Morphological, Mechanical, and Physical Properties of Four Bamboo Species

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Bamboo among other plants has unique properties and massive variety. The properties of bamboo species vary between species and along their culms. The aim of this study was to investigate the characteristics of four bamboo species: *Dendrocalamus pendulus (DP)*, *Dendrocalamus asper* (DA), *Gigantochloa levis* (GL), and *Gigantochloa scortechinii* (GS), and their three portions (bottom (B), middle (M), and top (T)). The number of fibre strands in vascular bundles and the single fibres extracted from every portion was studied. The distribution of fibres varied along the bamboo culms and between species. The DP species showed the highest water content and water absorption and the lowest mechanical properties. The DA species exhibited the best mechanical and physical properties. Moreover, the bottom portion of every species indicated the highest aspect ratio and tensile properties. The results indicated that before the application of bamboo culms in composite materials, the bamboo species should be characterized so that it can be utilised effectively as a renewable reinforcement in composites.

Keywords: Bamboo fibre; Mechanical properties; Mechanical testing; Natural fibres; Physical properties

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INTRODUCTION

The use of natural fibres from plants as reinforcement composite materials in many different fields of industrial application indicates that researchers and scientists are interested in replacing polymeric fibres with plant fibres because of increasing environmental concerns (Razali *et al.* 2015). Advantages such as renewability, biodegradability, recyclability, and sustainability of natural fibres outweigh those of synthetic fibres. They are lightweight, low-cost, and abundantly available (Alves Fidelis *et al.* 2013; Zakikhani *et al.* 2016). The main constituents of every lignocellulosic fibre are cellulose, hemicellulose, lignin, and pectin. Plant fibres have been classified into seven categories: fruit, bast, stalk, seed, leaf, wood, and grass (Jawaid and Khalil 2011).

Bamboo culms in the plant fibres category belong to the grass family Poaceae, subfamily Bambusoideae, and Bambuseae tribe. Bamboo grows naturally in diverse climates and has more than 1000 species from 70 genera that are found in abundance in Asia and South America (Zakikhani *et al.* 2014). In Peninsular Malaysia, bamboo is the second most economically important non-timber forest products after rattan (Mohamed and Appanah 2000). It has been reported that this part of Malaysia has 59 native bamboo species from genera such as *Dendrocalamus*, *Gigantochloa*, *Racemobamboos*, *Bambusa*, *Schizostachyum*, *Dinochloa*, and *Thyrsostachys* (Forestry Department of Peninsular Malaysia 2013). *Dendrocalamus pendulus*, *Dendrocalamus asper*, *Gigantochloa levis*, and *Gigantochloa scortechinii* are the most common and widespread species amongst the bamboo species (Mohamed and Appanah 2000).

Bamboo, in comparison with other plants, has significantly low density and high strength and stiffness (Osorio *et al.* 2011). The growth range of bamboo in the growing season is from 30 to 100 cm per day, making bamboo the fastest-growing plant in the world (Rao and Mishra 2012). The hollow cylindrical shape of bamboo is composed of an inner layer, outer layer, and diaphragms. In the anatomical structure of bamboo species, vascular bundles are distributed from the inner layer to the outer layer of the culm wall. The mechanical and physical properties of bamboo species are varied due to the structure of bamboo culms, density, average size, and the number of vascular bundles (Londoño *et al.* 2002; Zakikhani *et al.* 2014). The properties of bamboo vary between species and along the culm. As such, for the proper use of every bamboo species, it is essential to study both the mechanical and physical properties of every species (López 2003).

Bamboo has been widely used in traditional construction materials and in the manufacture of daily tools because of its high strength and low weight. However, the commercial use of bamboo fibres as reinforcement composite materials requires an appropriate extraction method (Zakikhani *et al.* 2014). Only a few investigations have attempted to extract long and fine bamboo fibres because of the difficulty of extracting long fibres from bamboo culms.

Researchers have previously used the mechanical method to extract long fibres from *Guadua angustifolia* species. The mean density and diameter of fibre bundles were 1.4 g/cm^3 and 150 µm, respectively. The long extracted fibres were treated with sodium hydroxide and their surface characteristics and mechanical properties were compared with untreated fibres. They found that untreated fibres had a greater stress transfer efficiency at high loads (Osorio *et al.* 2011). In another study, researchers used a retting procedure to extract long fibres. In their method, bamboo culms were peeled longitudinally, with thicknesses of 0.5 to 1.5 mm and widths of 10 mm. The retted bamboo strips were taken out of the water after three days and were beaten and scraped gently until fibres with a density of 0.910 g/cm^3 and a diameter range between 0.09 and 0.4 mm could be extracted. The obtained results indicated that the fibres were affected during the scraping, causing breakages in the fibre (Rao and Rao 2007).

In this study, the structure of four bamboo species (*Dendrocalamus pendulus*, *Dendrocalamus asper*, *Gigantochloa levis*, and *Gigantochloa scortechinii*), and their physical and mechanical properties, from their bottom to top portions, were investigated. The manual procedure was used to extract long fibres to identify the most proper species and a portion for composite preparation.

EXPERIMENTAL

Bamboo

Four types of bamboo, namely Akar (*Dendrocalamus pendulus*, DP), Betong (*Dendrocalamus asper*, DA), Beting (*Gigantochloa levis*, GL), and Semantan (*Gigantochloa scortechinii*, GS), were collected at the age of four from Pahang in Peninsular Malaysia. The bamboo culms were cut 15 cm above ground level and then subdivided equally into the bottom (B), middle (M), and top (T) portions according to their total length. To prevent the loss of moisture in the bamboo species, “Tree Wound” liquid was applied to the cross section of every culm as a pruning sealer.

