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RELATIONSHIP BETWEEN PHYSICAL, ANATOMICAL AND STRENGTH PROPERTIES OF 3-YEAR-OLD CULTIVATED TROPICAL BAMBOO *Gigantochloa scortechinii*

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ABSTRACT

The physical, anatomical and strength properties of 3-year-old cultivated tropical bamboo *Gigantochloa scortechinii* was studied. Five (5) culms of the bamboo were selected and harvested from the Bambusetum plot located in the Forest Research Institute Malaysia in Kepong. The anatomical study focussed on the vascular bundles and fibres located at the internodes and nodes No. 8 at the outer, middle and inner cross section of the bamboo. The sizes of the vascular bundles length, vascular bundles width, fiber length, fiber diameter, fiber lumens diameter, fiber walls thickness and fiber Runkle's ratio were measured in relation to the samples positions at the internodes, nodes, and positions in the cross-section of the bamboo culms. The physical study gives emphasis on the moisture content, basic density and dimensional stability. The strength properties study focused on the tension parallel to the grain and shear test. Both the physical and strength study were conducted at internodes and nodes No. 8 of the bamboo.

Keywords: bamboo *Gigantochloa scortechinii*, anatomy, fibre morphology, physical properties, strength properties.

INTRODUCTION

The timber production from the natural tropical forests will continue to be on the decline despite the increase in the world population 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 species reaches maturity within 3 - 4 years can provide material to replace timber in the coming future. Research and development which covers all aspects in bamboo silviculture, propagation, processing, properties and utilization of bamboo found naturally growing wild in the forest and cultivated has been intensified. However, study on cultivated bamboo stands has so far mostly confined to selected species in silviculture and fertilizers application to enhance growing (Azmy *et al*., 2007). Information on the properties such as anatomical and structural properties is rather limited.

The physical and strength properties of bamboo have been widely studied by many researchers all over the world (Li, 2004; Rafidah *et al*., 2010). However, the information on the relationship between the anatomical, physical and strength properties of some species in genus *Gigantochloa* is still limited. In this study, a tropical bamboo species *G. scortechinii* was studied. *G. scortechinii* is one of the most popular bamboo species in Malaysia due to its having good physical morphology and strength properties. 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 parallel to grain, the static bending and compression roller shear test for small size specimens were carried out.

Anatomical and physical characteristics of bamboo culms have been known to have significant effects on their durability and strength (Latif and Tamizi, 1993; Liese, 1985; Razak, 1998). Studies on the anatomical and physical properties of cultivated *Bambusa vulgaris* conducted by Razak *et al*. (2010) support this statement. Information generated on the anatomical properties of bamboo can be used to determine their possible proper utilization. Currently, bamboo used for making traditional products such as handicraft, basketry, and high-value added products of panels, parquets, furniture and construction materials. *G. scortechinii* bamboos are among the most popular tropical bamboo species for plantation. These bamboos are easily cultivated and possess thick culms wall, and having uniform sizes between the nodes and internodes. This makes them suitable as materials for industrial usage.

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. The objectives of the study was to determine the relationship between the anatomical, physical and strength of 3-year-old bamboo culms of the *G. scortechinii*.

MATERIALS AND METHODS

Materials

Culms of the cultivated 3-year-old bamboo *G. scortechinii* were harvested from the Bambusetum Plot,

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Forest Research Institute Malaysia (FRIM), Kepong, Selangor, Malaysia. The 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 ranging from 8-17 cm diameter. Each stem was marked and cut at nodes and internodes No. 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. A total number of 10 bamboo culms were taken for this study.

Sample preparation

The bamboo culms were divided into nodes and internodes, position in the bamboo culms wall (outer, middle 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.

Anatomical assessment

The technique used by Latif and Tamizi (1993) was used with some modification in measuring and counting the distribution of the vascular bundles on the bamboo surface at the cross section. The anatomical characteristic of the bamboo with two locations (node and internode) and three (3) positions (outer, middle and inner layer) of the bamboo culm were studied. Vascular bundles: Method of measuring the vascular bundles distribution and fibre dimensions was adopted from the technique used by Latif and Tamizi (1993). Vascular bundle size: The sizes of the vascular bundles were measured by the scanning electron microscope (SEM) images through it measuring tools.

