Anatomical, Physical, and Mechanical Properties of Thirteen Malaysian Bamboo species

Nordahlia Abdullah Siam,* Mohd Khairun Anwar Uyup, Hamdan Husain, Abd Latif Mohmod, and Mohd Fahmi Awalludin

The anatomical, physical, and mechanical properties of 13 Malaysian bamboos and the trend of these properties along the bamboo culms' height were examined. The results showed that these properties varied between the 13 species and they were also affected by the culm height. From the results obtained, the fibre morphology, as well as radial, longitudinal, and tangential shrinkage from green to oven-dry decreased from the basal to the top of the bamboo culm. In contrast, the opposite trend was observed for the density, modulus of rupture, modulus of elasticity, and percentage of the vascular bundle. The potential usage of 13 bamboo species is also considered.

Keywords: Anatomical properties; Physical properties; Strength properties; Malaysian bamboo

Contact information: Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia;
** Corresponding author: nordahlia@frim.gov.my*

INTRODUCTION

Bamboo is considered a fast-growing plant that is widely used for the manufacture of handicrafts, baskets, furniture, and general merchandise. The use of bamboo has evolved from traditional to more value-added products. According to Xing *et al.* (2015), bamboo can be regarded as the best alternative for replacing timber because bamboo has high strength and is fast-growing. As stated by Krause and Ghavami (2009), bamboo in its round form demonstrates excellent mechanical properties that make it useful for the construction industry and can reduce the need for steel. Bamboo is a cylindrical, usually hollow, light-weight, and functionally-graded material that demonstrates optimal characteristics for building truss elements that are frequently used in civil construction. In addition, Xing *et al.* (2015) reported that bamboo is an important raw material for housing and bridge construction in China. Bamboo has also been used in a wide range of engineering and civil construction applications including scaffolding, fiber-reinforced composites, and bridges (Tan *et al.* 2011). Because the uses of bamboo have become more diversified, it is important to understand the basic anatomical, physical, and mechanical properties of the particular bamboo to assess its suitability for the intended purposes. According to Abd. Latif *et al.* (1990), Razak *et al.* (2002, 2005, and 2010), and Wang *et al.* (2016), the anatomical properties of bamboo are important due to their effect on mechanical properties, preservative absorption, and properties of the end products, especially pulp and paper. Anatomical properties can also influence the bamboo's durability, toughness, workability, and strength (Liese 1985; Espiloy 1987; Razak *et al.* 2010). These findings were further supported with a study by Xin *et al.* (2015), where it was concluded that the anatomical structure of bamboo is basic knowledge for understanding the physical and mechanical properties as well as the utilizations of the bamboo.

Density and shrinkage are considered important factors for determining the suitability of bamboo for various applications, with density being associated with the mechanical properties (Anwar *et al.* 2005a; Abdullah *et al.* 2017). Determination of the mechanical properties of bamboo is important to fully understand its behaviour and performance in structural design and industrial use (Shahril and Mansur 2009; Correal and Arbelaez 2010; Gutu 2013).

There are at least 63 species of bamboo in Peninsular Malaysia. Of them, 25 are indigenous, while the rest are known only in cultivation (Abd. Razak and Abd. Latif 1995). From this total number of species, only 13 species are known to be commercially utilized, including *Bambusa blumeana* (buluh duri), *B. vulgaris* (buluh aur/minyak), *B. heterostachya* (buluh galah), *Gigantochloa scortechinii* (buluh semantan), *G. thoii* (buluh beting), *G. ligulata* (buluh tumpat), *G. wrayi* (buluh beti), and *Schizostachyum brachycladum* (buluh lemang) (Abd. Razak and Abd. Latif 1995). From these 13 species, *B. vulgaris* and *G. scortechinii* were reported as suitable for making particleboard, laminated bamboo boards, ply bamboo, and bamwood (Razak *et al.* 1997; Jamaluddin *et al.* 1999; Zaidon *et al.* 2004; Anwar *et al*. 2004, 2005b; Hanim *et al*. 2010; Anwar *et al*. 2011, 2012). An intensive study on bamboo properties should be conducted for all 13 bamboo species to assess each species' suitability for end products. Therefore, the objective of this study is to determine the anatomical, physical, and mechanical properties of the 13 species. The trends of these properties along the bamboo culm height were also examined. Based on the derived properties it will be used to determine the bamboo species for suitable end products.

EXPERIMENTAL

Materials

Field sampling

Thirteen species of Malaysian bamboo, *Gigantochloa thoii*, *G. scortechinii*, *G. ligulata*, *G. wrayi*, *G. brang*, *Schizostachyum brachycladum*, *S. grande*, *S. zollingeri*, *Bambusa vulgaris*, *B. blumeana*, *B. heterostachya*, *B. vulgaris cv Vittata*, and *Dendrocalamus asper*, were obtained from the bamboo plantation research plot, Forest Research Institute Malaysia (FRIM) campus (Kepong, Selangor, Malaysia). Five culms from each species were selected and harvested. Four-year-old bamboos were chosen in this study due to their level of maturity. Sattar *et al.* (1992) illustrated that bamboo culms start maturing at the age of three years. This age was determined by observing a tag that was placed on the culm during the shoot's sprouting stage. The bamboo culms were cut at approximately 20 cm above the ground level. Each culm was cut to a length of 12 m and was later subdivided into three equal lengths corresponding to the basal, middle, and top portions. The bamboo culms were split into eight sections using a splitting machine. For assessment on the anatomical, physical, and mechanical properties, split samples were tested at 12% moisture content. A split is a bamboo sample with the periphery and inner skin remaining intact.

Methods

Determination of the anatomical properties of bamboo

The anatomical studies on the types of vascular bundles and their distributions were conducted according to the method outlined by Abd. Latif and Mohd. Tamizi (1992). Bamboo sample blocks were cut into sections of 10 mm × 10 mm × culm wall thickness. The blocks were boiled in distilled water until the bamboo samples softened. Then, 25-µm thick sections were cut using a sledge microtome (Reichert, Vienna, Austria). Each section was stained with aqueous safranin-O (Sigma, New Delhi, India). These sections were washed with 50% ethanol and dehydrated using a series of ethanol solutions with concentrations of 70%, 80%, 90%, and 95% (Merck, Selangor, Malaysia). Then, one drop of Canada Balsam (Merck, Darmsladt, Germany) was placed on top of the section and covered with a cover slip. The slides were oven-dried at 60 °C for a few days.

