EFFECTS OF ANATOMICAL CHARACTERISTICS ON THE PHYSICAL AND MECHANICAL PROPERTIES OF *BAMBUSA BLUMEANA*

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ABD. LATIF MOHMOD, ASHAARI HJ. AMIN, JAMALUDDIN KASSIM & MOHD. ZIN JUSUH. 1993. Effects of anatomical characteristics on the physical and mechanical properties of *Bambusa blumeana*. This paper discusses the physical, mechanical and anatomical characteristics of one- to three-year–old *Bambusa blumeana.* The physical and mechanical properties such as moisture content, shrinkage, shear and static bending were correlated to the anatomical characteristics. Density and shrinkage, but not moisture content, were significantly correlated to radial/tangential ratio of vascular bundles. Except for the modulus of rupture, all the mechanical properties increased with age, height, density, frequency of vascular bundles and fibre wall thickness.

Key words: *Bambusa blumeana* - physical and mechanical properties - anatomical relationship

ABD. LATIF MOHMOD, ASHAARI HJ. AMIN, JAMALUDDIN KASSIM & MOHD. ZIN JUSUH. 1993. Pengaruh ciri-ciri anatomi terhadap sifat-sifat fizikal dan mekanikal *Bambusa blumeana*. Sifat-sifat fizikal, mekanikal dan anatomikal *Bambusa blumeana* pada peringkat-peringkat umur satu hingga tiga tahun adalah diperbincangkan dalam kertas kerja ini. Sifat-sifat fizikal dan mekanikal seperti kandungan kelembapan, kecutan dan lenturan statik juga di hubungkaitkan dengan ciri-ciri anatomikal yang di kaji. Melainkan kandungan kelembapan, nilai kepadatan dan pengecutan di dapati berhubung secara nyata terhadap nisbah jejari/tangen berkas-berkas vascular. Kecuali modulus pecah, semua sifat-sifat mekanikal dicerap sebagai meningkat mengikut umur, ketinggian batang, kepadatan, peningkatan taburan berkas-berkas vaskular dan ketebalan dinding gentian.

Introduction

The selection of bamboo for industrial uses, construction and housing is closely related to its physical and mechanical properties (Abd. Latif *et al.* 1990a) and anatomical characteristics (Espiloy 1987). Density, for example, helps to determine the physical and mechanical properties which characterize different kinds of wood and woody materials for their intended usage (Mitchell 1964, Gurfinkel 1973). Anatomical structure such as the fibre length, on the other hand, influences the physical and mechanical properties of the material which are often associated with its toughness, workability and durability (Parameswaran & Liese 1976, Espiloy 1987).

In this study, the physical, mechanical and anatomical properties of one- to three-year-old *Bambusa blumeana* (buluh duri) at three levels of culm height were determined. The inter-relationships of the different physical and mechanical properties in relation to the anatomical characteristics of the bamboo were also evaluated to assess its suitability particularly for various structural purposes.

Materials and methods

Nine culms each from 1-, 2- and 3 - *y* - old *Bambusa blumeana* obtained from the Forest Research Institute Malaysia (FRIM) at Kepong, Selangor, Malaysia were used in this study. The culm length, diameter, thickness, girth and number of internodes were recorded. Each bamboo sample was then equally divided into three portions of basal (B), middle (M) and top (T). The methods used for the determination of moisture content, oven-dry density, shrinkage and mechanical properties were based on IS 6874 (Anonymous 1973). Vascular bundles distribution and fibre dimensions were determined using the methods outlined by Jane (1933) and Wilson (1954), respectively.

Results and discussion

Physical characteristics

The physical characteristics of *B. blumeana* such as diameter, girth, internode length and thickness are presented in Table 1.

The stem of *B. blumeana* consists of a hollow culm with distinct nodes and internodes. The culms are tall with lengths of 17 - 19 *m* and diameters of about 7 - 9 *cm*. They are commonly found growing in clumps and are easily recognised by their thorny characteristics from the copious spreading low thorny branches (Holtum 1958). *B. blumeana* culm, like other bamboos, tapers from the base towards the tip with a decrease in diameter, girth, internode length and culm wall thickness. The total number of internodes were observed to be about 33 per culm with an average internodal length of 24 - 32 *cm* and 0.7 - 1.5 *cm* in culm wall thickness.