Extraction of a Single Bamboo Fibre

The bamboo species were cut using a wood saw machine according to their internode length. Every culm has several nodes and internodes. The microstructure of bamboo nodes is slightly different than that of internodes, and long fibres cannot be extracted from the diaphragm section. Hence, internodes were cut 2 cm up and 2 cm down from every other node to separate them from bamboo culms. The internodes of bamboo culms were cut into strips using a cast iron bamboo splitter. This procedure was carried out for every section of DA, DP, GS, and GL species. Bamboo strips were bundled and kept in water for 72 h to soften their structure. The retted bamboo strips were subsequently removed from the water and sliced longitudinally into thinner lumber strips, and the fibres were then extracted manually. Finally, the extracted fibres were air-dried (Zakikhani *et al.* 2016).

Measured Density of a Single Fibre

The densities of the bamboo fibres were calculated by finding the mass and the volume of the fibres separately and then using the equation for density. The volumes of the fibres were obtained using a win RHIZO measurement device (Regent Instruments Inc., Canada), with V representing the volume of the fibres. The fibres were weighed, with the resulting masses defined as M. The densities of 12 portions were obtained using the following equation:

$$\text{Density (g/cm}^3\text{)} = \frac{M}{V} \tag{1}$$

Measurement of Length and Diameter of Fibres

The fibres’ lengths were recorded using a ruler, and their diameters were obtained using a Leica stereomicroscope (Leica microsystems, Germany) instrument. The average diameter of 20 fibres and the length of the extracted fibres relevant to the length of the internodes were measured. The diameter of a single bamboo fibre has previously been assumed to be cylindrical in shape because of a lack of instruments required to determine the cross-section of a single plant fibre and easier procedures for calculating the average diameter of a fibre (Bodros and Baley 2008; Osorio *et al.* 2011; Yusriah *et al.* 2014) .

Moisture Content

The moisture content of fresh bamboo species was calculated using Eq. 2. The weight of four bamboo strips from four separate internodes per portion was measured before being heated in an oven at 75 °C until a constant weight was reached. Samples were taken out of the oven to have their weight measured every day for 13 days. The equation for moisture content is as follows (Ishak *et al.* 2013):

$$\text{Moisture content } MC = \frac{(W_i - W_0)}{W_0} \times 100 \tag{2}$$

In Eq. 2, W_i is the initial weight of fresh bamboo strips and W_o is the weight of oven-dried bamboo strips

Water Absorption of Bamboo Fibres

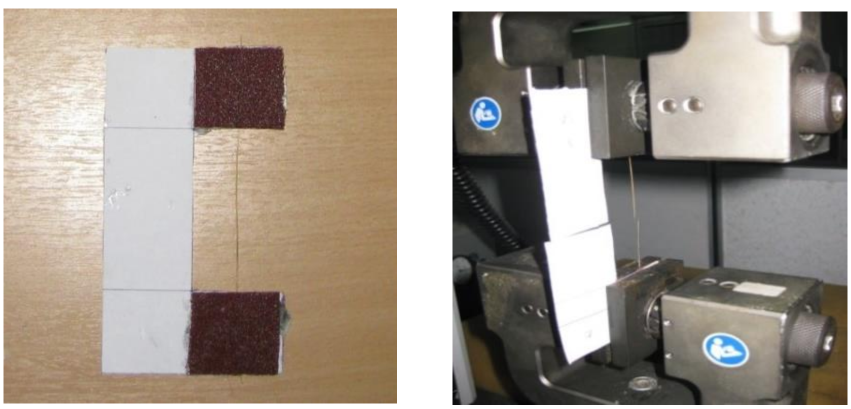
The water absorption of extracted bamboo fibres was calculated using Eq. 3 (Ishak *et al.* 2013). The weight of a bunch of extracted fibres was weighed per portion and recorded equally before being immersed in distilled water as M_o. The immersed bamboo fibres in the distilled water were removed every 8 h, wiped off with filter paper, and then weighed continuously for 72 h. Subsequently, the samples' weights were measured, and recorded separately from every other portion of the four bamboo species,

$$\text{Water absorption } WA = \frac{M_t - M_0}{M_0} \times 100 \quad (3)$$

where M_t is the mass of fibres after soaking in water at different time intervals and M_o is the mass of fibres before soaking in water

Tensile Testing

The tensile tests of single fibres were conducted using a 5-kN Instron 3365 (Instron, USA) machine. The bamboo fibres were visually chosen first; then to prevent any damage to the fibres, they were visualised under a Leica stereomicroscope (Leica microsystems, Germany) instrument. The diameters of the selected fibres were measured; they were then glued to cardboard according to the ASTM D3379-75 standard (1975) and tested using a gauge length of 70 mm and a cross head speed of 1 mm/min with a universal testing machine with a 5-kN load capacity (Instron 3365) (Fig. 1a). In this section, at least 10 successful tensile tests were separately performed on each three portions of four different bamboo species. In Fig. 1b, the failure of a single fibre is demonstrated.



(a) (b)

Fig. 1. Tensile test of (a) a prepared sample; (b) failure of a single fibre

Optical Microscopy Analysis of Bamboo Culms

Bamboo culms were cut into strips with widths of 2 cm. Then, the bamboo strips were cut into lengths between 2 and 3 cm using a hand saw. The 2-cm bamboo strips were boiled in water for 10 min so they could become soft enough to be sliced by a sliding microtome (Leica SM 2000R, Leica microsystems, Germany) into a thickness of 25 µm. After completing the sectioning process, a thin layer of bamboo cross-section was dehydrated and placed on top of a glass slide. The samples were then covered with clove oil, DPX (mountant for histology), and a cover glass. The prepared specimens were placed in an oven at 35 °C for three days. The cross-section of every portion of bamboo species was observed using an optical microscope (Leica Leitz DMRB, LabCommerce, Inc. USA).