The maceration technique was used to determine the fibre morphology. Bamboo splits (20 mm × 10 mm × culm wall thickness) were chipped into the size of a matchstick. Then, they were macerated using a mixture of 30% hydrogen peroxide:glacial acetic acid (1:1 ratio) at 45 °C (Wheeler *et al*. 1989; Abasolo *et al.* 2005) for 2 to 3 h until all of the lignin had dissolved and the cellulose fibres appeared whitish. The macerating solution was then carefully washed in distilled water until all traces of the acid disappeared. Then, the cellulose fibres were kept in the vials. The vials were then gently agitated to ensure sufficient separation of cellulose fibres. The vials were then half-filled with distilled water and securely capped. The macerated fibres were spread out on a glass slide, drops of safranin-O were added, and a cover slip was applied.

Quantitative measurements of the fibre length, diameter, wall thickness, and lumen diameter were made from the slides using an optical microscope (Olympus Corporation, Tokyo, Japan). The distributions of vascular bundles were determined by counting the number of vascular bundles per mm^2 on a cross-section. The fibre wall thickness was obtained by subtracting the value of fibre lumen diameter from fibre diameter and dividing by two. The aspect ratio (fibre length / fibre diameter) and Runkel ratio (2 × wall thickness / lumen diameter) (Singh and Mohanty 2007; Gülsoy *et al.* 2017) were also calculated.

Determination of some physical and mechanical properties

Physical properties of bamboo splits were tested using methods from the Indian Standards Institution (Anonymous 1976). Samples (20 mm × 20 mm × culm wall thickness) were obtained from the basal, middle, and top portions for analysis of density and shrinkage from green to oven-dry. A total of 1,560 specimens were used in the study.

The radial, longitudinal, and tangential sections of each sample were marked and measured with digital vernier calipers to the nearest 0.01 mm. All samples were placed in an oven dried and maintained at 103 ± 2 °C for 48 h and the shrinkage test was conducted during progress from green to oven-dry conditions. Shrinkage (S_o) was calculated according to Eq. 1,

$$S_o\,(\%) = \left(\frac{D_i - D_o}{D_i}\right) \times 100 \qquad (1)$$

where S_o is the shrinkage (%) from green to oven-dry conditions, D_i is the initial dimension length (mm), and D_o is the oven-dry dimension length (mm).

For the modulus of rupture (MOR) and modulus of elasticity (MOE), the split samples of 300 mm × 20 mm were obtained from the basal, middle, and top portions were air-dried in the shade for about one month and then conditioned for two weeks in a conditioning room at 65% relative humidity and 20 °C. A total of 60 specimens were prepared for this study. A 100 KN Shimadzu testing machine (Kyoto, Japan) was used and testing was performed with central loading and a cross-head speed of 0.65 mm/s with two supports over a span of 140 mm. The samples were tested in accordance to the procedure described by Gnanaharan *et al.* (1994).

Statistical analysis

Statistical analysis was performed using Statistical Analysis System (SAS) version 9.1.3 software (SAS Institute, Cary, NC). A one-way analysis of variance (ANOVA) was conducted to determine whether the differences in means were significant. If the differences were significant, the least significant difference (LSD) test was used to determine which of the means were significantly different from one another.

RESULTS AND DISCUSSION

Physical Characteristics

The identification of a bamboo species at the field usually begins by looking at its physical characteristics. Information gathered on the physical characteristics is important, as it quickens the identification of bamboo specimens that have an absolute characteristic distinction between species such as its culm height, internode length, and culm wall thickness. Based on the physical characteristics of bamboo species such as culm wall thickness, internode, and culm length, it can also be used to determine the suitable end products.

The physical characteristics of the 13 respective bamboo species in this study are presented in Table 1. The highest culm height at 32 m was recorded from *S. grande*, followed by *B. vulgaris cv vittata* (30 m), and *S. zollingeri* (22 m). The *S. grande* species had the longest internode length at 65 cm, followed by *S. zollingeri* (55 cm), and *S. brachycladum* (53 cm). The shortest internode length was measured from the *B. blumeana* species at 32 cm. The highest value of culm wall thickness was obtained from *D. asper* (16 mm), followed by *G. brang* (14 mm). The lowest culm wall thickness value was recorded from the *S. zollingeri* species at 4 mm.

From the result obtained, *Dendrocalamus asper*, *Gigantochloa*, and *Bambusa* have the thickest culm wall compared to *Schizostachyum*. On the other hand, *Schizostachyum* can be characterised by its longest internode and thinnest culm wall. Most *Bambusa* have shorter internode (except for *B. heterostachya*) as compared to other bamboo species. Based on the physical properties, species from the genus *Schizostachyum* is suitable for crafts, satay sticks, basketry, toothpick, water container and other general utility. This species is also use as vessels for cooking glutinous rice, called lemang. While, *D. asper*, *Bambusa* and *Gigantochloa* having the thickest culm wall makes it suitable for parquet, furniture and building structures.

Anatomical Properties

Liese (1998) described the four basic types of vascular bundles, which are vascular bundle types I, II, III, and IV. Type I vascular bundles are usually present in monopodial species of bamboos, whilst vascular bundles of type II, III, and IV are present in sympodial species of bamboos. Figure 1 shows anatomical structures of the 13 species studied. The vascular bundle type of Malaysian bamboo are classified as the following:

Type II: *S. brachycladum* and S. *zollingeri* with enlarged fibre sheath at the phloem side.

Type III: *G. thoii*, *G. scortechinii*, *G. ligulata*, *G. wrayii*, *G. brang*, *S. grande*, *B. heterostachya,* and *B. vulgaris cv. vittata* with one isolated fibre bundle.

Type IV: *B. vulgaris*, *B. blumeana*, and *D. asper* with a central vascular strand that has small sclerenchyma sheaths, and two isolated fibre strands located at the phloem and protoxylem sides.

The result obtained in this present study is similar with observation made by Grosser and Liese (1971). They also concluded that type IV vascular bundle is related to the thick walled internodes of large size bamboos as found in this study in *B. vulgaris*, *B. blumeana*, and *D. asper*.

