related to the MC as it reduces the strength of the element. Bending and compression strength have shown significant variation of bamboo for green and air-dry conditions (Lee et al., 1994; Chung & Yu, 2002). In general, the inner layer of every species of the bamboo showed highest MC compared to middle and outer layer. *G. scortechinii* showed higher MC compared to other species. The higher MC at the inner layer could be influenced by the anatomical structure of bamboo. The inner layer contains lower vascular bundles concentration lead to higher MC as compared to outer layer.

Table 2. Correlation Coefficients of Different Anatomical Characteristics with Selected Physical Properties of various bamboo species genera *Gigantochloa*

Properties	Species	Moisture Content	Specific Gravity
Number Vascular bundle	<i>G. brang</i>	-0.52*	0.64*
	<i>G. levis</i>	-0.46*	0.67*
	<i>G. scortechinii</i>	-0.76*	0.87*
	<i>G. wrayi</i>	-0.24*	0.57*
Vascular bundle length	<i>G. brang</i>	0.63*	-0.69*
	<i>G. levis</i>	0.64*	-0.69*
	<i>G. scortechinii</i>	0.55*	-0.64*
	<i>G. wrayi</i>	0.34*	-0.71*
Vascular bundle width	<i>G. brang</i>	0.27*	-0.43*
	<i>G. levis</i>	0.52*	-0.78*
	<i>G. scortechinii</i>	0.46*	-0.60*
	<i>G. wrayi</i>	0.28*	-0.53*
Fibre length	<i>G. brang</i>	0.29*	-0.28*
	<i>G. levis</i>	0.23*	-0.25*
	<i>G. scortechinii</i>	0.03n	-0.01n
	<i>G. wrayi</i>	0.05n	-0.03n
Fibre diameter	<i>G. brang</i>	-0.07n	-0.05n
	<i>G. levis</i>	0.09n	-0.17*
	<i>G. scortechinii</i>	-0.12*	-0.01n
	<i>G. wrayi</i>	-0.09n	-0.00n
Fibre lumen diameter	<i>G. brang</i>	0.15*	-0.23*
	<i>G. levis</i>	0.00n	-0.08n
	<i>G. scortechinii</i>	0.16*	-0.27*
	<i>G. wrayi</i>	0.02n	-0.12*
Fibre wall thickness	<i>G. brang</i>	-0.16*	0.06*
	<i>G. levis</i>	0.09*	-0.16*
	<i>G. scortechinii</i>	-0.39*	0.33*
	<i>G. wrayi</i>	-0.11*	0.04n

* significant, ⁿ not significant.

The MC has a correlation with the number of vascular bundle, vascular bundle length and vascular bundle width. The “r” values (see Table 3) for number of vascular bundle, vascular bundle length and vascular bundle width was -0.42, 0.42 and 0.37 respectively. But there was a very weak correlation between moisture content and fiber morphology. The correlation between moisture contents with fiber length, fiber diameter, fiber lumen diameter and fiber wall thickness was 0.16, -0.10, 0.25 and -0.25 respectively. This was probably due to the decreased in percentage of parenchyma cell (higher frequency of vascular bundle), the site of water storage (Liese, 1987). At the internodes, the cell structures were uniform in term of the distribution and pattern of vascular bundle and parenchyma cell. The mean MC at outer layer was 40.87 % (47.12 -53.62%), middle layer was 83.82% (81.07 -86.57%) and for inner layer was 125.90% (123.00-128.65). The MC is lower at the outer position and increase toward inner position. This was because the area that contents high fiber strand has low capacity for water storage.

Table 3. The strength properties and Analysis of Variance (ANOVA) between *Gigantochloa* species at different condition, location and position in bamboo culms

	Shear	Tensile	
		Strength	Modulus
SPECIES			
<i>G.brang</i>	5.22c	103.39b	2661.65c
<i>G.levis</i>	8.87a	117.31a	3793.31a
<i>G.scortechinii</i>	6.71b	122.16a	3456.58b
<i>G.wrayi</i>	7.12b	114.79a	3670.27ab
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 is not significant different at 0.05 probability level.

3.2 Specific Gravity

The result on SG at difference location and position in the bamboo culms are shows in Table 1. The higher SG was obtained for the *G.wrayi* and *G.brang* with values 0.77 for both species. *G.levis* follows with SG of 0.75 and *G.scortechinii* at 0.71.