Table 1. Physical characteristics of *Bambusa blumeana* culms

Property	Age (y) 1	2	3
Culm length (*cm*)	1890	1829	1738
Number of internodes per culm	32	33	34
Internode length (*cm*)			
a. Basal	21.2	26.5	30.5
b. Middle	33.4	34.1	35.0
c. Top	18.3	25.1	29.9
Internode diameter (*cm*)			
a. Basal	8.4	8.2	8.5
b. Middle	8.2	7.8	8.7
c. Top	7.7	7.3	8.1
Culm wall thickness (*cm*)			
a. Basal	1.14	1.10	1.46
b. Middle	0.86	0.72	1.03
c. Top	0.71	0.76	0.82
Girth (*cm*)			
a. Basal	26.1	25.2	27.0
b. Middle	26.6	24.5	27.3
c. Top	24.7	23.5	26.3

Note: a. Values shown are averages of 9 culms;
b. Shorter culm length at older ages are due to incidences of broken tips or drooping culms.

Anatomical properties

The anatomical properties of *B. blumeana* of the three age groups and at different portions of the culm are presented in Table 2. The respective summary of analysis of variance of the properties are given in Table 3. Table 4 gives the summary of correlation coefficients of different anatomical characteristics with age and height of bamboo.

Table 2. Anatomical characteristics of *B. blumeana*

	Age (y) 1			2			3		
Property	Basal	Middle	Top	Basal	Middle	Top	Basal	Middle	Top
1. Vascular bundle									
i. Distribution (no. m^{-2})	2.87	2.37	3.42	3.22	3.10	4.55	3.07	3.55	4.05
ii. Radial/tangential ratio	1.23	0.64	0.65	0.78	0.57	0.63	1.03	0.68	0.76
2. Fibre									
i. Length (*mm*)	2.36	2.47	2.09	2.17	2.20	2.02	2.33	2.36	2.15
ii. Diameter (x10^{-2} *mm*)	1.95	2.25	1.85	2.15	2.30	2.30	2.35	1.90	2.40
iii. Wall thickness (x 10^{-3}*mm*)	4.5	5.5	7.0	6.0	7.0	6.5	6.5	5.5	8.5
iv. Lumen diameter (x10^{-2}*mm*)	1.20	1.20	1.25	1.20	1.00	1.15	1.30	1.15	0.95

Table 3. Summary of analyses of variance on anatomical characteristics of *B. blumeana*

		Mean squares and statistical significance					
Source of variation	Df	Vascular bundle distribution	Radial/ tangential ratio	Fibre length	Fibre diameter	Fibre wall thickness	Lumen diameter
Age	2	9.87E3ns	5.30E-2ns	5.10E-2ns	9.56E-6ns	2.17E-6ns	1.72E-6ns
Height	2	1.90E4ns	2.73E-1ns	1.07E-1ns	2.22E-7ns	4.67E-6ns	2.72E-6ns
Age × Height	4	2.06E3ns	2.70E-2ns	6.00E-3ns	1.25E-5ns	1.83E-6ns	2.89E-6ns

Note: ns - not significant at $p < 0.05$.

Table 4. Correlation coefficients of different anatomical characteristics with age and height of *B. blumeana*

Characteristic	Age	Height
Vascular bundle distribution	0.18 ns	0.25 ns
Radial/tangential ratio of vascular bundle	0.02 ns	- 0.54 *
Fibre length	- 0.03 ns	- 0.24 ns
Fibre diameter	0.26 ns	0.04 ns
Fibre wall thickness	0.44 ns	0.31 ns
Lumen diameter	- 0.13 ns	- 0.19 ns

Note: ns - not significant at $p < 0.05$; * - significant at $p < 0.05$.