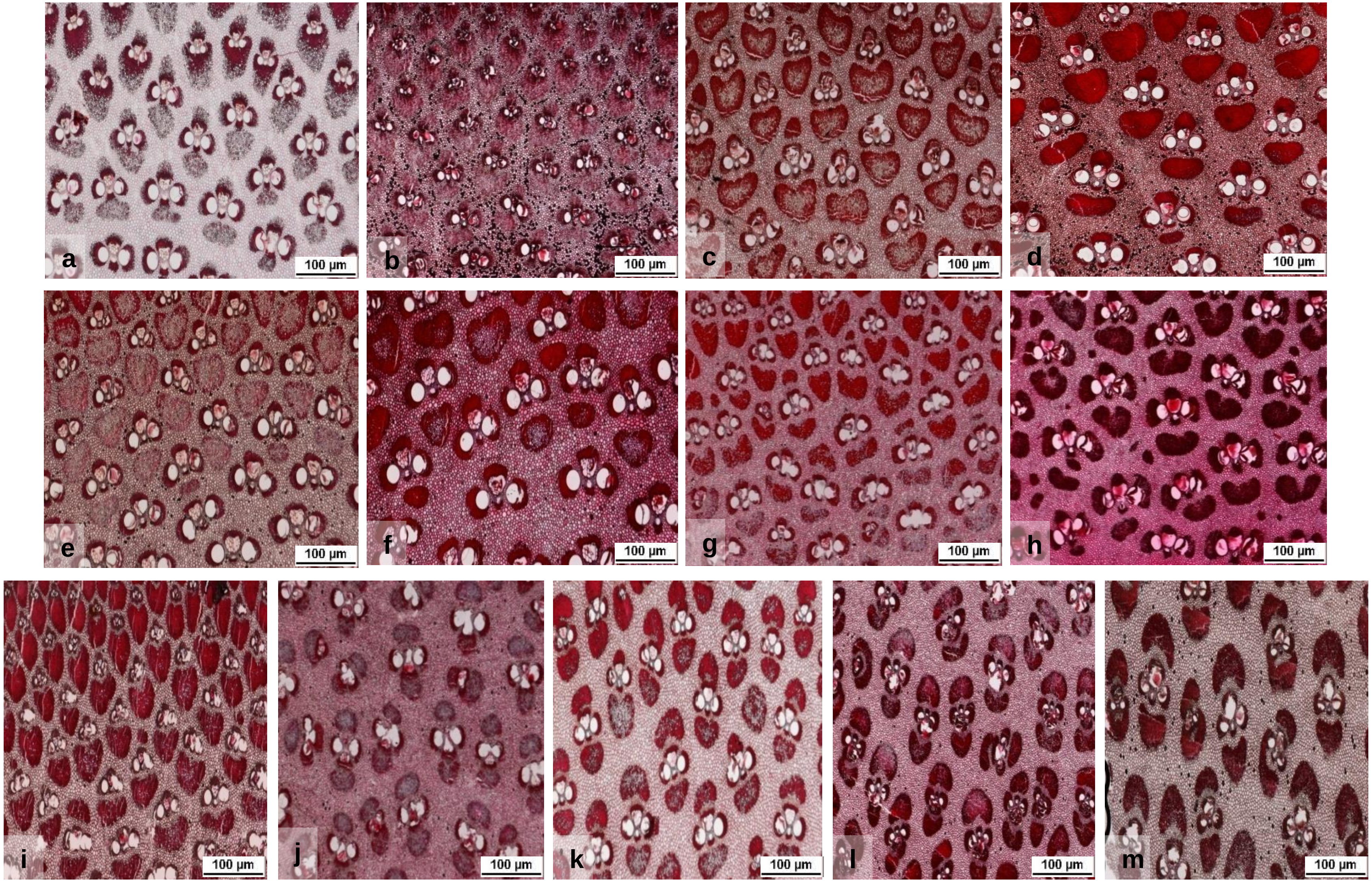

Fig. 1. Type of vascular bundle: a) and b) type II vascular bundle: *S.brachycladum* and *S. zollingeri*, respectively; c through j) type III vascular bundle: *G. thoii*, *G. scortechinii*, *G. ligulata*, *G. wrayii*, *G. brang*, *S. grande*, *B. heterostachya*, and *B. vulgaris* cv. *vittata*, respectively; k through m) type IV vascular bundle: *B. vulgaris*, *B. blumeana*, and *D. asper*, respectively

The fibre morphology is shown in Table 2. The results showed that fibre morphology varied among the species. From the 13 species, *G. thoii* and *G. ligulata* had the longest fibres, which were 4,070 µm and 3,930 µm, respectively. The results indicate that the mean value for fibre length of the 13 bamboo species ranged from 2,330 µm to 4,070 µm. The average length of bamboo fibre is longer than *Eucalyptus* spp., 568 µm to 1,140 µm, (Gominho *et al.* 2014; Carrillo *et al.* 2015) and is equivalent to *Pinus* spp., 2,300 µm to 3,600 µm (Ataç and Eroğlu 2013; Gulsoy and Ozturk 2015). Therefore, bamboo fibres are classified as long fibres according to the International Society for Wood Anatomy (Wheeler *et al.* 1989). Longer fibre length will contribute to the higher tearing resistance of paper (Sharma *et al.* 2011).

As stated by Liese (1998), fibre length is associated with internode length; however, in this study it shows that the fibre length is not correlated with the internode length. The fibre length, width, thickness, and lumen diameter for all of the species studied showed a significant decrease ($P < 0.05$) from the basal to the top of the culm. Razak *et al.* (2010) also reported a similar trend in fibre length and fibre wall thickness in *Bambusa vulgaris*. According to Liese (1998), the fibres are generally thicker at the basal portion than in the middle and top portion of the bamboo culm.

The highest mean percentage for vascular bundles was observed at the top portion of the bamboo culm, followed by the middle portion, and the lowest was at the basal portion (Table 2). Similar results were obtained by Xing *et al.* (2015) and Wang *et al.* (2016) in *Bambusa rigida* and *Dendrocalamus brandisii*, respectively. Nordahlia *et al.* (2011) also reported an increase in vascular bundles moving up the culm in *Schizostachyum brachycladum*, which was probably related to the decrease in culm wall thickness from the basal to the top of the bamboo culm. Grosser and Liese (1971) and Abd. Latif and Mohd Tamizi (1992) stated that the higher vascular bundles percentage at the top portion is mainly due to the tapering of the bamboo culm towards the top portion.