The SG at the internodes SG 0.74 and nodes 0.77. There was significantly different between location at node and internode. This was due to the higher vascular bundles concentration in outer layer compared to inner layer which contains lower vascular bundles concentration and higher amount of parenchyma. The bamboo SG has a close relation with vascular and ground tissues percentages which according to Janssen (1981), Espiloy (1987), Widjaja and Rashid (1987).

The SG for outer layer was 0.95, middle layer 0.73 and the inner layer was 0.58. The differences of SG 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 and the higher amount of vascular bundles, are probably responsible for the higher SG of this part of the culms.

The correlation value for SG (see Table 2) show strong correlation between the numbers of vascular bundle with SG. For all species the “r” values was 0.68. For the vascular bundle length and vascular bundle width, the “r” values were -0.63 and -0.53. There was weak correlation between fiber morphology properties with SG. The results obtained showed that SG of internode and node part of each bamboo species are only slightly different contrast with report by Hamdan et al. (2009) which noted that the nodes present along the culms height generally have higher density than those of the internodes due to lesser presence of parenchyma as well as lower MC and volumetric shrinkage. This was probably due to the techniques used in determining the density of the bamboo. In this study, the Radiation Densitometry was used to determine the density of the bamboo compared to the previous study which used the typical way to determine the density. *Gigantachloa levis* species showed highest value of specific gravity compared to the other bamboo species.

3.3 Shrinkage

3.3.1 Radial Shrinkage

The higher shrinkage value of radial shrinkage occurred in *G. scortechinii* (8.72%), follow by *G. wrayi* and

Gbrang which was 6.68% and 6.29% respectively and under one group (see Table 1). The lowest radial shrinkage was *Glevis* (5.67%). It shows, there was significant difference between location at node and internode. The radial shrinkage was higher at internodes compare to the node. It shows, there was significant different between position. The inner layer was the higher radial shrinkage and it reduce toward the outer layers. The radial shrinkage for the bamboo genera *gigantochlao* ranged from 5 to 9%. The correlation in Table 7 shows that it has a relationship with number of vascular bundle with “r” the values was -0.34 to -0.48 for all species. The correlation between fiber morphology and radial shrinkage was very weak.

3.3.2 Tangential Shrinkage

The higher tangential shrinkage was observed for *G.scortechinii* (11.74%), follow by *G.brang* (10.71%), *G.wrayi* (9.68 %) and the lowers *G.levis* (7.52%). It shows there was significant difference between location at node and internode. The tangential shrinkage was higher at node compare to the internode. It shows, there was significant different between position. The inner layer was the higher tangential shrinkage and it reduce toward the outer layers. The conclusion from this study, the tangential shrinkage for bamboo genera *gigantochlao* was about 6-13%. The correlation in Table 2 shows that it has a relationship between the tangential shrinkage and the number of vascular bundle with “r” the values was -0.35 to -0.57 for all species. The correlation between fiber morphology and tangential shrinkage was very weak.

3.3.3 Volumetric Shrinkage

High volumetric shrinkage occurred in *G.scortechinii* (16.83%), follow by *G.wrayi* (12.59 %) and the last group was *G.levis* and *G.brang* with the values of 11.08 and 10.72% respectively (see Table 1). There was significant difference between location at node and internode. The volumetric shrinkage was higher at internode compare to the node. The volumetric shrinkage for bamboo genera *gigantochlao* ranged between 10-15%. The correlation (see Table 7) shows relationship between volumetric shrinkage and the number of vascular bundle with “r” the values was -0.20 to -0.50 for all species. The correlation between fiber morphology and volumetric shrinkage was very weak.

The inner layer showed greater shrinkage compared to middle and outer layer. This is due to the higher amount of parenchyma in the inner layer compared to middle and outer layer. Bamboo, like wood, changes its dimensions when it loses moisture. The MC changes with the changes in the relative humidity and temperature of the surrounding environment.

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 takes place leading to radial and longitudinal shrinkage. This will result in the setting up of internal stresses between the fibers. These stresses exceed the cohesion of the fibers leading to warping. It was also observed that the radial shrinkage is about 0.5% and that of longitudinal shrinkage is negligible as in the case of other wood members.