RESULTS AND DISCUSSION

Characterization of Four Bamboo Species

Features of bamboo species

The differences in properties between bamboo species can primarily be defined by the structure of bamboo culms. The morphologies of bamboo culms vary between bamboo species (Liese 2003). In Fig. 2, the differences between the outer diameters of four bamboo species are shown separately. It can be seen that the diameter in the four bamboo species, decreased from the bottom to the top portions due to the reduction of wall thickness. The diameter of bamboo culm and wall thickness are correlated with shrinkage (Liese 2003).

In Fig. 2, the graphs of *Dendrocalamus pendulus* (DP) and *Dendrocalamus asper* (DA) show a more uniform reduction of wall thickness than those for *Gigantochloa scortechinii* (GS) and *Gigantochloa Levis* (GL) amongst the bamboo species. The wall thickness of DA from the bottom to the top portions was the greatest when compared with the other species, followed by DP. On the other hand, GS has the thinnest wall thickness. The wall thickness of GL at the bottom and middle portions is slightly similar to DP, except for the top portion, which has thinner wall thickness. Although the wall thickness of the *Dendrocalamus* genus, including DA and DP species, were the widest, the total outer diameters of GL from the bottom to the top portions were the largest, followed by GS.

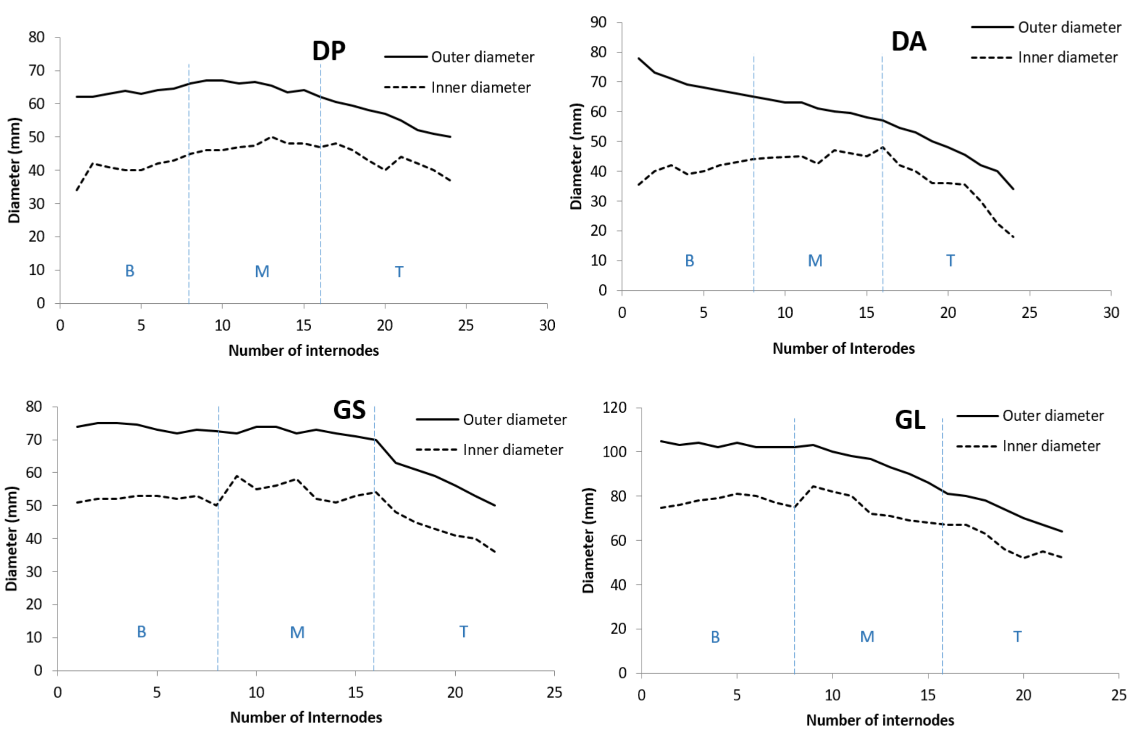


Fig. 2. Inner and outer diameters of (a) DP, (b) DA, (c) GS, and (d) GL

The length of the internodes of bamboo species is an effective factor in various bamboo applications and varies from species to species (Yu 2007). The lengths of the internodes of the four species are shown in Fig. 3, which indicates a change with height (Amada and Untao 2001). The lengths of the internodes in GL and GS were longer than those found in DA and DP. In addition, it can be seen that the structure of bamboo culms are different between species, and even between two species having the same genus.

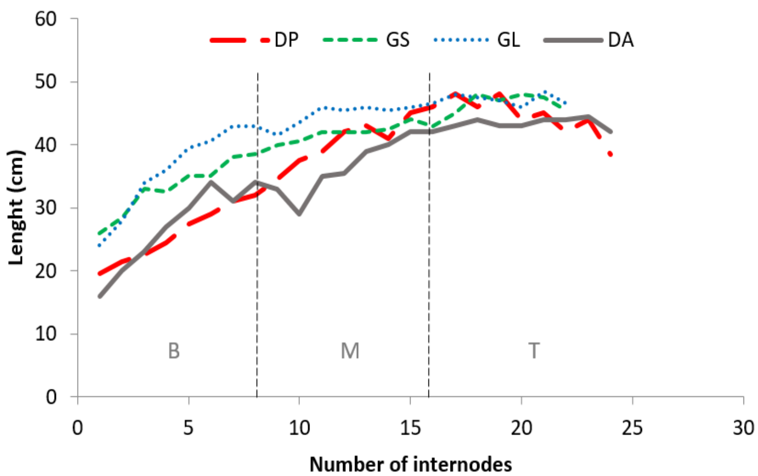


Fig. 3. Lengths of internodes of four species

Morphological properties of bamboo culms

The hollow cylindrical bamboo culms consisted of skin, bamboo timber, and pitch rings. In Fig. 4, a very special distribution and arrangement of the vascular bundles from the inner layer to the outer layer of bamboo timber is shown clearly. The bundle densities were lower in the inner layer and it increased closer to the outer layer of the bamboo culms. In contrast, the distributions of the parenchyma cells decreased from the pitch ring to the skin. The size of vascular bundles towards the middle layer became larger in the bamboo culms and also more widely spread, but longer and smaller towards the outer layer. This finding agrees with previous research on the subject (Grosser and Liese 1971). The structures of vascular bundles, depending on the species, include various amounts and shapes of fibre strands (Grosser and Liese 1971; Liese 1998). The differences in vascular bundles between species can be seen in Fig. 4 and Table 1.