In terms of Runkel ratio (Fig. 2), *G. thoii* had the highest mean value, which was 4.53, followed by *G. ligulata* (4.30) and *B. vulgaris* (4.25), while the lowest value was obtained from *S. zollingeri* (1.01). Fibre with a Runkel ratio below 1 is classified as fine raw material, and fibre with a Runkel ratio greater than 1 is considered inferior. Fibre with a Runkel ratio equal to 1 is classified as secondary fibre raw material (Wu 1997; Zhan *et al.* 2015). As shown in Fig. 2, all of the bamboo species had Runkel ratios greater than 1, which indicated they belong to the inferior raw material for papermaking. According to Kiaei *et al.* (2014), a high Runkel ratio shows that the fiber is stiff and less flexible.

For aspect ratio (Fig. 3), the highest mean value was obtained by *B. vulgaris* (177.15), followed by *B. vulgaris* cv. *vittata* (176.70) and *G. ligulata* (174.13), whereas *G. wrayi* had the lowest value of 114.10. The aspect ratio of pulp fibers for papermaking should be above 100, and a larger ratio results in a better fiber for papermaking (Wang *et al.* 2008; Yang *et al.* 2008; Wang *et al.* 2016). All of the bamboo species in this study showed aspect ratios above 100 and longer fibre indicating good suitability for pulp raw material but greater in Runkel ratio. Similar results were obtained by Chandra and Susi (2018), Wang *et al*. (2016), Zhan *et al*. (2015), and Sharma *et al*. (2011), where they also found the aspect ratios were above 100, there were longer fibres, but the Runkel ratio was greater than 1. However, Chandra and Susi (2018) suggested the use of more chemicals during the cooking process to enable this fibre to be used efficiently.

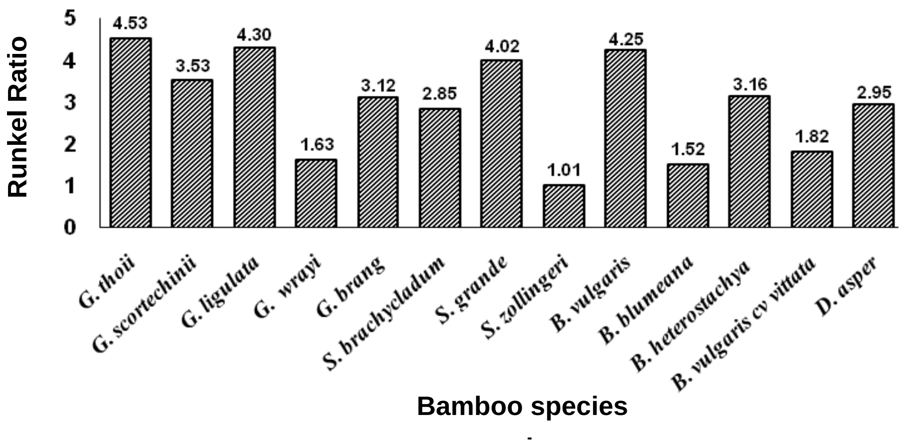

Fig. 2. The Runkel ratio of the 13 Malaysian bamboo fibres

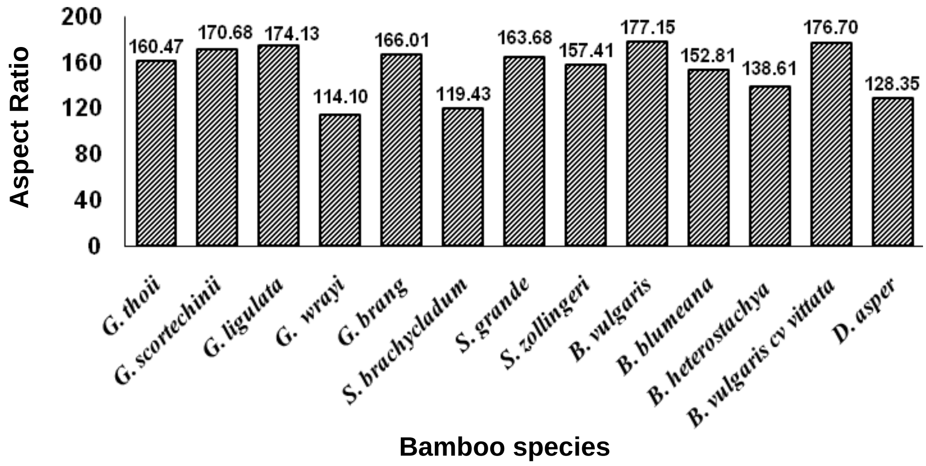

Fig. 3. The aspect ratio of the 13 Malaysian bamboo fibres

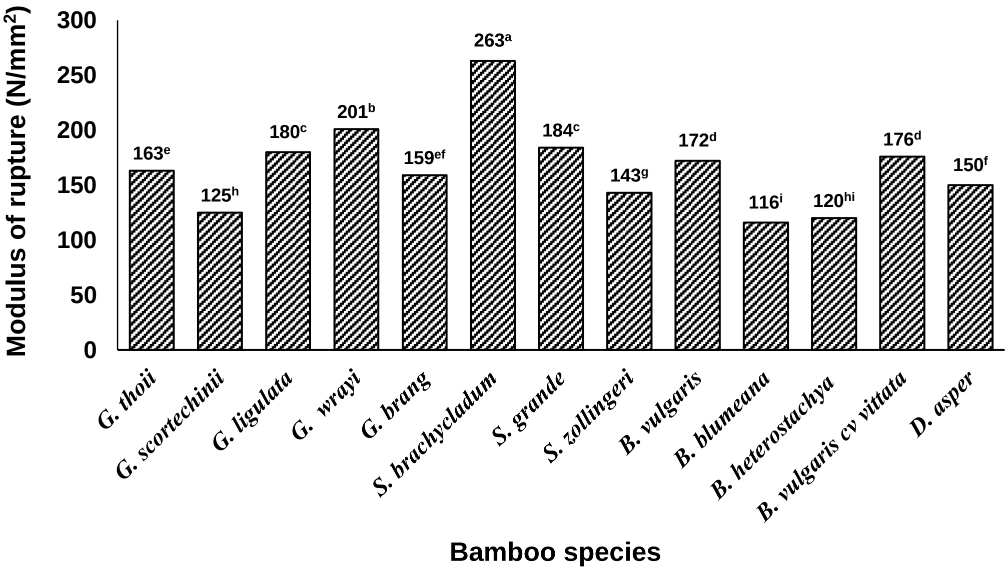

Fig. 4. Modulus of rupture for the 13 Malaysian bamboos

Density, Shrinkage, and Mechanical Properties

Table 3 presents the density and shrinkage properties. Figures 4 and 5 show mechanical properties that include the MOR and MOE of the 13 common bamboo species in Malaysia.