The frequency of vascular bundles varies insignificantly with age and height of the culm. The highest and lowest mean concentrations of vascular bundles were observed in the top portion of the 2- *y* - old culm (5 bundles mm^{-2}) and middle portion of the 1- *y* - old culm (2 bundles mm^{-2}), respectively. The higher density of vascular bundles at the top portion of bamboo is explained by Grosser and Liese (1971) as a result of the decrease in culm wall thickness. Since the decrease compensates the gradual decrease in the actual number and size of the vascular bundles, they get close together in thinner culm walls (towards the top).

The vascular bundle size (measured as radial/tangential ratio) differs insignificantly with height and age of the bamboo culm. The radial/ tangential ratio of vascular bundles was observed to correlate insignificantly with age but decrease significantly with height of the culm ($R = -0.54$ at $p < 0.05$). The reason for the higher ratio of vascular bundle size nearer the basal portion is probably due to presence of more matured tissues (whereby the radial diameter decreases faster than the tangential diameter of the vascular bundles within the height of a culm) in this region (Abd. Latif & Mohd. Tamizi 1992).

The fibre length of *B. blumeana* obtained in this study ranges between 2.02 - 2.47 *mm* and is not affected by age and culm height. The fibre length, however, tends to decrease towards the top portion and older samples (R = - 0.03 and - 0.24 at $p < 0.05$, respectively). As mentioned by many researchers, the fibre length within and between the bamboo culm may vary as the individual characteristics of the bamboo itself (Grosser & Liese 1971, Pattanath 1972).

Fibre wall thickness is not significantly affected by either age or height positions but tends to increase with these parameters (R = 0.44 and 0.31, respectively). This may be reflected by the decrease of lumen diameter with increase of age and height of the culm. The average fibre wall thickness observed in this study, nevertheless, ranges from 4.5 - 8.5 μm.

Effects of culm characteristics and anatomical structures on physical properties

The average physical properties of *B. blumeana* and the summary of the respective analysis of variance are given in Tables 5 and 6. Table 7 gives the summary of correlation coefficients of different physical properties with culm and anatomical characteristics of the bamboo.

Table 5. Average physical properties *B. blumeana*

Age (y)								
1			2			3		
B	M	T	B	M	T	B	M	T
Moisture content (%)								
97.0	87.3	79.3	79.6	70.2	57.3	95.8	79.5	57.5
Oven-dry density ($kg\ m^{-3}$)								
430	463	497	493	530	580	513	603	620
Radial shrinkage (%)								
10.05	6.34	6.45	8.85	6.37	6.00	8.07	6.05	5.68
Tangential shrinkage (%)								
20.00	11.97	9.89	19.45	10.60	9.42	17.98	9.04	6.32

Note: B= basal, M= middle, T= top.

The initial moisture content of *B. blumeana* varies insignificantly with age, height and the interaction of age and height but tends to decrease with increases of age (R = - 0.20) and height (R = - 0.50). The initial moisture content, regardless of age and height, varies between 57 and 97 %. The highest and lowest mean initial moisture contents were observed in the respective basal portions of the 1- *y* - old culm (97 %) and the top portion of the 2- *y* - old specimens (57 %), respectively. The results further indicate that *B. blumeana* possesses the highest and lowest moisture content at age one and two, respectively. This indicates the thick-walled fibres and greater concentration of vascular bundle distributed in the mature tissues of the older bamboos (R= 0.70 and 0.43, respectively).

Table 6. Summary of analysis of variance on physical properties of *B. blumeana*

Source of variation	Df	Mean squares and statistical significance			
		Physical properties			
				Shrinkage	
		Moisture content	Density	Radial	Tangential
Age	2	535.86ns	15672.22**	1.53**	12.84**
Height	2	1024.19ns	13605.56**	16.25**	190.39**
Age × Height	4	60.85ns	3280.55**	0.40ns	0.57**

Note: ns = not significant at $p < 0.05$;
** = highly significant at $p < 0.01$.