Physical properties

Moisture content (MC) were determined using difference between green sample and oven drying method described by ASTM D 4442 standard. Basic density (BD) was determined by the volumetric measurement method described by ASTM standard D-2395. 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, 2003). 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 BD 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.

Moisture content (MC)

The MC values were determined using the difference between the green sample and the oven drying method described by ASTM D143: Determination of MC at green condition (ASTM, 1990). 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 culm wall thickness mm to determine the MC at green condition. The weight of the samples was recorded. Then, samples were placed in oven set at 60°C for 24 hours and later reset at 102°C for 24 hours. The bamboo sample was then removed from the oven and cooled in desiccators for 30 minutes. All samples were taken out and weighted for the second time and recorded.

Basic density (BD)

The BD 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 culm wall 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 obtained. 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.

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 (1990).

Determination of fibre morphology bamboo maceration

The bamboo splits (20 mm x 10 mm x culm wall thickness) were cut tangentially and divided into 3 equal portions (inner, middle, outer). Each portion sliced radially into match stick sizes using sharp knifes. Macerates were prepared from match-stick sizes bamboo by placing them

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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 becomes soft and white. A drop or two 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 fibres. Safranin was used to colour the extracted fiber to red. One hundred (100) undamaged or unbroken fibres 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.

Strength properties tension parallel to grain

Tension tests parallel to the grain are seldom investigated for bamboo. There was no report on tension strength for the *G. scortechinii*. 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 difficult 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.

Shear test

The shear test was performed in accordance to BS EN 314-1:2004 (BS, 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^{o}C and at a relative humidity of 30% (± 2%) before testing. The green samples were tested directly.

RESULTS AND DISCUSSION

Moisture content (MC)

The results on the MC of the bamboo culms in green condition are tabulated in Table-1. The analysis of variance was also included in the Table-1. The highest MC was observed in the inner layer of the bamboo at 125.90%. The MC at the internodes was 94.45% and for the node was 78.61%. The MC was higher at the internodes compare to the nodes. The anatomical factor may contribute to the differences of the MC between two locations. At the internodes, the metaxylem vessels structure was more uniform and large, while at the nodes the metaxylem vessels are not uniform and smaller. The MC at the outer layer was 49.87%, middle layer 83.82% and for the inner layer was 125.90%. The MC is lower at the outer position and increase toward the inner positions. This is because the area contents high fiber strand and thus has low capacity for water storage. According to Liese (1985), the differences in the MC might be due to difference in some inherent factors such as age, anatomical features and chemical composition. 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 and Yu, 2002).

Basic density (BD)

Table-1 shows the result on BD at difference locations and positions in the bamboo. The BD at the internodes and nodes were 0.74 and 0.77 g/cm^3 respectively. There were significant differences between location at internodes and nodes. 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 BD has a close relation with vascular and ground tissues percentages which according to Janssen (1981); Espiloy (1987); Widjaja and Risyad (1987). The BD for outer layer was 0.95 g/cm^3, middle layer 0.73 g/cm^{3}and the inner layer was 0.58 g/cm^3. The differences of BD at both the nodes and internodes were due to the fiber wall thickness. In the nodes, fibres have thicker cell walls and the high proportion of fibres in every vascular bundle and the higher amount of vascular bundles, are probably responsible for the higher BD of this part of the culms.

Shrinkage

The higher shrinkage value occurred in the inner layer (radial shrinkage at 8.63%, tangential shrinkage 13.50%) (shown in Table-1). There were significant differences in the shrinkage values between locations and positions. The radial shrinkage was higher at the internodes compare to the nodes but higher at the nodes in the tangential shrinkage. The inner layer was the higher radial shrinkage and it reduces toward the outer layers. The radial shrinkage for the bamboo genus *Gigantochlao* ranged from 5.04 to 8.63%, and tangential shrinkage between 6.52 to 13.50%.