The dimensional stability shown by bamboo occurs in timber as well. This behavior occurs in timber because the orientation of most of the microfibrils (S2 layer) is aligned parallel to the longitudinal axis. 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 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 broad fibril layer which are parallel to the axis is greater when 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 microfibrillar net in proportion to the amount of liquid evaporated (Panshin and De zeeuw, 1970). The moisture content changes with the changes in the relative humidity and temperature of the surrounding environment. Once the bamboo is cut, loss of water takes 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. It was also observed that the radial shrinkage is about 0.5% and that of longitudinal shrinkage is negligible as in the case of other wood members (Tamizi et al., 2011).

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S2 and S3)), the broad fibril layer which are parallel to the axis is greater when compared to the narrow lamellae.

3.4 Strength Properties

3.4.1 Compression Roller Shear Strength

Results of analysis of variance (ANOVA) and the mean average for compression roller shear strength are tabulated in Table 3 and Table 4. Based on statistical analysis, there was three significant difference group was observed between species at 95% confidence level. The higher compression roller shear was *G.levis* (8.87 MPa), followed by *G.wrayi* (7.12 MPa) and *G.scortechinii* (6.71 MPa) under one group and the lowers was *G.brang* (5.22 MPa).

There was a significant difference between green and air dry sample. The results for compression roller shears for green was 5.76 MPa and for the air dry was 8.20 MPa. The shear strength for air dry sample was nearly 30% higher than the green sample. The result for green condition showed that *G.levis* shear strength was 3.67-12.76 MPa, followed by *G.wrayi* from 3.11-8.62 MPa, *G.brang* from 1.83-6.62 MPa and the lowest was *G.scortechinii* from 1.29-6.14 MPa. For the air dry condition, the shear strength was increase; the result showed that *G.levis* was 4.33-12.91MPa, followed by *G.wrayi* 3.54-12.13 MPa and *G.brang* 3.22-8.30 MPa and *G.scortechinii* 4.95-12.67 MPa.

The analysis of variance showed significant difference for the compression roller shears strength between this two locations. This result, irrespective of species and condition of the sample. Node shear strength (15-20%)> Internode shear strength. At difference position, the result for analysis of variance showed that, it was there was all position was significant difference.

Table 4. Strength Properties of Compression Roller Shears between *Gigantachloa spp*

Sample	Location	Mean Compression Roller shear (MPa)			
		<i>G. brang</i>	<i>G.levis</i>	<i>G. scortechinii</i>	<i>G.wrayi</i>
(Green sample)					
Internode	Outer	4.80 (±0.60)	8.62 (±0.31)	4.23 (±0.75)	5.17 (±0.51)
	Middle	5.07 (±0.31)	9.07 (±0.53)	5.64 (±0.88)	6.06 (±0.73)
	Inner	2.13 (±0.70)	3.67 (±0.40)	2.90 (±0.86)	3.51 (±1.19)
Node	Outer	5.51 (±0.85)	9.70 (±2.25)	5.61 (±1.00)	8.34 (±2.58)
	Middle	5.66 (±0.42)	13.76 (±1.74)	6.14 (±0.48)	9.62 (±2.06)
	Inner	1.87 (±0.14)	5.42 (±0.81)	1.84 (±0.40)	3.94 (±2.65)
(Air-dry sample)					
Internode	Outer	6.37 (±2.32)	10.29 (±2.38)	9.22 (±2.22)	8.25 (±0.50)
	Middle	6.57 (±2.26)	12.05 (±2.00)	9.92 (±0.91)	10.04 (±1.35)
	Inner	3.22 (±0.59)	4.33 (±1.25)	4.95 (±1.40)	3.54 (±0.79)
Node	Outer	8.30 (±1.17)	11.70 (±1.53)	8.90 (±4.17)	10.60 (±2.59)
	Middle	9.62 (±1.04)	12.91 (±1.82)	12.67 (±1.36)	12.13 (±2.38)
	Inner	3.51 (±0.60)	4.96 (±1.56)	8.49 (±1.05)	4.20 (±1.31)

Standard deviations shown in parentheses.

