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Wood physical, Anatomical and Mechanical properties of Big Leaf Mahogany (*Swietenia macrophylla* Roxb) a potential exotic for South India

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Abstract

Big leaf mahogany (*Swietenia macrophylla Roxb.*) *belonging to family Meliaceae is a most valuable timber tree species of the world. Due to the dwindling timber resource base, large scale cultivation of this species has to be enhanced through introduction to other suitable ecoclimatic conditions of the world. The wood quality of S. macrophylla introduced at Olavakkode research range at Dhoni, Palakkad in Kerala, south India were evaluated. Five trees were randomly selected from the research plot of the Kerala Forest Department and standard tests of wood physical, mechanical and anatomical properties were conducted on green, air-dry and oven-dry specimens. Results of the study indicated that the Swietenia macrophylla logs had a volume of 0.17* m^3 *and bark thickness was 2.9± 2.1 mm. Heartwood percentage was 89±3 and the logs had sawn wood recovery of 54%. Most of the wood physical and anatomical properties varied along the radial directions from pith to periphery. Physico-mechanical properties were correlated with anatomical properties. Most of the wood quality parameters were comparable to teak. Hence, the species has tremendous potential for afforestation in the state. As wood physical, anatomical and mechanical properties of a timber species determine quality; its evaluation is a prerequisite for the establishment of commercial plantations of this species having high potential for various end uses.*

Keywords: *Swietenia macrophylla,* Big leaf mahagony, wood quality, wood anatomy.

Introduction

Big leaf mahogany (*Swietenia macrophylla* Roxb.) is one of the most commercially important timber tree species in neo-tropical forests belonging to the family *Meliaceae*. It is naturally distributed from southern Mexico to the southern Amazon basin of Bolivia, Brazil and Peru along an arc[1]. Efforts to grow monospecific plantations of this species were all in vain for decades due to attack of the shoot boring insect, *Hypsipyla grandella*, hence, even in the native range, we have to rely upon natural forests[2]. Continuing harvests have led to the progressive expansion into previously unlogged forests as diameter limits dropped with changing markets and new sources from Brazil, Bolivia and Peru were utilized[3-4]. On a global level, the source of mahogany timber is Peru and the major importer being the United States. Across much of its home range, deforestation as well as timber harvesting has severely decreased the resource base of mahogany, leading to concern about both survival of the species and sustainability of its commercial trade[4-5]. It has been introduced to several Asian countries due to restrictions in logging of this tree in its native habitats and mahogany timber grown in these plantations is the major source of international trade in genuine mahogany today. It is imperative to record the wood quality parameters prior to large scale expansion of plantations outside its natural range. Wood quality assessment involves the consideration of a large number of anatomical, physical and mechanical properties of wood. Certain wood properties are reported to be good indicators of timber properties and uses. The literature on wood properties of hardwoods grown as exotics has been very limited except for eucalypts, in comparison to that devoted to the conifers. The research wing of the Kerala forest department has initiated research trials of this species from 1924 onwards at Olavakkode research range at Dhoni to evaluate the growth performance of this species. The present investigation focuses on evaluation of physical, mechanical and anatomical properties of *S. macrophylla* and interrelationship of these properties. The study also aims at bringing to light the variation if any, of the timber quality of the above species when they are grown outside their natural home range. The study is also expected to provide information helpful in fixing the optimum age of exploitation of different plantation grown species as well as to ascertain the most appropriate end-use with the presently available raw material as wood characteristics of plantation grown trees cannot be assumed to be the same as expected from fully mature trees of identical species grown in natural forest. Combining growth measurements with information on wood quality parameters will help in taking judicious management decisions for raising and management of these species in the state.