The details of vascular bundles are shown in Fig. 4. It has been previously reported that every vascular bundle embedded in parenchyma tissue is composed of two metaxylem vessels (phloem and protoxylem), which are attached to the fibre sheaths (Grosser and Liese 1971). Metaxylem consists of two large vessels, which differed in size amongst the four species and their respective portions (bottom, middle, and top). The vessels were surrounded by small parenchyma cells (Fig. 4b), and sclerenchyma sheaths (Fig. 4c). The parenchyma cells were larger in the ground tissue of the bamboo timber (Fig. 4c). Parenchyma tissue becomes lignified when water transfers into the bamboo culm (Liese 1998). The phloem is located between two large vessels consisting of several sieve tubes. Both the phloem and protoxylem were separately surrounded by sclerenchyma sheaths (Fig. 4b). In Fig. 4c the breakage of the cells can be seen. These cracks occurred because the intercellular of pectin was destroyed or cooked off (Schott 2003). In this case, the cell walls could not stand whilst being stuck to each other.

The locations of fibre strands in a vascular bundle are shown in Fig. 4e. Figure 5 reveals the types and differences between the bamboo species. Figure 5 shows a complete vascular bundle from the middle layers of a middle portion for every species. It can be seen that the complete vascular bundles for both GL and GS, belonging to the *Gigantochloa* genus, are composed of three parts: the central vascular strand and two fibre strands on each side of the central strand. However, the types of vascular bundles in DP and DA are composed of two parts: the central vascular strand and one fibre strand inside the central strand (Grosser and Liese 1971).

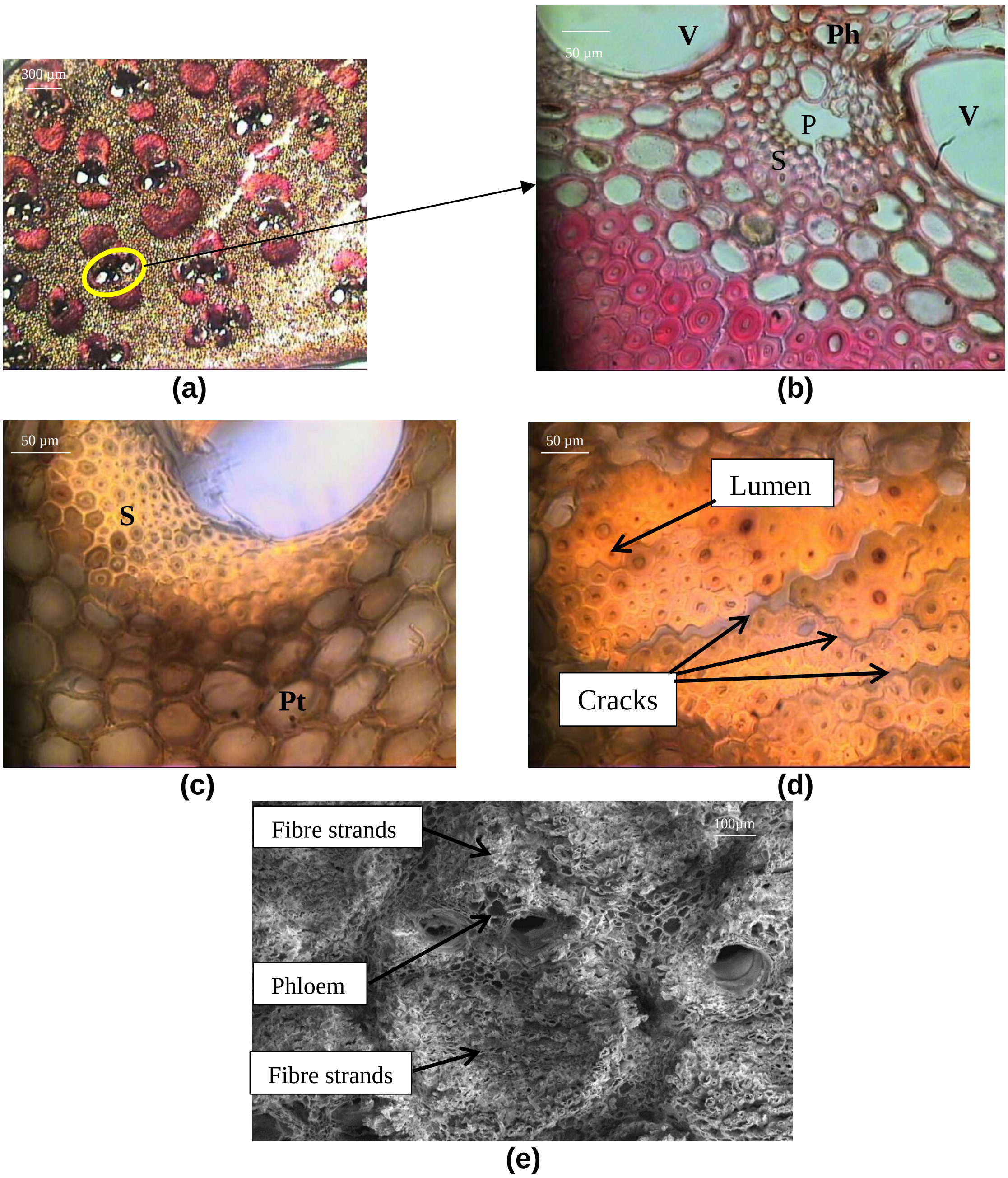


Fig. 4. (a) Distribution of vascular bundles from inner layer to middle layer; (b) v: vessels, ph: phloem, s: sclerenchyma sheaths, p: protoxylem; (c) s: sclerenchyma sheaths, pt: parenchyma tissue; (d) f: strand fibres; (e) pulled out fibres and cells