The compressive for all species increased with the increase the number of vascular bundle which is increase from inner to outer part of the bamboo (Rafidah et al., 2010; Li, 2004) that the compression strength increases from the central to the outer part. It is also noted that the number of vascular bundle increased from the bottom to the top section (Tommy et al., 2004). The *G. Levis* with a greater number of vascular bundles provides a consistent strength and performs better than other species.

3.4.2 Tensile Strength

The results show that the tensile strength for various bamboo species at difference condition (green and air-dry), location (node and internode) and position (outer, middle and inner layer) (see Table 5). Based on statistical

analysis, there was two significant different group was observed between species at a 95% confidence level. The higher group was *G.scortechinii* (122.16 MPa), follow by *G.levis* (117.31 MPa) and *G.wrayi* (114.79 MPa) and the lower was *G.brang* (103.39 MPa). That mean *G.brang* has significant difference with the other species.

There was a significant difference between green and air dry sample. The result for tensile strength for green was 89.95 MPa and for the air dry was 138.87 MPa. Table 5 showed the variation of mechanical properties of tensile strength for *Gigantachloa spp*. The result for green condition showed that *G.levis* tensile strength was from 37.12-149.66 MPa, followed by *G.wrayi* from 62.02-163.68 MPa, *G.brang* from 56.17-96.94 MPa and *G.scortechinii* from 35.14-123.11Mpa. For the air dry condition, the tensile strength was increase; the result showed that *G.levis* was 76.30-208.06 MPa, followed by *G.wrayi* 63.70-178.27 MPa and *G.brang* 69.63-184.80 MPa and *G.scortechinii* 74.08-208.06 MPa. It can be seen that air dry samples showed better tensile strength almost 35% compared to green samples (Air dry (35%)> Green). This may be due to the fact that bamboo behaves similar to wood whereby the mechanical properties increase with decrease in moisture content (Hamdan, 2004).

Table 5. Strength Properties of Tensile Strength between *Gigantachloa spp*

Sample	Location	Mean Tensile strength (MPa)			
		<i>G. brang</i>	<i>G.levis</i>	<i>G. scortechinii</i>	<i>G.wrayi</i>
(Green sample)					
Internode	Outer	96.94 (±8.95)	149.66 (±16.25)	123.11 (±13.92)	163.68 (±16.63)
	Middle	81.96 (±7.01)	128.91 (±12.86)	86.62 (±10.78)	122.21 (±15.10)
	Inner	75.18 (±6.67)	113.94 (± 9.43)	79.81 (±9.09)	112.21 (±11.22)
Node	Outer	88.56 (±10.73)	116.91(±14.51)	77.30 (±9.10)	75.14 (±16.43)
	Middle	61.27 (±3.00)	72.00 (±05.41)	69.81 (±5.63)	73.12 (±8.59)
	Inner	56.17 (±5.38)	37.12 (±12.06)	35.14 (±5.00)	62.02 (±12.31)
(Air-dry sample)					
Internode	Outer	184.80 (±9.48)	208.06 (±14.35)	204.9 (±17.13)	178.27 (±11.45)
	Middle	167.09 (±14.84)	186.44 (±13.10)	219.56 (±14.40)	175.16 (±13.21)
	Inner	135.33 (±12.41)	152.23 (± 19.28)	152.10 (±17.48)	174.03 (±12.49)
Node	Outer	140.05 (±12.67)	85.86 (±13.86)	179.11 (±15.68)	105.54 (±14.55)
	Middle	83.70 (±9.49)	80.28 (±13.37)	164.32 (±11.83)	72.39 (±15.03)
	Inner	69.61 (±9.10)	76.30 (±11.41)	74.08 (±10.55)	63.70 (±7.48)

Standard deviations shown in parentheses.

The analysis of variance for tensile strength at difference location in Table 3, showed, there was significant difference between the internode strips and node strips. The internode was higher tensile strength which was 144.68 MPa compared to the node which was 84.36 MPa. This value without consider the species, 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%)> node tensile strength).

Result from the Table 5 also showed that the tensile strength increase from inner to outer part of the bamboo for every bamboo species. Analysis of variance showed that, there was significant difference between the outer, middle and inner strips. The higher was at the outer layers which was 135.93 MPa, Middle 115.49 MPa and the lowers was the inner layer which was 91.81 MPa. 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% more stronger than inner layer. (Outer layer (15%)> middle layer (15%)> inner layer). Difference in tensile strength, the outer layer strength was 30% higher than the inner layer.