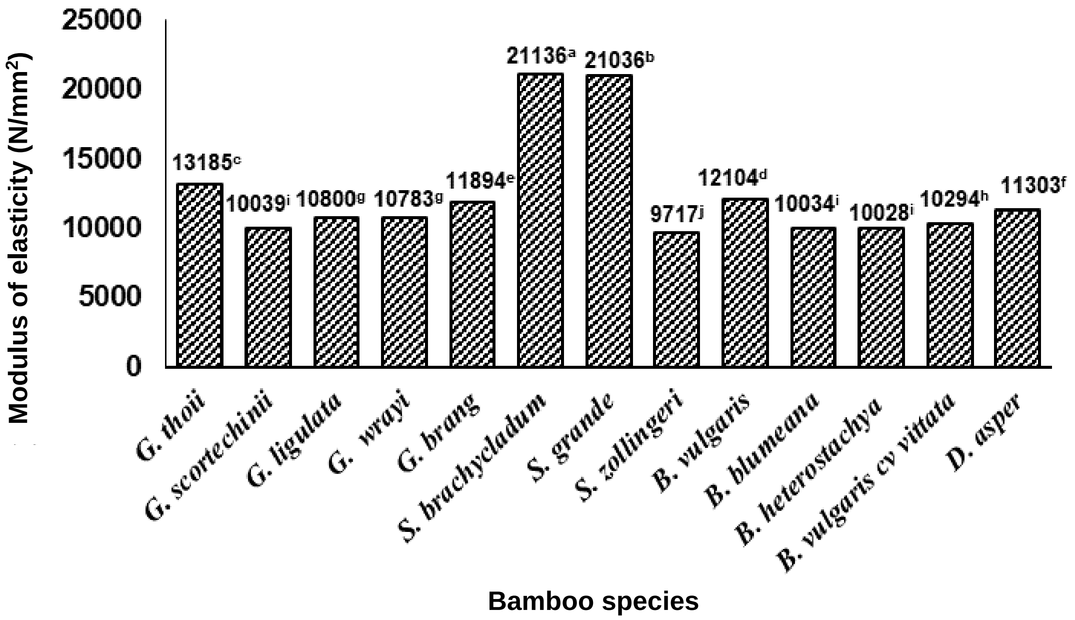

Fig. 5. Modulus of elasticity for the 13 Malaysian bamboos

Among the 13 species, *G. thoii* showed the highest density which was 751 kg/m^3 compared to the other species. Whilst *S. brachycladum* and *G. wrayii* showed the highest MOR which was 263 N/mm^2 and 201 N/mm^2 respectively. In contrast, *S. brachycladum* and *S. grande* showed the highest MOE which was 21,100 N/mm^2 and 21,000 N/mm^2, respectively.

Based on this present study, *G. scortechinii*, *G. thoii,* and *Dendrocalamus asper* have potential for structural application since these species have higher density, MOR, and thicker culm walls, but exhibit slightly lower MOE. *S. zollingeri* exhibited the lowest density (355 kg/m^3), which is suitable for general utility purposes, crafts, and decorative panels. Detail usage of each species based on density, MOR, and MOE are tabulated in Table 1.

The results showed that the density increased from the basal towards the top of the bamboo culm for all of the species studied (Table 3). Increases in density values from the basal to the top of the bamboo culm were also reported in *Dendrocalamus pendulus, D. asper, Gigantochloa levis*, *G. scortechinii* (Zakikhani *et al.* 2017), and *D. strictus* (Bhonde *et al.* 2014). According to Liese (1987), Abd. Latif and Mohd Tamizi (1992), and Wang *et al.* (2016), this trend may be associated with the higher value of vascular bundles, coupled with the increase in silica content from basal to the top. Correal and Arbelaez (2010) also mentioned that a high amount of schlerenchyma fibers at the top portion can also contribute to the high density at the top portion of the bamboo culm. The results for radial, longitudinal, and tangential shrinkage from green to oven-dry conditions are presented in Table 3. It can be seen that the shrinkage value decreased from the basal to the top of the bamboo culm. According to Anwar *et al.* (2005), the basal portion shrinks more than the other bamboo culm portions probably due to the presence of higher initial moisture content and lower number of vascular bundles.

Table 1. Physical Characteristics, Density, MOR, MOE, and Uses of 13 Species of Commercial Malaysian Bamboos

Species	Local Name	Culm Height (m)	Internode Length (cm)	Culm Wall Thickness (mm)	Density Kg/m^3	MOR N/mm^2	MOE N/mm^2	Uses
Gigantochloa thoii	Buluh beting	21	35	12	751	163	13,185	Furniture, parquet, structures
Gigantochloa scortechinii	Buluh semantan	21	42	10	641	125	10,039	Furniture, parquet, structures
Gigantochloa ligulata	Buluh tumpat	18	37	12	442	180	10,800	Furniture component, basketry, crafts
Gigantochloa wrayi	Buluh beti	18	38	12	628	201	10,783	Furniture, blinds, crafts
Gigantochloa brang	Buluh brang	19	40	14	536	159	11,894	Furniture, blinds, crafts
Schizostachyum brachycladum	Buluh lemang	21	53	5	588	263	21,136	Crafts, cooking vessels
Schizostachyum grande	Buluh semeliang	32	65	6	633	184	21,036	Crafts, blinds
Schizostachyum zollingeri	Buluh nipis	22	55	4	355	143	9,717	Crafts, basketry, cooking vessels
Bambusa vulgaris	Buluh minyak	16	33	9	610	172	12,104	Furniture, parquet, blinds
Bambusa blumeana	Buluh duri	16	32	11	478	116	10,034	Furniture, parquet, crafts
Bambusa heterostachya	Buluh galah	20	41	9	531	120	10,028	Furniture, parquet, crafts, blinds
Bambusa vulgaris cv vittata	Buluh gading	30	33	11	546	176	10,294	Furniture, parquet, crafts
Dendrocalamus asper	Buluh betong	20	37	16	559	150	11,303	Furniture, parquet, structures

Table 2. Fibre Morphology Along the Culm Height of 13 Commercial Malaysian Bamboos