Material and Methods

The sample plot of mahogany was located at Dhoni in the Olavakkode research range and it lies between 10^0 86'N and 76^0 62'. Generally, the December and January are the coldest months here and the minimum temperature of about 22-23^{0}C and April and May are the hottest months with a maximum temperature of 35-39^{0}C. The rainfall ranges between 3000 mm to 5000 mm. The soil type is red soil, moderately deep to deep with distinct ABC horizons, containing varying amount of ferruginous gravels. The girth at breast height (GBH) and height of the trees selected for wood quality estimation were 1.23 and 20 m (Tree no. 1), 1.13 and 18 m (Tree no. 2), 1.23 and 20 m (Tree no. 3), 1.11 and 15 m (Tree no. 4) and 1.56 and 13 m (Tree no. 5) respectively. The selected trees were felled and cross cut to logs using a chain saw. The basal portion of the trunks was converted to sections of 1.5 m length. Later, 5 cm thick transverse discs were cut from the base of these sections. These discs were used for measuring bark thickness and to find out heartwood - sapwood percentage. The logs after cross cutting were converted into scantlings of cross section 6 cm x 6 cm in a saw mill and transported to the Rubber Research Institute of India, Kottayam for assessing mechanical properties. For this purpose, the wood sections were sawn to scantlings having cross sectional area of 2 cm x 2 cm. These were finally converted to small clear specimens as per IS 2455: 1990 (ISI 1990) for analysing mechanical properties.

Physical properties: The wood physical properties studied were moisture content (MC), specific gravity (SPG) and shrinkage (radial and tangential). There were three samples from pith, middle and periphery regions for each tree (N = 45). Heartwood % was calculated by placing the entire wood cross section on a tracing sheet and working out the percentage of the inner zone using a graph. Bark thickness was determined using a digital vernier caliper in four different radii and the average was taken.

Mechanical properties: The mechanical properties studied included compression parallel and perpendicular to grain and static bending tests using a Universal Testing Machine (UTM-Shimadzu 100KgN). Compression strength parallel to grain was assessed on by loading samples of size 2 cm x 2 cm x 8 cm with its longitudinal axis along the direction of movement of head. Parameters like compressive stress at limit of proportionality ($CS_{at\ LP}$), compressive stress at maximum load ($CS_{at\ ML}$) and modulus of elasticity (MOE) were recorded. In order to determine compression strength perpendicular to grain, samples of size 2 cm x 2 cm x 10 cm were loaded such that the tangential plane faces the stress. Parameters like $CS_{at\ LP}$, crushing strength at compression of 2.5 mm ($CS_{at\ 2.5mm}$), MOE were determined. The Static bending test was conducted by loading samples of size 2 cm x 2 cm x 30 cm in such a way that the stress is on the tangential plane. Parameters like modulus of elasticity (MOE), modulus of rupture (MOR), maximum load (ML), fibre stress at limit of proportionality ($FS_{at\ LP}$), horizontal shear at limit of proportionality ($HS_{at\ LP}$) and horizontal shear at maximum load ($HS_{at\ ML}$) were also determined. There were five replications for each mechanical property studied.

Anatomical properties: The anatomical properties were studied after sectioning using microtomy and preparation of slides. Wood samples of size 1 cm x 1cm x 1cm were boiled in water for 20 minutes and thin microscopic sections of size 15-20 µm were taken using a sledge microtome (*Leica SM 2000 R)*. From each tree, five samples were taken from pith, middle and periphery regions (N = 75). Permanent sections were prepared by double staining and mounted on a glass slide using DPX mountant. Images of the sections were captured to measure various wood anatomical parameters using an image analysis system (Labomed Digi 2) running the software (Labomed Digi Pro 2). Vessel diameter was determined on the transverse sections (TS) using the image analysis software. Vessel frequency was calculated by counting the number of vessels in a randomly selected area per field and using the formula given below.

$$\text{Vessel frequency} = \frac{\text{Number of vessels x } 10^6}{\text{Area in sq.microns}}$$

The height and width of the rays were measured on the tangential longitudinal sections (TLS) for each tissue type. Tissue proportions including the percentage of rays, vessels, parenchyma and fibres were measured on the transverse sections (TS).