The tangential shrinkage for bamboo *G. scortechinii* about 6.52-3.50%. There was significant difference between location at nodes and internodes. The tangential shrinkage was higher at nodes compare to the internodes. There was significant different between position. The inner layer was the higher tangential shrinkage and it reduced toward the outer layers.

The volumetric shrinkage occurred in *G. scortechinii* ranges from 10.40 to 15.45%. There was significant difference between location at nodes and internodes. The volumetric shrinkage was higher at internodes compare to the node. 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).

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 lamallae showing fibrillar angle of 80 - 90° to the axis and the broader ones with fibrilar angle almost parallel to the axis. Although the fibres 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.

Table-1. The physical properties and the ANOVA between location and position.

	Physical properties				
	Moisture content (%)	**Basic density** (g/cm^3)	**Shrinkage** (%)		
			Radial (%)	**Tangential** (%)	**Volume** (%)
Location					
Internodes	94.45a	0.74b	7.00a	9.17b	14.83a
Nodes	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

Vascular bundle distribution

The results for the vascular bundles distribution were shown in Table-2. Different number of vascular bundle in the internode and the node sections were observed in the bamboo culm. The number of vascular bundle for *G. scortechinii* were 13.24 bundle/4 mm^2 at outer position, 6.44 bundle/4 mm^2 at middle position and 3.50 bundle/4 mm^2 at inner position at the internodes and, 10.55 bundle/4 mm^2 at outer position, 5.80 bundle/4 mm^2 at middle position and 2.75 bundle/4 mm^2 at inner position bundle/4 mm^2 at the nodes. These were in agreement with Latif (1995) finding in the number of vascular bundles in *G. scortechinii*. The anatomical features within and between culm of different or even the same bamboo species may vary as the individual characteristic of the bamboo itself (Pattanath, 1972; Soeprayitno *et al*., 1990).

The distributions of vascular bundles in the internodes were higher than the nodes. The vascular bundles were also observed to be higher in number and more compacted in the outer layers of the bamboo culm than those in the inner layers. This observation was also made by other researchers (Liese, 1992, Latif and Tamizi 1993). Li (2004) in his studies on a monopodial bamboo *P. pubescens* found that the numbers of vascular bundles were higher compared to the simpodial bamboo species. Similar trend was reported in sympodial bamboo *Phyllostachys pubescens* (Wenyue *et al*., 1981). This indicates that bamboo possesses long and small vascular bundle at the outer zone, but short and big towards the inner zone (Liese, 1985).

Vascular bundle length

The results on the vascular bundles length is shown in Tables 2 and 3. The vascular bundle lengths at internodes were 869.67 µm and at the nodes were 1058.94 µm. The vascular bundles lengths were longer at the nodes than the internodes. The vascular bundle length for outer layer position was 748.54 µm, middle layer 1013.25 µm and for inner layer was 1131.42 µm. The vascular bundles

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lengths were longer at the middle than at the outer and inner periphery.

Vascular bundle width

The results on the vascular bundles width is also shown in Tables 2 and 3. The vascular bundle's width at the internodes was 585.42 µm and nodes 630.70 µm respectively. The average of the width at different position showed significant difference between the internodes and nodes. The vascular bundles widths were observed to be higher at the nodes. 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 different between the vascular bundles in samples position. Vascular bundle width was widened at the inner and smaller toward the outer periphery position. This is due to the size of vascular bundle which were smaller and compact at the outer layer, dense to the inner layer of bamboo culms.

Table-2. Number of vascular bundle (per 4 mm$^{2)}$ of *Gigantochloa scortechinii*.