This phenomenon can be related to the higher content of 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.

Table 6. Correlation Coefficients of Different Moisture content, Specific Gravity and Anatomical Characteristics with Physical Properties of various bamboo species genera *Gigantochloa*

Properties	Species	Shrinkage		
		Radial	Tangent	Volumetric
Moisture Content	<i>G. brang</i>	0.29*	0.16*	0.34*
	<i>G. levis</i>	0.40*	0.44*	0.36*
	<i>G. scortechinii</i>	0.58*	0.61*	0.61*
	<i>G. wrayi</i>	0.34*	0.28*	0.38*
Specific Gravity	<i>G. brang</i>	-0.35*	-0.28*	-0.35*
	<i>G. levis</i>	-0.44*	-0.49*	-0.34*
	<i>G. scortechinii</i>	-0.52*	-0.61*	-0.55*
	<i>G. wrayi</i>	-0.59*	-0.61*	-0.45*
Number Vascular bundle	<i>G. brang</i>	-0.48*	-0.42*	-0.40*
	<i>G. levis</i>	-0.36*	-0.35*	-0.32*
	<i>G. scortechinii</i>	-0.49*	-0.57*	-0.50*
	<i>G. wrayi</i>	-0.34*	-0.51*	-0.32*
Vascular bundle length	<i>G. brang</i>	0.37*	0.35*	0.14*
	<i>G. levis</i>	0.39*	0.47*	0.39*
	<i>G. scortechinii</i>	0.34*	0.42*	0.34*
	<i>G. wrayi</i>	0.43*	0.64*	0.17*
Vascular bundle width	<i>G. brang</i>	0.32*	0.53*	0.12*
	<i>G. levis</i>	0.38*	0.47*	0.22*
	<i>G. scortechinii</i>	0.16*	0.33*	0.20*
	<i>G. wrayi</i>	0.31*	0.51*	0.24*
Fibre length	<i>G. brang</i>	-0.05n	-0.13*	0.21*
	<i>G. levis</i>	0.12*	0.07n	0.24*
	<i>G. scortechinii</i>	0.11*	0.02n	0.14*
	<i>G. wrayi</i>	0.00*	-0.08n	0.09n
Fibre diameter	<i>G. brang</i>	-0.18*	-0.31*	-0.18*
	<i>G. levis</i>	-0.11*	-0.11*	-0.23*
	<i>G. scortechinii</i>	-0.15*	-0.13*	-0.17*
	<i>G. wrayi</i>	-0.24*	-0.22*	-0.14*
Fibre lumen diameter	<i>G. brang</i>	0.13*	0.31*	-0.04n
	<i>G. levis</i>	0.06n	0.05n	-0.09n
	<i>G. scortechinii</i>	0.04n	0.10*	0.06n
	<i>G. wrayi</i>	0.07n	0.14*	-0.01n
Fibre wall thickness	<i>G. brang</i>	0.13*	-0.18*	-0.18*
	<i>G. levis</i>	0.20*	-0.10*	-0.05n
	<i>G. scortechinii</i>	-0.28*	-0.33*	-0.34*
	<i>G. wrayi</i>	-0.23*	-0.18*	-0.16*

* significant , ⁿ not significant.

3.4.3 Tensile Modulus

Analysis of variance (ANOVA) on tensile modulus properties are tabulated in Table 6 and the result in Table 7. The results show that the tensile modulus for various bamboo species at difference condition (green and air-dry), location (node and internode) and position (outer, middle and inner layer). Based on statistical analysis, there was three significant different group was observed between species at a 95% confidence level. The higher group was *G. levis* (3793 MPa), follow by *G. wrayi* (3670 MPa) and *G. scortechinii* (3456 MPa) and the lower was *G. brang* (2661 MPa).