Species	Height Level	Fibre Length (µm)	Fibre Diameter (µm)	Fibre Lumen Diameter (µm)	Fibre Wall Thickness (µm)	Frequency of Vascular Bundle (mm^{-2})
G. thoii	Basal	4,478 [a]	28.9 [a]	6.1 [a]	14.1 [a]	15 [c]
	Middle	3,900 [b]	25.5 [b]	6.0 [a]	12.8 [b]	17 [b]
	Top	3,835 [c]	22.1 [c]	4.3 [b]	10.1 [c]	23 [a]
	Mean	**4,071**	**25.5**	**5.0**	**12.2**	**18**
		(3,099 to 5,043)	**(20.5 to 30.5)**	**(2 to 8)**	**(9 to 15)**	**(16 to 24)**
G. scortechinii	Basal	2,488 [a]	17.0 [a]	4.1 [a]	6.8 [a]	13 [b]
	Middle	2,310 [b]	14.8 [b]	3.2 [b]	5.4 [b]	14 [b]
	Top	2,180 [c]	10.4 [c]	2.2 [c]	4.3 [c]	21 [a]

	Mean	**2,326** (**1,753 to 2,899**)	**14.1** (**10.0 to 19.1**)	**3.2** (**1.3 to 5.1**)	**5.5** (**3.4 to 7.5**)	**16** (**6 to 26**)
G. ligulata	Basal	4,146 a	22.9 a	4.7 a	9.7 a	10 c
	Middle	3,885 b	22.1 a	4.7 a	9.5 a	13 b
	Top	3,758 c	22.7 a	3.6 b	8.5 b	16 a
	Mean	**3,930** (**3,216 to 4,643**)	**22.6** (**18.5 to 26.6**)	**4.3** (**1.6 to 7.0**)	**9.2** (**7.5 to 10.8**)	**13** (**10 to 16**)
G. wrayi	Basal	3,040 a	25.8 a	14.1 a	9.0 a	10 c
	Middle	2,953 b	24.0 b	10.0 b	6.1 b	12 b
	Top	2,262 c	22.3 c	5.0 c	6.0 b	15 a
	Mean	**2,753** (**2,257 to 3,248**)	**24.0** (**20.5 to 27.5**)	**10.3** (**4.1 to 15.6**)	**7.0** (**4.4 to 9.6**)	**12** (**9 to 15**)
G. brang	Basal	3,863 a	24.2 a	9.7 a	8.6 a	6 c
	Middle	3,435 b	22.1 b	4.0 b	7.5 b	7 b
	Top	3,330 c	18.2 c	3.7 c	7.1 b	9 a
	Mean	**3,543** (**2,895 to 4,190**)	**21.4** (**15.0 to 28.0**)	**6.0** (**5.0 to 11.0**)	**7.7** (**4.0 to 11.0**)	**7** (**5 to 10**)
S. brachycladum	Basal	3,195 a	23.0 a	6.4 b	9.0 a	14 b
	Middle	2,758 b	22.3 b	6.9 a	8.2 b	14 b
	Top	2,566 c	21.5 c	6.0 b	6.5 c	16 a
	Mean	**2,840** (**2,638 to 3,552**)	**22.2** (**18.0 to 26.0**)	**6.4** (**4.0 to 8.4**)	**7.9** (**6.0 to 10.0**)	**15** (**8 to 22**)
S. grande	Basal	2,849 a	16.0 a	3.4 a	7.0 a	10 c
	Middle	2,262 b	14.8 b	3.3 a	6.5 a	12 b
	Top	2,242 b	14.0 b	3.0 a	5.0 b	15 a
	Mean	**2,451** (**2,105 to 2,900**)	**15.0** (**12.0 to 18.0**)	**3.1** (**2.4 to 5.8**)	**6.1** (**4.1 to 8.8**)	**12** (**7 to 19**)
S. zollingeri	Basal	2,723 a	19.2 a	12.8 a	3.6 a	8 c
	Middle	2,285 b	15.1 b	7.3 b	3.3 a	10 b
	Top	1,970 c	11.0 c	4.2 c	3.3 a	12 a

	Mean	**2,326 (1,850 to 2,955)**	**14.8 (10.7 to 19.9)**	**8.1 (2.9 to 13.2)**	**3.3 (2.0 to 4.8)**	**10 (8 to 12)**
B. vulgaris	Basal	2,753 ^{a}	13.3 ^{b}	3.3 ^{a}	9.1 ^{a}	9 ^{b}
	Middle	2,486 ^{b}	14.3 ^{a}	3.7 ^{a}	7.0 ^{b}	12 ^{a}
	Top	2,244 ^{c}	14.9 ^{a}	3.6 ^{a}	5.7 ^{c}	13 ^{a}
	Mean	**2,494 (1,825 to 3,159)**	**14.1 (9.5 to 18.8)**	**3.5 (1.4 to 5.6)**	**7.1 (3.4 to 9.5)**	**11 (8 to 14)**
B. blumeana	Basal	3,438 ^{a}	20.3 ^{a}	10.4 ^{a}	7.2 ^{a}	10 ^{c}
	Middle	2,773 ^{b}	18.5 ^{b}	7.1 ^{b}	5.2 ^{b}	15 ^{b}
	Top	2,505 ^{c}	18.0 ^{b}	5.5 ^{c}	4.7 ^{c}	18 ^{a}
	Mean	**2,905 (2,382 to 3,458)**	**18.9 (14.3 to 23.5)**	**7.6 (3.1 to 12.1)**	**5.7 (3.8 to 7.5)**	**14 (10 to 20)**
B. heterostachya	Basal	4,022 ^{a}	28.1 ^{a}	7.2 ^{a}	12.0 ^{a}	10 ^{c}
	Middle	3,757 ^{b}	27.0 ^{b}	6.0 ^{b}	11.6 ^{a}	15 ^{b}
	Top	3,512 ^{c}	25.4 ^{c}	4.4 ^{c}	8.0 ^{b}	17 ^{a}
	Mean	**3,764 (3,180 to 4,148)**	**26.8 (23.0 to 29.1)**	**5.8 (4.0 to 10.2)**	**10.5 (7.3 to 13.0)**	**14 (9 to 18)**
B. vulgaris cv. *vittata*	Basal	4,130 ^{a}	23.8 ^{a}	8.8 ^{a}	7.8 ^{a}	9 ^{c}
	Middle	3,710 ^{b}	20.4 ^{b}	7.2 ^{b}	6.1 ^{b}	12 ^{b}
	Top	2,935 ^{c}	16.8 ^{c}	5.0 ^{c}	5.0 ^{c}	17 ^{a}
	Mean	**3,592 (2,826 to 4,158)**	**20.3 (16.0 to 24.1)**	**6.9 (4.2 to 10.7)**	**6.3 (4.1 to 8.5)**	**13 (8 to 19)**
D. asper	Basal	3,460 ^{a}	25.0 ^{a}	8.0 ^{a}	9.7 ^{a}	10 ^{c}
	Middle	2,920 ^{b}	24.5 ^{a}	5.8 ^{b}	8.3 ^{b}	12 ^{b}
	Top	2,613 ^{c}	20.5 ^{b}	4.5 ^{c}	8.0 ^{b}	16 ^{a}
	Mean	**2,998 (2,261 to 3,734)**	**23.3 (19.9 to 26.8)**	**6.1 (2.7 to 9.5)**	**8.6 (7.2 to 10.1)**	**13 (10 to 16)**

Values in parentheses are standard deviations. Cell values differing by a letter in the superscript in each column are significantly different at the 0.05 probability level.