The different vessel sizes and fibre areas from three portions of every species given in Table 1 indicate that the area of fibre strand in GL is the largest followed by DP, while DA and GS have a lower area of fibre strands. Vascular bundles located on the top portion of all species are more compacted with smaller area of fibre strands than the bottom portions. The areas of fibre strands in DP and GS were higher in the middle portion. In bamboo species, fibre strands form the structure of a bamboo culm like a skeleton (Yu 2007). Moreover, the vessel sizes of each portion are not similar across species (Wahab *et al.* 2010).

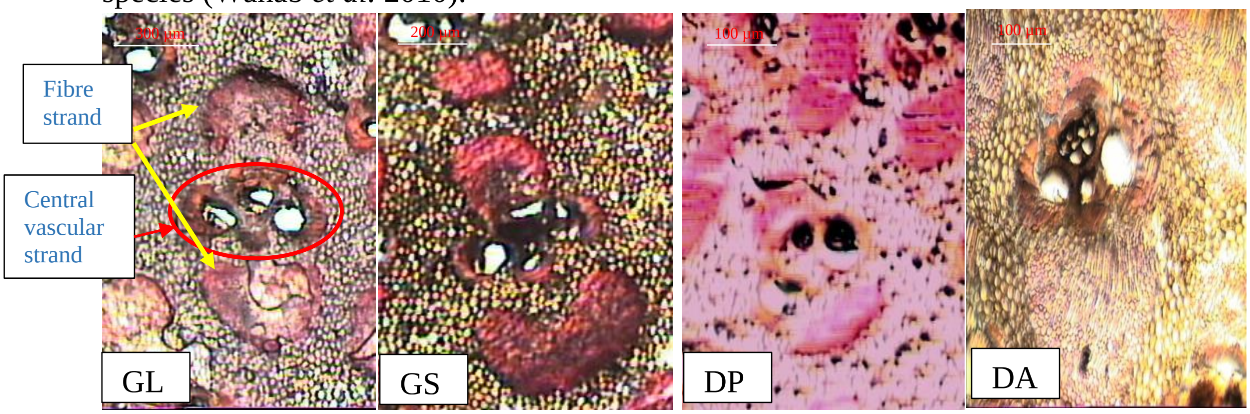


Fig. 5. Vascular bundles of the middle sections of the middle portion of GL, GS, DP, and DA

The vessel diameters in the bottom portion of the species were the largest, and this amount decreased by 20% and 27% to the top portion, except for GS, which declined by 48%. The difference in the shape of vascular bundles from the middle layer of the middle portion of every species can be seen in Fig. 5.

Table 1. Differences in Amount of Fibre Strands and Diameter of Vessels

Bamboo species	Bamboo portions	Area of fibres (μm^2)	Diameter of vessels (µm)
DP	B	10,984	117
	M	12,082	100
	T	8,585	94
	Mean	10,550	104
DA	B	12,251	138
	M	7,126	123
	T	5,740	100
	Mean	8,372	120
GL	B	18,092	127
	M	10,836	100
	T	5,979	95
	Mean	11,635	107
GS	B	7,901	127
	M	12,512	78
	T	5,402	65
	Mean	8,605	90

Moisture content of bamboo species

The moisture contents of four bamboo species from different portions are illustrated in Fig. 6. The moisture content of the bamboo species has an effect on the use of bamboo in the material selection process. It is an important factor that should be considered before utilization of bamboo as a reinforced composite material because of its significant influence on the biological properties of fibre reinforced composites (Rowell *et al.* 2000). In natural fibre reinforced composites, several parameters can be determined using the moisture content, such as tensile strength, dimensional stability, electrical resistivity, and swelling behaviour (Razali *et al.* 2015). Plant fibres have the ability to hold water molecules because of their internal structure. Therefore, it is essential to consider the amount of moisture content to achieve high resistance and greater dimensional stability for the fibre reinforced composite.

Different from other plants, the capacity for water retention in bamboo species correlates with a number of parenchyma cells, which is different for every species (Yu 2007). In Fig. 6, it can be clearly observed that the moisture content of bamboo culms varies between species and their portions. The moisture content of the bottom part is considerably higher than that of other portions. This is because there is a higher amount of parenchyma cells at the bottom portion of a bamboo culm zone compared to the top (Yu 2007). In DP and GS, the moisture content of the bottom portions was the most at approximately 65%, whereas the same portion in GL and DA had a lower percentage of moisture content. The second considerable amount belonged to the middle portion of DP, which was slightly less than the bottom portion of DP and the same as the bottom portion of GS. In DA, GS, and GL, the middle portions had similar moisture contents, 50%.

The lowest percentage of moisture content shown in the graph was observed for the top portion of every species. This indicated that the number of parenchyma cells from the bottom to the top portions in the bamboo timber zone decreased as the height of the bamboo culm increased and vascular bundles became more compact. The moisture content of the top portion of GL and DA, at approximately 30%, was lower than those of DP and GS. Interestingly, the moisture content of DP, from the bottom to the top portions, was found to be the highest, at over 60%. The percentages of this quantity in DA and GL were less than the GS and DP species in the bottom, middle, and top portions. Therefore, these two species may be more favourable than other species when used as fibre reinforced composite materials. It can be concluded that the moisture content of bamboo species is not constant from the bottom to the top portion of a bamboo culm, and neither are their mechanical and physical properties (Wakchaure and Kute 2012). The reduction in water content from the bottom to the top portions of bamboo species was previously reported (Anokye *et al.* 2014).