There was a significant difference between green and air dry sample. The result for tensile modulus for green was 4003 MPa and for the air dry was 2786 MPa. Table 7 showed the variation of mechanical properties of tensile modulus for *Gigantachloa spp.* The result for green condition showed that *G. levis* tensile modulus was from 2043-4802 MPa, followed by *G.wrayi* from 2752-4712 MPa, *G.brang* from 2056-3227 MPa and *G.scortechinii* from 1203-3086 Mpa. For the air dry condition, the tensile modulus was increase; the result showed that *G.levis* was 3184-5023 MPa, followed by *G.wrayi* 2595-4818 MPa and *G.brang* 2018-3638 MPa and *G.scortechinii* 3387-5258 MPa. It can be seen that air dry samples showed better tensile modulus almost 35% compared to green samples (Air dry (35%) > Green). This may be due to the fact that bamboo behaves similar to wood whereby the mechanical properties increase with decrease in moisture content (Hamdan, 2004).

The analysis of variance for tensile modulus at difference location in Table 3, showed, there was significant difference between the internode strips and node strips. The internode was higher tensile modulus which was 3545 MPa compared to the node which was 3245 MPa. The difference in tensile strength almost 5-10% higher in the internode strip compared to the node strips. (Internode tensile modulus (5-10%) > node tensile modulus).

The result (see Table 6) also showed that the tensile modulus increase from inner to outer part of the bamboo for every bamboo species. Analysis of variance showed significant difference between the outer, middle and inner strips. The higher was at the outer layers which was 4061 MPa, Middle 3344 MPa and the lowers was the inner layer which was 2779 MPa. Difference in tensile modulus in this experiment showed that the outer layer has 15-18% stronger from the middle layer, and the middle layer has 15-18% stronger than inner layer. This can be related to the higher content of vascular bundles in which can lead to the higher density of the outer part and increase the tensile modulus of the outer part than the inner part of the bamboo. Tensile strength and Young's modulus also increase with the increase in cellulose content and decreasing micro-fibril angle (Li, 2004).

3.5 Correlation between Shear with MC, SG, Anatomy

The shear has a negative correlation, where the values of 'r' were -0.35 and -0.41 for the air dry and wet samples respectively for all species (see Table 7). Initially, moisture content was high and the strength of the shear roller was lower. Specific gravity correlated significantly with the roller shear tests with a values of 'r' were -0.38 and 0.35 on the air dry and wet samples respectively for all species. This shows that at high specific gravity, the roller shear strength was also a high. Specific gravity plays a direct role in the roller shear strength test in bamboo.

The number of vascular bundle has a positive relationship with the roller shear test where the 'r' values were 0.29 and 0.35 on the air dry and wet samples respectively for all species. This means that a high number of vascular bundle was also high roller shear strength. The presence of vascular bundle, contributed greatly to the strength of the roller shear.

The vascular bundle size (for length and width) has negative relationship with the roller shear tests. In the vascular bundle length, the values of 'r' were -0.35 and -0.33 in the air dry and wet samples respectively for all species. This shows the longer length of vascular bundle the lower of roller shear strength. Vascular bundle width did 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 has a correlation with roller shear tests. The positive correlation with r values were 0.22 and 0.28 on air dry and wet samples respectively. This means the thick of fiber wall, the higher of roller shear strength.

3.6 Correlation between Tensile Strength with MC, SG and Anatomy

Table 7 shows the correlation between tensile strength with the moisture content at initial of bamboo sample. It has a negative and weak correlation. The values of 'r' were -0.15, and -0.25 in air dry and wet samples respectively for all species. Where, at the initial bamboo has high moisture content, tensile strength was low.

The specific gravity has a positively correlated with tensile strength. The values of 'r' were 0.31 and 0.30 for air dry and wet samples respectively for all species. This means, the increase of specific gravity, tensile strength also increases.

Table 7. Correlation Coefficients of Moisture Content, SG and Anatomical Characteristics with Strength of various bamboo species in genera *Gigantochloa*