Table 7. Summary of correlation coefficients of physical properties with age, height, culm characteristics and anatomical structures of *B. blumeana*

Parameter	Physical properties			
			Shrinkage	
	MC	Density	Radial	Tangential
Age	- 0.20ns	0.64**	- 0.28ns	- 0.24ns
Height	- 0.50ns	0.61*	- 0.82**	- 0.91**
Internode length	- 0.10ns	0.40ns	- 0.41ns	- 0.27ns
Culm:				
a. Diameter	0.67*	- 0.15ns	0.40ns	0.41ns
b. Wall thickness	0.70*	- 0.27ns	0.66*	0.74*
Vascular bundles:				
a. Distribution	0.43ns	- 0.35ns	- 0.25ns	- 0.21ns
b. Size	- 0.21ns	0.53*	0.57*	0.51*
Fibre dimensions:				
a. Length	- 0.33ns	0.28ns	0.11ns	0.14ns
b. Wall thickness	- 0.38ns	0.50*	- 0.37ns	- 0.44ns
c. Diameter	- 0.72*	- 0.13ns	- 0.13ns	- 0.08ns
d. Lumen diameter	- 0.48*	0.21ns	0.21ns	0.25ns

Note: ns = not significant at $p < 0.05$; * = significant at $p < 0.05$;
** = highly significant at $p < 0.01$.

The density was observed to be in the range of 430 - 620 $kg\ m^{-3}$ with the highest mean value at the top portions of the 3-y-old culm (620 $kg\ m^{-3}$). The density of *B. blumeana*, in addition, increased from 37 to 53 % with maturity in the one- to three-year-old culms. Again, this reflects the thicker fibres wall and greater concentration of vascular bundle distributed in the mature tissues of the older bamboos (Abd. Latif *et al.* 1990b, Abd. Latif & Mohd. Tamizi 1992).

It appears that the density of bamboo does not vary much with height, but tends to have a higher value near the top of the culm (Table 5). This could be associated with the decrease in culm wall thickness ($R= -0.27$ at $p < 0.05$, Table 7). Since the decrease compensates for the gradual decrease in the actual number and size of the vascular bundles, they get close together in thinner culm walls (towards the top), thus reducing the initial moisture content but increasing the density (Grosser & Liese 1971, Abd. Latif & Mohd. Tamizi 1992).

Regardless of age and height, the radial and tangential shrinkage of *B. blumeana* range from 5.4 - 9.5% and 6.4 - 20.1%, respectively. The magnitudes of shrinkage are almost similar in that they generally decrease with age and height of the culm (Table 7). The 1-*y*-old culm was observed to shrink at an average of 15 - 22% more compared to the 3-*y*-old bamboo in the respective radial and tangential surfaces, thus indicating that the older bamboo is more dimensionally stable than the young ones. The radial and tangential shrinkages of *B. blumeana*, as above, are also found to decrease according to the height of the culm. While the average radial and tangential shrinkages at the basal portion of the 2-*y*-old culm are about 8 and 19 %, respectively, the shrinkage values at the top portion are approximately 6 and 12 % on both radial and tangential surfaces. Again, the higher density due to a relative higher amount of vascular bundles and low initial moisture content could account for the minimal shrinkage in the top portion. With the increase of oven-dry density and decrease in moisture content, and supported by the higher proportion of vascular bundles per square unit and age, the shrinkage decreases (Killmann 1983).

Effects of anatomical structure, culm characteristics and physical properties on strength of B. blumeana

The results from the tests on the mechanical properties are as presented in Table 8, and the summary of the respective analysis of variance are shown in Table 9. Table 10 gives the summary of correlation coefficients of different mechanical properties with culm characteristics, anatomical structure and physical properties of *B. blumeana.*

The results indicate that all the mechanical properties vary significantly ($p < 0.01$) at all ages and culm heights. The general concensus is that as bamboo matures, the culm wall thickens and becomes hard which results in maximum strength (Young & Haun 1961, Zhou 1981, Liese 1987).

The strength properties obtained here from *B. blumeana* are somewhat similar to those of other woody materials. Table 8 reveals that shear (S), compression parallel to grain (CPL), the modulus of elasticity (MOE) and stress at proportional limit increase gradually with height and age. Modulus of rupture (MOR), however, decreases with increase of height at all ages. The correlation ($R= -0.85$ at $p < 0.01$) presented in Table 10 supports this finding. This is probably explainable in the sense that the ability of a bamboo pole with thinner culm wall on the top portion to withstand the maximum bending load is much less than that of the thicker culm wall of the basal portion ($R = 0.91$ at $p < 0.01$). Table 10 also reveals that MOE is not significantly affected by age ($R = 0.37$ at $p < 0.05$). This is seen to be an advantage in the use of *B. blumeana* in a product whereby its MOE does not warrant preselection of old or young materials.