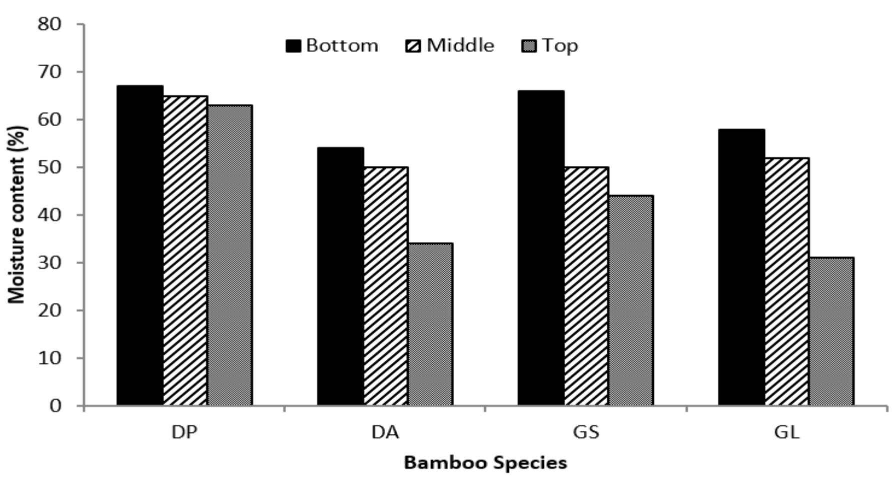


Fig. 6. Moisture content of bamboo species

Characterisation of Single Bamboo Fibres from Four Species

Dimensions and density of single fibres

The dimensions and densities of four different bamboo species and their portions are given in Table 2. Although the strength of single plant fibres can be affected by the length of a single fibre, the most important parameter is the ratio of fibre length to the diameter (aspect ratio) (Peltola *et al.* 2011). Moreover, this parameter can be used to characterise the mechanical performance of natural fibres (Robinson and Robinson 1994). In Table, it can be seen that the diameter, length, and density of fibres varied between the species and their portions. The lengths of extracted fibres in DP, DA, and GS were between 200 and 440 mm. The DP had the highest fibre length range. In contrast, the results also showed that GL had the lowest fibre lengths from the bottom to top portions. The length of the fibres in all of the species varied from the bottom to the top portions, because of differences in the internode lengths along the bamboo culms. This was observed in the previously mentioned results. In addition, the extracted fibres from the middle portions were longer than other parts.

The diameters of the extracted fibres were discovered to decrease at the bottom portions in all bamboo species, while the aspect ratios increased. It should be noted that the aspect ratio determines the efficiency and strength of the fibres (Peltola *et al.* 2011). The density of fibres increased from the bottom to the top portions because of the denser distribution of fibres in the top portions (Londoño *et al.* 2002). The bottom portion of all species had the highest aspect ratio; DA had the highest, followed by GS, DP, and GL. This means that the bottom portion of DA species is able to transfer more stress through the matrix. In plant fibres, long fibres with high aspect ratios produce proper bonding and interaction with the matrix (Wallenberger and Weston 2004).

Table 2. Physical Properties of Bamboo Fibres

Bamboo species	Bamboo portion	Average extracted fibre diameter (µm)	Extracted fibre length (mm)	Density (g/cm^3)	Aspect ratio
DP	B	327.72 (30.86)[a]	210-405	0.0605	859.32
	M	389.51 (24.62)	200-440	0.0651	812.33
	T	415.69 (34.33)	220-400	0.0751	675.92
DA	B	275.19 (28.45)	210-340	0.1203	949.09
	M	370.40 (33.39)	200-360	0.122	825.80
	T	310.81 (35.24)	205-355	0.1258	809.18
GS	B	325.09 (33.25)	265-325	0.0831	934.66
	M	375.46 (19.41)	200-440	0.0917	888.92
	T	405.68 (37.30)	240-340	0.1009	720.98
GL	B	290.34 (35.66)	160-280	0.1095	713.11
	M	305.32 (29.36)	180-320	0.1189	678.62
	T	375 (25.30)	175-305	0.1213	574.66

[a] Standard deviation of the samples' mean are written in the parentheses.

Specific gravity

The specific gravity of a bamboo culm varies along the culm because of the variation in anatomical structure (Malanit 2009). According to Chaowana (2013) and Malanit (2009), the specific gravity is correlated with the moisture content and water absorption of a bamboo species along the bamboo culm, wherein as the specific gravity increases, the moisture content and water uptake decrease. In Fig. 7, it can be observed that the value of specific gravity increased from the bottom to the top portions of the four species.

The DA and GL had the greatest values for specific gravity, while DP and GS showed lower values in all three portions. The bottom portions of the four species showed the lowest specific gravity because of their low density of fibres, which can be observed in Table. By relating the reduction of water content in bamboo species from the bottom to the top portions and with the specific gravity results in

Fig and moisture absorption in

Fig. , it is interesting to note that the obtained results are in good agreement with another study's findings (Malanit 2009). The obtained results suggest that the specific gravity changed along a bamboo culm from the bottom to the top portions. Therefore, when producing bamboo composite materials from DP, DA, GS, and GL, the variation in this value should be considered.