Properties	Species	Shear Strength		Tensile Strength			
		Air dry Condition	Green Condition	Strength (Air-dry)	Modulus (Air-dry)	Strength (Green)	Modulus (Green)
Moisture Content	<i>G. brang</i>	-0.62*	-0.72*	-0.23*	-0.26*	-0.26*	-0.55*
	<i>G. levis</i>	-0.56*	-0.53*	-0.20*	-0.23*	-0.27*	-0.62*
	<i>G. scortechinii</i>	-0.34*	-0.56*	-0.44*	-0.52*	-0.40*	-0.63*
	<i>G. wrayi</i>	-0.43*	-0.32*	-0.40*	-0.27*	-0.07n	-0.14*
Specific Gravity	<i>G. brang</i>	0.58*	0.73*	0.39*	0.39*	0.36*	0.59*
	<i>G. levis</i>	0.54*	0.45*	0.37*	0.34*	0.41*	0.72*
	<i>G. scortechinii</i>	0.56*	0.47*	0.50*	0.49*	0.54*	0.70*
	<i>G. wrayi</i>	0.46*	0.35*	0.18*	0.60*	0.29*	0.37*
Number Vascular bundle	<i>G. brang</i>	0.23*	0.46*	0.32*	0.33*	0.30*	0.25*
	<i>G. levis</i>	0.28*	0.23*	0.29*	0.26*	0.27*	0.38*
	<i>G. scortechinii</i>	0.38*	0.40*	0.59*	0.64*	0.53*	0.39*
	<i>G. wrayi</i>	0.49*	0.42*	0.29*	0.30*	0.32*	0.25*
Vascular bundle length	<i>G. brang</i>	-0.37*	-0.59*	-0.42*	-0.47*	-0.38*	-0.32*
	<i>G. levis</i>	-0.57*	-0.54*	-0.36*	-0.39*	-0.32*	-0.28*
	<i>G. scortechinii</i>	-0.38*	-0.35*	-0.55*	-0.38*	-0.21*	-0.30*
	<i>G. wrayi</i>	-0.50*	-0.32*	-0.23*	-0.28*	-0.33*	-0.22*
Vascular bundle width	<i>G. brang</i>	-0.03n	-0.24*	0.15*	0.18*	0.15*	-0.03n
	<i>G. levis</i>	-0.05n	-0.20*	0.03n	0.09n	0.01n	-0.12*
	<i>G. scortechinii</i>	-0.00n	-0.40*	-0.17*	-0.04n	-0.00n	-0.11*
	<i>G. wrayi</i>	-0.07n	-0.14*	0.00n	-0.01n	0.02n	-0.04n
Fibre length	<i>G. brang</i>	-0.14*	-0.10*	0.15*	0.18*	0.15*	-0.03n
	<i>G. levis</i>	-0.01n	-0.14*	0.03n	0.09n	0.01n	-0.12*
	<i>G. scortechinii</i>	0.00n	0.10*	-0.17*	-0.04n	-0.00n	-0.11*
	<i>G. wrayi</i>	0.07n	0.01n	0.00n	-0.01n	0.02n	-0.04n
Fibre diameter	<i>G. brang</i>	0.20*	0.07n	-0.07n	-0.06n	-0.06n	-0.10*
	<i>G. levis</i>	0.02n	0.12*	0.04n	0.03n	0.03n	-0.17*
	<i>G. scortechinii</i>	0.29*	0.19*	0.13*	0.01n	-0.06n	-0.18*
	<i>G. wrayi</i>	0.24*	0.18*	-0.05n	-0.11*	0.10*	0.00n
Fibre lumen diameter	<i>G. brang</i>	-0.04n	-0.09n	-0.07n	-0.06n	-0.06*	-0.11*
	<i>G. levis</i>	-0.06n	-0.09n	0.15*	0.11*	0.15*	-0.10*
	<i>G. scortechinii</i>	-0.13*	-0.06n	0.31*	0.23*	0.13*	-0.20*
	<i>G. wrayi</i>	-0.07n	-0.07n	0.04n	0.04n	0.05n	0.02n
Fibre wall thickness	<i>G. brang</i>	0.25*	0.19*	-0.12*	-0.14*	-0.12*	-0.06n
	<i>G. levis</i>	0.23*	0.12*	0.00n	0.00n	-0.00n	-0.15*
	<i>G. scortechinii</i>	0.28*	0.37*	-0.20*	-0.29*	-0.25*	-0.02*
	<i>G. wrayi</i>	0.30*	0.21*	-0.08n	-0.14*	-0.13*	-0.00n

* significant, ⁿ not significant.

Number of vascular bundle has a positive correlation with the tensile strength of which the values of 'r' were 0.32 and 0.35 for air-dry and wet samples respectively for all species. This means the increase of vascular bundle number, tensile strength was also increase.