Density of bamboo, which is closely related to the relative proportions of vascular bundle and ground tissue, plays an important role in the development of mechanical properties of bamboo (Janssen 1981, Espiloy 1987, Widjaja & Risyad 1987) and this explains the increase in strength as the height increases.

Table 8. Average mechanical properties of *B. blumeana* in green condition

Age (y)								
1			2			3		
B	M	T	B	M	T	B	M	T
Shear (MPa)								
3.99	4.56	4.63	4.35	4.59	4.69	4.65	4.86	4.96
Compression parallel to grain (*MPa*)								
19.58	20.85	22.21	22.37	26.66	27.77	25.33	27.80	28.85
Stress at proportional limit (*MPa*)								
21.21	23.65	23.06	23.36	23.91	39.53	23.83	24.05	42.32
Modulus of elasticity (× 1000 *MPa*)								
2.83	2.93	4.39	3.01	3.22	4.50	3.44	3.52	5.82
Modulus of rupture (×10 *MPa*)								
10.23	7.41	4.68	13.19	9.13	6.26	16.00	11.19	7.43

Note: B = basal, M = middle, T = top.

Table 9. Summary of analysis of variance on mechanical properties of *B. blumeana*

		Mean squares and statistical significance				
		Mechanical properties				
				Static bending		
Source of variation	Df	Shear	CPL	SPL	MOE	MOR
Age	2	0.29**	66.82**	95.99**	1.28E6**	2.36E3**
Height	2	0.29**	23.36**	272.54**	6.11E6**	7.68E3**
Age x Height	4	0.26*	1.44**	62.32**	1.84E6ns	1.52E2**

Note: CPL = Compression parallel to grain; SPL = Stress at proportional limit; MOE = Modulus of elasticity; MOR = Modulus of rupture; ns = not significant at $p < 0.05$; * = significant at $p < 0.05$; ** = highly significant at $p < 0.01$.

Table 10. Correlation coefficients of culm characteristics, anatomical structures and physical properties on mechanical properties of *B. blumeana*

Properties	S	CPL	SPL	MOE	MOR
Age	0.65**	0.82**	0.67**	0.37ns	0.47*
Height	0.63**	0.49*	0.41ns	0.77**	- 0.85**
Internode length	0.48ns	0.47ns	0.03ns	- 0.15ns	0.34ns
Culm:					
a. Diameter	- 0.12ns	- 0.19ns	- 0.48ns	- 0.41ns	0.69*
b. Wall thickness	- 0.30ns	- 0.20ns	- 0.38ns	- 0.42ns	0.91**
Moisture content	- 0.48*	- 0.51*	- 0.60*	- 0.62**	0.28ns
Density	0.90**	0.81**	0.51*	0.61**	0.16ns
Vascular bundle:					
a. Distribution	0.12ns	0.24ns	0.25ns	0.13ns	- 0.23ns
b. Radial/tangential ratio	- 0.35ns	- 0.29ns	- 0.18ns	-0.12ns	0.42ns
Fibre dimensions:					
a. Length	- 0.02ns	- 0.13ns	- 0.18ns	- 0.19ns	0.25ns
b. Diameter	0.32ns	0.31ns	0.39ns	0.31ns	- 0.20ns
c. Wall thickness	0.53*	0.46ns	0.45ns	0.63**	- 0.22ns
d. Lumen diameter	- 0.02ns	0.11ns	- 0.17ns	- 0.02ns	0.24ns

Note: ns = not significant at $p < 0.05$; *= significant at $p < 0.05$;
** = highly significant at $p<0.01$; S = Shear; CPL= Compression parallel to grain;
SPL = Stress at proportional limit; MOE= Modulus of elasticity;
MOR = Modulus of rupture.