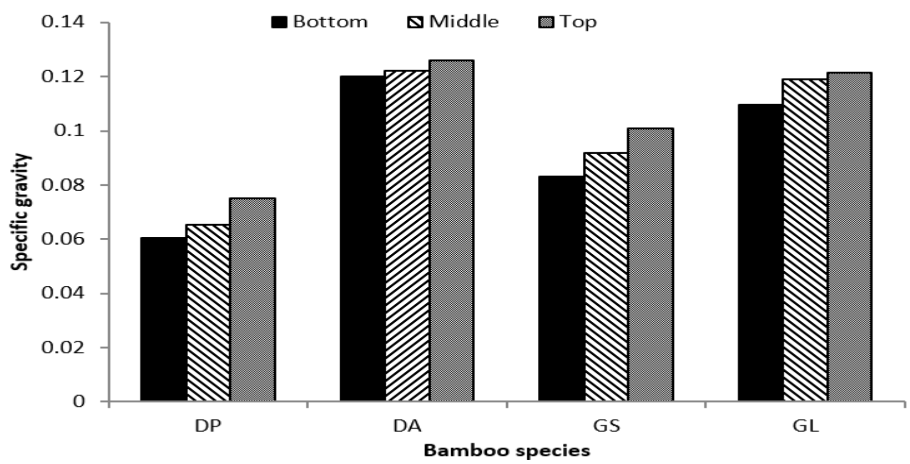


Fig. 7. Variation of specific gravity in three portions of four species

Water absorption of single fibres

The water absorption behaviours of four bamboo species from the bottom to the top portions are indicated in

Fig. . The water absorption of DP fibres in the three portions was the topmost, between 125% and 180%, followed by GS fibres (100% to 125%). The water absorptions of the bottom, middle, and top portions of DA and GL fibres were approximately equal, in between 54% and 76%.

On the other hand, the water absorptions of the bottom portions were the maximum amongst all the species. There was a minor difference in the percentage of water absorption between the bottom and middle portions of DP, DA, GS, and GL fibres, with variations of 15%, 3%, 7%, and 6%, respectively. In contrast, the lowest moisture absorption was observed for top portions of the DP, GS, GL, and DA fibres, at 125%, 103%, 58%, and 54%, respectively.

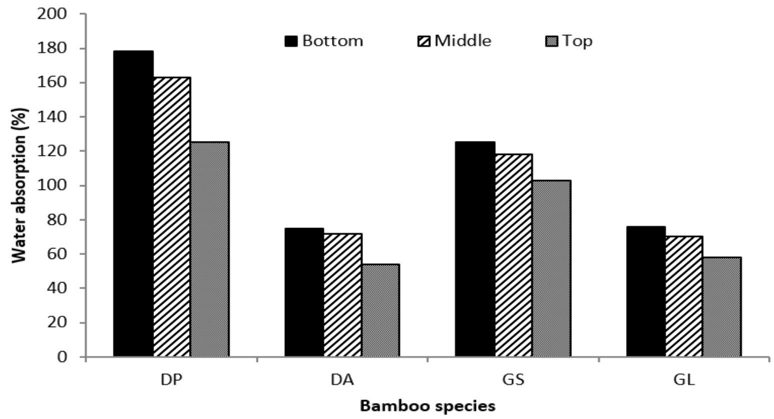


Fig. 8. Water absorption of DP, DA, GS, and GL

The water absorption of the bamboo species was proportional to the specific gravity, as shown in

Fig. The variety of results in DP, DA, GS, and GL fibres are the consequence of differences in the anatomical structure between every bamboo species. The increase in specific gravities from the bottom to the top portions displayed that fibres became denser along the bamboo culm. In addition, increases of moisture absorption at bottom portions were due to the absorption of water molecules through the lumen into the layers of cell walls (Baley 2002). On the other hand, from the bottom to the top portions of a bamboo species, the thickness of fibrous cell walls expanded while the lumen size diminished. Thus, the reduction of water uptake in the top portion occurred in four species. The lumen and wall thickness of a single fibre can be observed in Fig. 9.

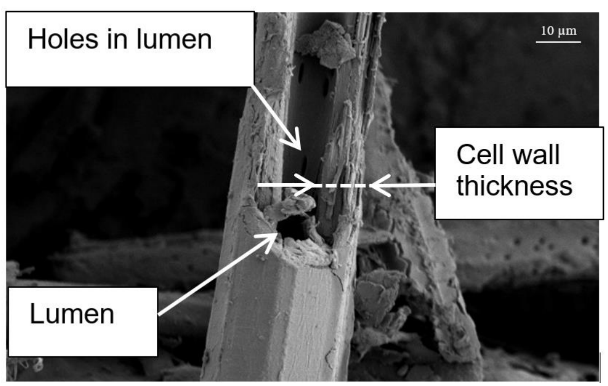


Fig. 9. Cross-cutting of a single bamboo fibre

Tensile properties of a single bamboo fibre

The tensile properties of single plant fibres depend on several parameters, such as the method of extraction, type of species, weather conditions, soil quality, and level of plant maturity (Baley 2002). The factors most responsible for the mechanical properties of bamboo fibres are lignin, cellulose, and the angle of cellulose microfibrils. The percentage of lignin in bamboo fibres is higher than that in other plant fibres (Han and Rowell 1996), and the angles of cellulose microfibrils in bamboo are very small. In addition, the main lignocellulosic components of bamboo, such as cellulose, hemicellulose, and lignin; the age of the bamboo culm; layer; height; and the condition of growth vary between species (López 2003; Malanit 2009).

The tensile strength, Young's modulus, strain to failure, specific tensile strength, and specific Young's modulus of DP, DA, GS, and GL are demonstrated in Table. The mechanical properties of DA are highest along its culm, followed by GL, GS, and DP, with 2%, 43%, and 46% differences in tensile strength and 12%, 2%, and 45% differences in Young's modulus, respectively. It can be asserted that the tensile strength of DA fibres was very similar to that of GL fibres, and GS fibres had tensile strengths similar to DP fibres. In contrast, DP fibres have the lowest modulus of elasticity, while the value of Young's modulus was identical in DA, GS, and GL fibres. The high value of Young's modulus, which indicates the stiffness of single fibres, could be related to the lignin content, structure of plant fibres, and the method of extraction (Osorio *et al.* 2011).