Vascular bundle size (for length and width) has negative relationship with the tensile strength. In the vascular bundle length, the values of 'r' were 0.38 and 0.40. While the vascular bundle width were 0.38 and 0.36 for air-dry and wet samples respectively for all species. This shows 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 was insignificant. There is no clear relationship of tensile strength with fiber morphology.

3.7 Correlation between Tensile Modulus with MC, Specific Gravity, Anatomy and Fiber Morphology

Table 7 shows the correlation between tensile modulus with the moisture content at initial of bamboo sample. It has a negative correlation, where the values of 'r' were -0.12 and -0.46 for air-dry and wet samples respectively for all species. Where, the higher moisture contents at the initial bamboo sample have a low tensile modulus.

Specific gravity significantly correlated with the tensile modulus with the values of 'r' were 0.36 and 0.39 for air-dry and wet samples respectively for all species. This shows at high specific gravity, the tensile modulus was also high. Specific gravity plays a role in determining the strength of the tensile modulus in bamboo.

Number of vascular bundle has a positive relationship with the tensile modulus, where the values of 'r' were 0.37 and 0.35 for air-dry and wet samples respectively for all species. This means the high number of vascular bundle, the tensile modulus was also high. The numbers of vascular bundle give an affect on tensile modulus.

Vascular bundle size (length and width) has a negative correlation with the tensile modulus. In the vascular bundle length, the values of 'r' were -0.43 and -0.24. While the vascular bundle width were -0.38 and -0.25 for air-dry and wet sample respectively and for all species. This shows that the larger size of the vascular bundle the lower tensile modulus.

The correlation between tensile modulus with fiber morphology was not strong and some are insignificant. There is no clear relationship of tensile modulus with fiber morphology.

4. Conclusion

The morphology fibers showed significant differences between species in terms of length, diameter and lumen size. Each species has different characteristics of fiber. The vascular bundle for these genera are around 4-7/4mm² and it is dense at the outer position which was 8.5 vascular bundle/4mm², middle 4.88 vascular bundle/4mm² and at the inner position was 3.4 vascular bundle per/4mm². The vascular bundle length between 845 - 1183 µm and a width of 530 - 759 µm. The fibre length were between (1745.00 -2039.98 µm), diameter (17.26 - 22.75 µm), lumen (3.83 - 8.66 µm) and wall thickness (1.35 - 5.31µm).

The moisture content in the bamboo ranged between 73 - 112%, the MC is higher in the internode approximately 95% compared with the node that is 78%. Position at inner layer of bamboo has the highest MC which is 126%, middle layer was 83% and outer layer was 41%. The density increases from outer to the inner layer of the bamboo. It starts from 500 kg/m³ at inner and increased to more than 820 kg/m³ at outer part of bamboo at 12% moisture content. The specific gravity for all species tested was about 0.69 - 0.78, but the inner position is 0.58, middle 0.73 and outer positions is 0.94. The shrinkage in the radial, tangential and the volume is around (5 - 9, 7 - 12, 10 - 17%) respectively for all species. Position in a higher rate of shrinkage was at the inner (8.6, 13.50, 15.44%), follow by the middle (6.85, 9.72, 12.57%) and outer (5.04, 6.52, 10.40%) respectively. On the average surface roughness of bamboo for these genera are around 2.95 - 3.82, 18.17 - 25.71, and 28.67 - 39.55 respectively.

The tensile strength for the tested bamboos ranged between 103.38-122.15 MPa. The tensile strength of dried bamboo is 138.87 MPa compared with 89.95 MPa for green bamboo. The tensile modulus ranged between 2661.65 - 3793.13 MPa. The tensile modulus of air-dried bamboo is 4003.85 MPa compared with 2786.96 MPa for green bamboo. The MOR for the bamboos studied ranged between 91.19-132 MPa. The MOR for dried bamboo was 142.21 MPa compared to the green bamboo 99.56 MPa. The MOE for the bamboos varied between 11961.70 - 20430.40 MPa. MOE of air-dried bamboo were 17610.00 MPa and green bamboo 13777.80 MPa. The shear strength at different thickness (Roller shear) ranged between 5.22 - 8.87 MPa. The shear of dried bamboo was 8.20 MPa compared to 5.76 MPa for green bamboo.

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