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)
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)

Values in bracket represent the standard deviation

Table-3. Analysis of variance for anatomical properties between location and 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

Values followed by the same letter in a column is not significant different at 95% probability level

Fiber length

The results for the fiber length study showed in Table-4 indicates significant differences between the positions and portions. The fiber length obtained for internodes were 2074.24 µm and nodes 1672.62 µm. The fiber lengths were longer at the internodes compare to the nodes. At the internodes, the anatomy structure was consistent but at the nodes it was quite twisted. The anatomical factor, may be contribute the different fiber length between two positions. The fiber lengths for outer layer position was 1698.52 µm, middle layer 2060.41 µm and for inner layer was 1861.35 µm. Significant differences were observed in the fiber length at the internodes, nodes and between the cross-sectional position of the bamboo. The fiber length shows considerable differences within one culm (Liese and Grosser, 1972). The results from this study showed that bamboo fiber length from *G. scortechinii* 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 in relation to its properties and utilization. They reported that the fibres contribute 60-70% by weight of the total culm tissue. Certain species generally have shorter fibres, such as *Phyllostachys edulis* (1.5 mm), *Ph. pubescens* (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 clearly shorter, but still longer than hardwood (1200 µm). In fact it is longer than *Eucalytus spp* (960-1.0400 µm) was popular as a source of short fiber pulp for paper industry (Horn and 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 (see 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 were 18.49 µm, middle layer 22.36 µm and inner layer 19.56µm.

The fiber diameter of the *G. scortechinii* in this study ranged between 18.23 -22.36 µm. The previous studies on the fiber diameter for *G. scortechinii* were 23-37 µm (Latif, 1995), while the studies on the species of *bambusa* genera found that; fiber diameter for *B. blumeana* were 12.0 µm (Ireana, 2009), *B. vulgaris* was 16.9-18.0 µm (Razak *et al*., 2010), 20-42 µm (Latif, 1995). This study found that the fiber diameter were 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 on this study showed that the fiber diameter *Gigantochloa* genera (17-22.8µm) was bigger than *Eucalytus spp* (15.5 - 16.3µm).

Lumen diameter

The lumen diameter was 4.43 µm at internodes and 6.18 µm at the nodes (shown in Table-4). The diameter at different position showed that the outer layer was 5.44 µm; middle layer 5.51 µm and inner layer 5.96µm. similar results were obtained but smaller than those obtained by Latif (1995). The lumen diameter for *Bambusa* were 1.6 µm for B. *blumeana* (Ireana, 2009), 2.3-2.6 µm for *B. vulgaris* (Razak *et al*., 2010). The lumen diameter for *Eucalytus spp* was 8.5-9.5 µm. The mean average for lumen diameter at different position showed that for the lumen diameter at node was 6.18 µm and for the internodes was 4.43µm. The results showed the lumen diameter were larger at the nodes compare 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 results showed the lumen diameter was largest at the inner and smaller toward the outer layer and it was a significantly difference.

Wall thickness

The fibres wall thickness was 6.90 µm at internodes and 7.02 µm at the nodes (Table-4). The thickness at different position showed that the outer layer were 7.03 µm, middle layer 8.43 µm and inner layer 6.80µm. The results showed the wall thickness are thicker at the nodes as compare to the internodes and it was a significantly difference between this two position. The mean average for wall thickness at difference position showed that at 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 is thicker at the outer and thinner toward the inner layer. *B. blumeana* which was 5.01 µm (Ireana, 2009), *B. vulgaris* which was 7.1-7.6 µm (Razak *et al*, 2010), 2.5-13.3 µm (Latif, 1995). As a comparison, the fiber wall thickness of *G. scortechinii* almost similar with fiber wall thickness of *Eucalytus* spp which were 4.3 µm and 3.29-3.86 µm (Viane *at el*., 2009), respectively.

Table-4. Analysis of variance for fibre morphology between location and position.

		Fibre morphology				
		Fibre length (µm)	**Fiber diameter** (µm)	**Lumen diameter** (µm)	**Wall thickness** (µm)	**Runkle's ratio** (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 is not significant different at 95% probability level

Fiber Runkle's Ratio

The fiber Runkle's ratio was greater at the internodes than at the nodes (shown in Tables 4 and 5). It shows there were significant differences of the Fiber Runkle's ratio between position at nodes and internodes of the bamboo.