Table 3. Mechanical Properties of Four Species of Bamboo Fibres

Species	Parts	Tensile strength (MPa)	Young's modulus (GPa)	Strain to failure (%)	Specific tensile strength ($MPa.cm^3/g$)	Specific Young's modulus ($GPa.cm^3/g$)
DP	B	293.47 (65.44)[a]	13.942 (1.66)[a]	2.7	4850.744	230.4463
	M	215.73 (32.01)	12.860 (1.56)	2.66	3313.825	197.5422
	T	196.31 (29.92)	9.252 (0.98)	2.62	2613.981	123.1957
	Mean	235.17	12.081	2.66	3592.85	183.72
DA	B	916.49 (98.2)	39.444 (8.36)	2.72	7618.371	327.8803
	M	258.36 (40.59)	14.797 (3.22)	2.22	2117.705	121.2869
	T	140.79 (18.15)	10.889 (1.32)	1.91	1119.157	86.55803
	Mean	436.54	21.71	2.28	3618.411	178.5751
GS	B	374 (40.11)	31.260 (6.95)	2.60	4500.602	376.1733
	M	238.71 (26.58)	16.603 (1.71)	2.34	2603.162	181.0578
	T	151.30 (22.85)	16.534 (1.29)	1.94	1499.504	163.8652
	Mean	245.67	21.465	2.29	2867.756	240.3654
GL	B	750.66 (85.08)	23.634 (4.43)	2.47	6855.342	215.8356
	M	306.53 (59.37)	18.251 (2.01)	2.3	2578.049	153.4987
	T	221.52 (25.16)	15.527 (1.8)	2.16	1826.216	128.0049
	Mean	426.23	19.137	2.31	3753.202	165.7798

[a] Standard deviation of the samples' mean are written in the parentheses.

The bamboo fibres at the bottom portions of the four species showed higher strength and modulus compared with the middle and top portions. The high values at the bottom portions could be attributed to the chemical composition of bamboo species, which differ along a bamboo culm (López 2003). The lowest Young's modulus and tensile strength for DP suggest that DP consists of lower amounts of holocellulose and lignin.

The specific tensile characteristics of the four species and their portions showed the same trend of reduction from bottom to top portions. According to the physical properties of bamboo portions given in Table, the density of bamboo culms increased from the bottom to the top portions (Londoño *et al.* 2002). Therefore, it was expected that the specific Young's moduli and tensile strengths of the bottom portions of the four species would become the highest, and the top portions become the lowest. Between the four species, the specific Young's modulus of DA, DP, and GS fibres was very similar. Although GL fibres showed the lowest stiffness, its specific tensile strength was significant. This means that GL fibres have the proper strength to withstand failure under a tension load.

Figure 10 shows typical stress-strain curves of the middle portions of the four bamboo species. The single bamboo fibres show brittle behaviour. The obtained linear elastic behaviour of bamboo fibres up to failure was observed under tensile load. In this analysis, the differences in the fracture behaviour of single fibres between species were more related to the plant characteristics (Maria *et al.* 2010), as discussed in the previous section. As demonstrated in Table, the strains to failure of the four different species were approximately similar. Although DP fibres exhibit the lowest tensile strength, they showed the highest mean strain to failure. This means that the capability of DP fibres to resist changes in fibre structure without crack formation is better than the other bamboo fibres.

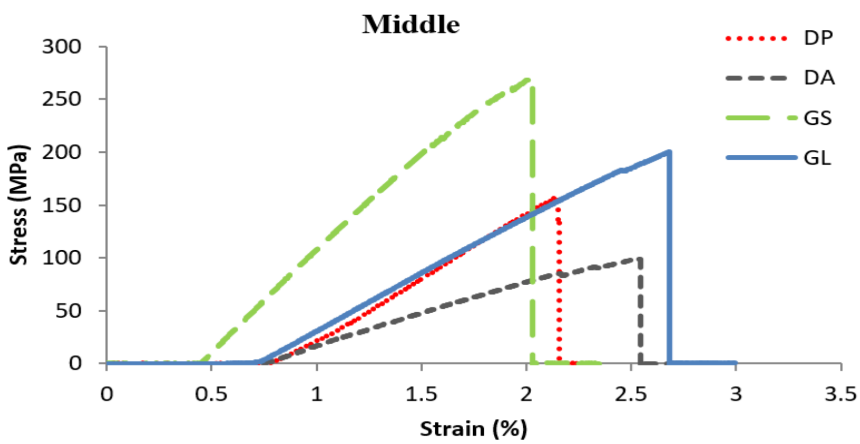


Fig. 10. Typical tensile stress-strain curves of the middle portions of the four bamboo species

CONCLUSIONS

1. The lengths of the extracted single bamboo fibres varied along the culms because of variations in the length of internodes. The aspect ratio, which indicates the strength and efficiency of fibres, decreased from the bottom to the top portions. The bottom portion of every species showed the best mechanical and physical properties. However, the top portion revealed the lowest percentage of physical properties. The highest and the lowest mechanical and physical properties of single bamboo fibres belonged to DA and DP, respectively.

2. The distribution of fibres in a bamboo culm was found to be different between species along the culm and from the inner layer to the outer layer of the bamboo culm wall. The number of fibres increased from the inner layer to the outer layer and became denser from the bottom to the top portion. Even the length of internodes was different along the bamboo culms. The fibre contents of GL and DP species were numerous amongst the other species. The moisture content of the DP species, in its all portions, was the highest when compared with GL, GS, and DA species. The bottom portion in every species had significant percentage of water content.
3. The length, diameter, and density of extracted fibres varied between species and along the culms. Extracted fibres from the middle portions had the longest fibres when compared with the bottom and the top portions. The bottom portion of every species was found with considerable aspect ratio, and water absorption decreased along the bamboo culms.
4. The obtained results demonstrated that the aspect ratio and modulus of elasticity at the bottom portion of DA species were the highest, followed by GS B, DP B, and GL B, respectively. However, among species, GL fibres had excellent specific strength.

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