Table 3. Density, Shrinkage, MOR, and MOE Along the Culm Height of 13 Commercial Malaysian Bamboos

Species	Height Level	Density (kg/m^3)	Shrinkage From Green to Oven Dry (%)			MOR (N/mm^2)	MOE (N/mm^2)
			T	L	R		
G. thoii	Basal	700 ^{c}	7.71 ^{a}	1.88 ^{a}	13.04 ^{a}	151 ^{c}	11,808 ^{c}
	Middle	751 ^{b}	7.03 ^{b}	1.52 ^{b}	12.55 ^{b}	161 ^{b}	13,248 ^{b}
	Top	802 ^{a}	6.69 ^{c}	1.35 ^{c}	10.76 ^{c}	176 ^{a}	14,500 ^{a}
	Mean	**751**	**7.14**	**1.58**	**12.12**	**163**	**13,185**
		(649 to 853)	**(5.02 to 8.89)**	**(0.73 to 2.81)**	**(8.03 to 13.72)**	**(130 to 196)**	**(10,066 to 16,304)**
G. scortechinii	Basal	599 ^{c}	8.58 ^{a}	0.70 ^{a}	11.58 ^{a}	122 ^{b}	9,243 ^{c}
	Middle	624 ^{b}	8.13 ^{a}	0.51 ^{b}	10.47 ^{b}	125 ^{b}	10,989 ^{a}
	Top	700 ^{a}	6.48 ^{b}	0.48 ^{c}	7.17 ^{c}	128 ^{a}	9,885 ^{b}
	Mean	**641**	**7.73**	**0.56**	**9.77**	**125**	**10,039**
		(573 to 709)	**(5.51 to 9.94)**	**(0.05 to 1.12)**	**(5.75 to 13.78)**	**(105 to 146)**	**(8,043 to 12,034)**
G. ligulata	Basal	377 ^{c}	3.57 ^{a}	0.32 ^{a}	7.93 ^{a}	170 ^{c}	9,788 ^{c}
	Middle	455 ^{b}	2.54 ^{b}	0.26 ^{b}	7.64 ^{a}	180 ^{b}	10,900 ^{b}
	Top	494 ^{a}	2.28 ^{c}	0.27 ^{b}	6.75 ^{b}	190 ^{a}	11,712 ^{a}
	Mean	**442**	**2.80**	**0.28**	**7.42**	**180**	**10,800**
		(369 to 507)	**(1.49 to 4.10)**	**(0.04 to 0.53)**	**(3.82 to 11.02)**	**(160 to 202)**	**(9,500 to 11,800)**
G. wrayi	Basal	601 ^{c}	2.96 ^{a}	0.47 ^{b}	4.06 ^{a}	189 ^{c}	6,296 ^{c}
	Middle	634 ^{b}	2.89 ^{b}	0.85 ^{a}	3.13 ^{b}	197 ^{b}	12,368 ^{b}
	Top	650 ^{a}	2.79 ^{c}	0.26 ^{c}	3.07 ^{c}	217 ^{a}	13,686 ^{a}
	Mean	**628**	**2.88**	**0.53**	**3.43**	**201**	**10,783**
		(591 to 666)	**(1.09 to 4.68)**	**(0.02 to 1.08)**	**(1.78 to 5.09)**	**(179 to 219)**	**(6,200 to 13,945)**
G. brang	Basal	475 ^{c}	7.56 ^{a}	0.39 ^{a}	8.43 ^{a}	142 ^{c}	8,833 ^{c}
	Middle	539 ^{b}	6.54 ^{b}	0.27 ^{b}	8.15 ^{b}	163 ^{b}	13,223 ^{b}
	Top	593 ^{a}	6.49 ^{b}	0.27 ^{b}	7.06 ^{c}	171 ^{a}	13,626 ^{a}
	Mean	**536**	**6.86**	**0.31**	**7.90**	**159**	**11,894**
		(479 to 593)	**(6.06 to 7.67)**	**(0.01 to 0.61)**	**(6.32 to 9.50)**	**(138 to 180)**	**(8,529 to 14,859)**
S. brachycladum	Basal	551 ^{c}	8.14 ^{a}	0.10 ^{c}	10.80 ^{a}	207 ^{c}	15,817 ^{c}
	Middle	599 ^{b}	5.51 ^{b}	0.40 ^{a}	7.44 ^{b}	220 ^{b}	21,540 ^{b}