The Runkle's ratio at difference position showed that at the outer layer were 2.16, middle 1.42 and at the inner layer was 0.97 at the internodes, and at the outer layer was 1.71, middle 1.06 and at the inner layer was 0.79 at the nodes. The result showed that the fiber Runkle's ratio is greater at the middle and thinner toward the inner and outer layer. It was a significantly difference between this three position. If the Runkle's ratio value is more than one, this meant the fiber properties were hard and difficult to felting during the paper production. The quality of the paper will be gross and poor bonding if Runkle's ratio value more than one. If the Runkel's ratio less than one, it indicates the fiber has a thin fiber wall and easily to felting. The quality of the paper will be better and bonding will be good. This indicates that *G. scortechinii* could be a source to replace short-fiber pulp that was imported from

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abroad. *Eucalytus spp*, the Runkle's ratio is 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.

Table-5. Runkle's ratio of *Gigantochloa scortechinii*.

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

Values in bracket represent the standard deviation

Shear strength

Results of analysis of variance (ANOVA) and the mean average for shear strength are tabulated in Table-6. There was a significant difference between green and air dry sample. The results for compression roller shears for green conditions were 5.76 MPa and for the air dry 8.20 MPa. The shear strength increases from green to air dry condition. The strength also increases with the increase of the number of vascular bundle from inner to outer part of the bamboo and from nodes to internodes (Rafidah *et al*. 2010; Li, 2004).

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

	Shear (MPa)	**Tensile strength** (MPa)	**Tensile 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 is not significant different at 0.05 probability level

Tensile strength and modulus

Analysis of variance (ANOVA) on Tensile Strength properties are tabulated in Tables 6 and 7. The results of the tensile strength and modulus are at difference condition (green and air-dry), location (nodes and internodes) and position (outer, middle and inner layer). The results for tensile strength for green condition was 89.95 MPa and for the air dry was 138.87 MPa, at internodes 144.68 MPa, nodes 84.14 MPa, at outer layer 135.93 MPa, middle layer 115.49 MPa and inner layer 91.81MPa.

For the tensile modulus, the values were 4003.85 at air-dry condition, 2786.96 at green condition, internodes 3545.49, nodes 3245.33, at outer layer 4061.64 MPa, middle layer 3344.80 MPa and inner layer 2779.79 MPa. The analysis of variance for tensile strength at difference location in Table-9, showed, there was significant difference between the internodes and nodes. The result showed that the tensile strength increases from inner to outer layers of the bamboo for every bamboo species. Analysis of variance showed significant difference between the outer, middle and inner layers. 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 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.

The results (shown in Tables 6 and 7) also showed that the tensile modulus 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. 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 and modulus strength also increases with the increase in cellulose content and decreasing micro-fibril angle (Li, 2004).

Table-7. Strength properties of 3 year-old *Gigantachloa scortechinii*.

Sample	Location	**Mean tensile strength** (MPa)	**Mean tensile modulus** (MPa)	**Mean compression roller shear (**MPa)
(Green sample) Internodes	Outer	123.11 (±13.92)	3086 (±327)	4.23 (±0.75)
	Middle	86.62 (±10.78)	1833 (±153)	5.64 (±0.88)
	Inner	79.81 (±9.09)	1672 (±102)	2.90 (±0.86)
Nodes	Outer	77.30 (±9.10)	2705 (±288)	5.61 (±1.00)
	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) Internodes	Outer	204.92 (±17.13)	5258 (±271)	9.22 (±2.22)
	Middle	219.56 (±14.40)	5036 (±251)	9.92 (±0.91)
	Inner	152.10 (±17.48)	4195 (±385)	4.95 (±1.40)
Nodes	Outer	179.11 (±15.68)	5362 (±470)	8.90 (±4.17)
	Middle	164.32 (±11.83)	5532 (±456)	12.67 (±1.36)
	Inner	74.08 (±10.55)	3387 (±351)	8.49 (±1.05)