Further statistical analysis was conducted to study the effects of physical and anatomical characteristics on the mechanical properties and the results are summarized in Table 10. The analysis indicates that except for the MOR (which depends on the thickness of culm wall), the other properties, namely S, CPL, SPL and MOE are correlated or highly correlated with density and moisture content. On the average, the correlation is observed to be negative with moisture content but positive with density. This implies that the increase in density (lower moisture content) reflects the higher amount of wood substance which thus influences the strength of the material (Limaye 1952, Sekhar *et al.* 1962, Panshin & De Zeeuw 1970, Killmann & Lim 1985). Furthermore, with decreasing moisture content, the cellulosic tissues become more compact with the absence of water molecules among the microfibrillar net (Janssen 1981).

The analysis further indicates that vascular bundle distribution is positively correlated with all the strength properties except with MOR. This implies that the increase in the amount of the vascular bundle might be accompanied by increment in the greater number of sclerenchyma and conducting cells, and density and thus increases the strength properties (Sulthoni 1989). Vascular bundle size (radial/tangential ratio) and fibre length are positively correlated with compression strength (R= 0.02 and 0.15 at $p < 0.05$), stress at proportional limit (R= 0.27 at $p < 0.05$, and 0.52 at $p < 0.01$, respectively) and MOE (R= 0.54 at $p < 0.01$, and 0.37 at $p < 0.05$, respectively). This indicates that the decrease in tangential size of the vascular bundle (mature stage or higher radial/tangential ratio) might be accompanied by the increment of strength properties, while the bamboo with longer fibres might be able to stand higher load before it is permanently deformed and fails (Espiloy 1987, Siopongco & Munandar 1987, Widjaja & Risyad 1987). Fibre length is observed to correlate negatively with shear strength ($R=-0.40$ at $p<0.01$). Suzuki (1948) and Espiloy (1987) suggested that this shear failure is likely to occur when the fibres are longer. Janssen (1981) and Sulthoni (1989) further added that the shear stress was determined by the thickness of cell wall or density rather than the percentage of the parenchyma fibres.

The cell wall thickness was found to correlate positively with compression strength ($R = 0.34$ at $p < 0.05$), stress at proportional limit ($R = 0.35$ at $p< 0.01$) and MOE ($R = 0.29$ at $p < 0.05$), but negatively correlated with MOR ($R= - 0.33$ at $p<0.05$). As stated by Liese (1987), the similar pattern of fibre length and cell wall thickness relationship with mechanical properties is due to the strong correlation within each fibre dimension (except for the lumen diameter).

By comparing the mechanical properties of bamboo with those of Malaysian timbers in the grouping as proposed by Engku Abdul Rahman (1975), S, CPL and SPL in green condition qualify bamboo to be placed under strength group A, that is, common to basic grade. Based on MOE and MOR, however, bamboo may be placed under groups C and D of the standard corresponding to basic grade.

Janssen (1981) demonstrated that bamboo is as strong as wood in tension, bending and compression strengths but much weaker in shear. This inferior shear property may discourage the selection of bamboo for a particular use, especially in locations where strength in jointing is crucial. The tension,bending and compression strengths, however, are useful in basketry and handicraft making in which split bamboo (commonly of younger age) is used.

Since bamboo is hollow, of small size, and usually not straight, it has limitation in uses such as columns, beams, trusses and pilings. Nevertheless, bamboo has proven to have better properties in certain uses such as flooring in comparison to kempas (*Koompasia malaccensis*) of the timber strength group A (Abd. Latif *et al.* 1990b).

Conclusion

All the anatomical structures studied vary insignificantly with age and height of the culm. These features, however, tend to increase with age (except for fibre length and lumen diameter) and height (except for radial/tangential ratio of vascular bundles, fibre length and lumen diameter).

The physical properties, on the other hand, correlate negatively with age and height (except for density). With an exception of moisture content, the density and shrinkages are observed to be governed significantly by the size of vascular bundles indicating that the older *B. blumeana* is more dimensionally stable than the younger.

The effects of age and height on mechanical properties are significant. With an exception of MOR, all the mechanical properties increase with age and culm height. The strength also increases with increase of density, amount of vascular bundles and fibre wall thickness.

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