	Top	620 a	3.74 c	0.31 b	6.34 c	363 a	26,051 a
	Mean	**588**	**5.79**	**0.27**	**8.20**	**263**	**21,136**
		(526 to 652)	**(3.14 to 8.30)**	**(0.06 to 0.68)**	**(4.46 to 11.00)**	**(201 to 370)**	**(15,7062 to 6,250)**
S. grande	Basal	605 c	10.44 a	0.68 a	13.14 a	155 c	14,655 c
	Middle	620 b	6.64 b	0.50 b	6.76 b	175 b	22,401 b
	Top	674 a	6.44 c	0.46 c	6.45 c	222 a	26,051 a
	Mean	**633**	**7.84**	**0.55**	**8.78**	**184**	**21,036**
		(520 to 745)	**(4.28 to 11.45)**	**(0.07 to 1.02)**	**(3.83 to 13.64)**	**(139 to 225)**	**(8,996 to 32,654)**
S. zollingeri	Basal	324 c	9.59 a	0.54 a	14.60 a	131 b	9,132 c
	Middle	368 b	8.60 b	0.29 b	11.78 c	137 b	9,435 b
	Top	372 a	6.09 c	0.27 b	12.54 b	161 a	10,585 a
	Mean	**355**	**8.09**	**0.36**	**12.99**	**143**	**9,717**
		(315 to 394)	**(5.74 to 10.45)**	**(0.02 to 0.72)**	**(7.30 to 18.67)**	**(127 to 162)**	**(8,869 to 10,600)**
B. vulgaris	Basal	589 c	6.41 a	2.90 a	9.21 a	153 c	9,570 c
	Middle	604 b	5.86 b	1.52 b	8.33 b	174 b	11,767 b
	Top	637 a	5.45 c	1.25 c	7.87 c	190 a	14,974 a
	Mean	**610**	**5.91**	**1.90**	**8.47**	**172**	**12,104**
		(564 to 656)	**(4.14 to 7.68)**	**(0.54 to 2.95)**	**(5.26 to 10.90)**	**(144 to 200)**	**(8,215 to 15,992)**
B. blumeana	Basal	456 c	7.23 a	0.96 a	13.04 a	110 b	9,125 c
	Middle	478 b	6.23 b	0.74 b	12.40 b	111 b	10,046 b
	Top	501 a	5.82 c	0.28 c	9.76 c	128 a	10,931 a
	Mean	**478**	**6.40**	**0.66**	**11.70**	**116**	**10,034**
		(453 to 503)	**(5.04 to 7.76)**	**(0.10 to 1.41)**	**(9.37 to 14.01)**	**(102 to 130)**	**(9,068 to 10,999)**
B. heterostachya	Basal	461 b	5.73 a	1.21 b	12.93 a	105 c	9,060 c
	Middle	465 b	4.92 b	1.98 a	11.86 b	122 b	10,210 b
	Top	664 a	3.43 c	1.26 b	8.95 c	133 a	10,814 a
	Mean	**531**	**4.70**	**1.49**	**11.23**	**120**	**10,028**
		(424 to 670)	**(3.38 to 6.08)**	**(0.56 to 2.42)**	**(7.75 to 14.71)**	**(102 to 140)**	**(9,058 to 10,850)**
B. vulgaris cv vittata	Basal	523 c	4.37 a	0.44 a	7.43 a	161 c	7,216 c
	Middle	540 b	3.35 b	0.31 b	6.44 b	176 b	10,905 b

	Top	575 ^{a}	3.01 ^{c}	0.35 ^{b}	4.63 ^{c}	189 ^{a}	12,761 ^{a}
	Mean	**546**	**3.58**	**0.37**	**6.17**	**176**	**10,294**
		(489 to 603)	**(1.69 to 5.47)**	**(0.22 to 0.51)**	**(4.10 to 8.23)**	**(1452 to 06)**	**(7,200 to 13,374)**
D. asper	Basal	486 ^{c}	6.29 ^{a}	0.48 ^{a}	8.30 ^{a}	131 ^{c}	9,953 ^{c}
	Middle	573 ^{b}	4.50 ^{b}	0.36 ^{b}	7.07 ^{b}	145 ^{b}	10,583 ^{b}
	Top	617 ^{a}	2.10 ^{c}	0.36 ^{b}	5.87 ^{c}	175 ^{a}	13,374 ^{a}
	Mean	**559**	**4.30**	**0.40**	**7.12**	**150**	**11,303**
		(471 to 646)	**(2.06 to 6.55)**	**(0.15 to 0.64)**	**(5.70 to 8.54)**	**(127 to 180)**	**(9,630 to 13,500)**

Values in parentheses are standard deviations. Cell values differing by a letter in the superscript in each column are significantly different at the 0.05 probability level. T = Tangential, L = Longitudinal, R = Radial, MOR = Modulus of rupture, and MOE = Modulus of elasticity

Increases in MOR and MOE (Table 3) were observed along the culm height in all 13 species studied. This was consistent with results obtained in *Gigantochloa scortechinii* (Hamdan *et al.* 2009; Shahril and Mansur 2009), *Dendrocalamus latiflorus*, *Dendrocalamus merrillanus*, *Bambusa vulgaris* (Leoncio 2017), and *Dendrocalamus strictus* (Bhonde *et al.* 2014). The increasing tendency of the MOR and MOE in all species studied was accompanied by the higher amount of vascular bundles along the culm height (Table 2). Moreover, the increasing mean density towards the top portion (Table 3) also influenced the increase in MOR and MOE. This is further supported by the findings of Correal and Arbelaez (2010) and Archila-Santos *et al.* (2014), who also stated that the increase in MOR and MOE was influenced by the density and percentage of vascular bundle.

CONCLUSIONS

1. The anatomical, physical, and mechanical properties of 13 commercial Malaysian bamboo species were successfully evaluated and the properties were different between the species. This information is important to assess bamboo suitability for various end products. From the 13 species that have been studied, *G. thoii* and *G. ligulata* had the longest fibres, which were 4,071 µm and 3,930 µm, respectively.
2. *G. thoii* showed the highest density, which was 751 kg/m^3 compared to the other species. Whilst *S. brachycladum* and *G. wrayii* showed the highest MOR, which was 263 N/mm^2 and 201 N/mm^2, respectively. In contrast, *S. brachycladum* and *S. grande* showed the highest MOE, which was 21,136 N/mm^2 and 21,036 N/mm^2, respectively.
3. *S. brachycladum* and *S. zollingeri* showed type II vascular bundles with the enlarged fibre sheath at the phloem side. In contrast, *G. thoii*, *G. scortechinii*, *G. ligulata*, *G. wrayii*, *G. brang*, *S. grande*, *B. heterostachya*, and *B. vulgaris* cv *vittata* had type III vascular bundles with one isolated fibre bundle. Alternatively, *B. vulgaris*, *B. blumeana*, and *D. asper* had type IV vascular bundles with a central vascular strand that had small sclerenchyma sheaths, and two isolated fibre strands located at the phloem and protoxylem sides.
4. In terms of Runkel ratio, it was shown that all 13 species had inferior raw material for papermaking where the Runkel ratios were greater than 1. However, the aspect ratio of the 13 species of bamboo showed good suitability for pulp raw material where the aspect ratios were above 100.
5. The results obtained in this study demonstrated that fiber morphology and shrinkage from green to oven-dry conditions decreased from the basal to the top of the bamboo culm in all of the species studied. In contrast, the opposite tendency was observed in the percentage of vascular bundles, density, MOR, and MOE.

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