Standard deviations shown in parentheses

Correlation between shear and tensile strength with MC, BD, anatomy

Initially, the moisture content were high and the strength of the shear roller was lower (shown in Table-8). Basic density correlated significantly with the shear tests. This shows that at high specific gravity, the roller shear strength was also a high. Basic density plays a direct role in the shear strength test in bamboo. The number of vascular bundle has a positive relationship with the shear test. This means that a high number of vascular bundle was also high shear strength. The presence of vascular bundle, contributed greatly to the strength of the roller shear. Vascular bundle size (for length and width) has negative relationship with the roller shear tests. The 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. This means the thick of fiber wall, the higher of roller shear strength.

Table-8 shows the correlation between tensile strength with the moisture content at initial of bamboo sample. It has a negative and weak correlation. Where, at the initial bamboo has high moisture content, tensile strength was low. The specific gravity has a positively correlated with tensile strength. This means, the increase of specific gravity, tensile strength also increases. Number of vascular bundle has a positive correlation with the tensile strength. This mean 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. This shows the larger size of vascular bundle the lower the tensile strength. The correlations between tensile strength with fiber morphology were not strong and some of them were insignificant. There was no clear relationship of tensile strength with fiber morphology.

Table-8. Correlation coefficients of moisture content, basic density and anatomical characteristics with strength.

Properties	**Shear strength** (MPa)		**Tensile strength** (MPa)			
	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	-0.00ns	-0.40*	-0.17*	-0.04ns	-0.00ns	-0.11*
Fibre length	0.00ns	0.10*	-0.17*	-0.04ns	-0.00ns	-0.11*
Fibre diameter	0.29*	0.19*	0.13*	0.01ns	-0.06ns	-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

CONCLUSIONS

The moisture content in the bamboo ranged between 78.61-125.90%, the MC is higher in the internode approximately 94.45% compared with the node that is 78.61%. Position at inner layer of bamboo has the highest moisture content which is 125.90%, middle layer was 83.82% and outer layer was 49.87%.

The basic density for all species tested was about 0.58-0.95 g/cm^3, but the inner position is 0.58 g/cm^3, middle 0.73 g/cm^{3}and outer positions is 0.95 g/cm^3.

The shrinkage in the radial, tangential and the volume is around (5.04 - 8.63, 6.52-13.50, 10.40-15.45%) respectively for all species. Position in a higher rate of shrinkage was at the inner (8.63, 13.50, 15.45%), follow by the middle (6.85, 9.72, 12.57%) and outer (5.04, 6.52, 10.40%) respectively.

The morphology fibres showed significant differences between portion and position in terms of length, diameter and lumen size. Each species has different characteristics of fiber. The vascular bundle for this species ranged around 3.50-13.24/4mm^2 and it is dense at the outer position which is 10.55 vascular bundle/4mm^2, middle 5.80 vascular bundle/4mm^2 and at the inner position was 2.75 vascular bundle per/4mm^2. The vascular bundle length between 785.40 - 1449.64 µm and a width of 382.41-691.88 µm. The fibre length was between (1672.62-2074.24 µm), fiber diameter (18.23-22.36 µm), lumen diameter (5.44-6.18 µm) and fiber wall thickness (6.80 - 8.43µm).

The tensile strength for the tested bamboos ranged between 84.14-144.68 MPa. The Tensile Strength of dried bamboo is 138.87 MPa compared with 89.95 MPa for green bamboo. The Tensile Modulus ranged between 2779.79-4061.64 MPa. The Tensile Modulus of air dried bamboo is 4003.85 MPa compared with 2786.96 MPa for green bamboo.

The shear strength of the bamboos studied ranged 3.90-9.18 MPa. The strength for dried bamboo was 8.20 MPa compared to the green bamboo 5.76 MPa. The strength for the internodes was 6.24 MPa and the nodes at 7.72 MPa. The strength at the outer layers 7.85 MPa, middle layers 9.18 MPa and the inner layers 3.90 MPa.

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