Statistical analysis: One way analysis of variance was conducted to find the variation in physical and anatomical properties along the radial direction. Pearson's correlation coefficient and linear regression equations among wood properties were developed using SPSS 18 for Windows.

Results and Discussion

In general, *Swietenia macrophylla* logs had a volume of 0.17 m^3 and bark thickness was 2.9± 2.1 mm. Heartwood percentage was 89 ±3 and the logs had sawn wood recovery of 54 %. With regard to moisture content of the wood, $MC_{(g\text{-}od)}$ varied significantly (p=0.01) along the radial direction (table1) and it showed an increasing trend towards periphery. Analysis of variance revealed significant variation $SPG_{(g)}$ and $SPG_{(od)}$ due to radial positions with an increasing pattern from pith to periphery (p=0.01). The average oven dry specific gravity of the wood was 0.53. Variation in radial and tangential shrinkage along the radial direction was not statistically significant. The tangential shrinkage recorded for *S. macrophylla* at all conditions was higher compared to radial shrinkage. The ratio of tangential to radial shrinkage was 1.3 with the exception of green to air dry conditions.

The data on mechanical properties of *S. macrophylla* are given in table 2. Of the two conditions mechanical properties were higher at air-dry conditions than green wood except in compression perpendicular to grain.

The anatomical properties of *Swietenia macrophylla* also significantly varied along the radial directions (table 3). The vessel area (p=0.01) and diameter (p=0.05) varied significantly along the radial directions from pith to periphery and increased from inner to outer tissue. The dimensions ray elements also varied significantly from pith to periphery (p=0.05). The ray height and width increased from pith whereas, ray frequency declined from pith to periphery. Among the fibre dimensions, the length and wall thickness varied significantly due to position (p=0.01). The percentage contribution of vessel, ray, fibre and parenchyma also didn't show significant variation along the radial directions.

Variation along radial direction is the best known and most studied within tree variability in wood, which is generally reflected as radial pattern of change in wood characteristics of juvenile and mature wood. The radial change in wood properties varies in magnitude and type in different species[6-8]. Our study also confirmed that the magnitude of physical and anatomical properties of wood varied from pith to periphery. In the present study, specific gravity values in all condition increased from pith to periphery and the oven dry specific gravity (0.53) was lower compared to teak and natural grown *P. dalbergioides*[9-10] (table 4). On an average, the specific gravity towards the periphery was 1.4 to 1.5 times higher compared to that at the pith region. Among the physical properties, specific gravity is a key wood property as it had a major influence on the yield and quality of both fibrous and solid wood products [11-12]. Specific gravity differs between species, sites, trees and within the tree. Generally, it tends to increase from the centre of the tree to the bark. The lower specific gravity of *S. macrophylla* might be due to its lower average values for vessel diameter and vessel area as well as high vessel frequency. Similarly, in Eucalyptus genus the most common trend found for basic density was an increase radially from pith to bark and axially from the base to apex[13-15]. This is in conformity with the pattern of radial variation in specific gravity found in *S. macrophylla*. Swelling and shrinkage could also be considered as 'intelligent' characteristics of wood because wood can change dimensions by itself in response to the atmosphere[16]. In the present investigation, tangential shrinkage was higher than radial shrinkage in three conditions. Along the radial positions, the middle region recorded a higher specific gravity was inconsistent with *Acacia mangium* which had a decreasing tangential shrinkage towards periphery[17].

Similar to physical properties, anatomical characters of *S. macrophylla* also showed radial pattern of variation from pith to periphery. Carlquist[18] stated that among anatomical characters, vessels are of great significance and are important cellular constituents designed to perform the function of water and mineral nutrients conduction of living trees. Radial variation of anatomical properties showed different patterns with species. Bhat et al.[19] reported that the fibre length in most trees increases from trunk piths bark side to the maximum level and after reaching the maximum frequency stay in balance and then decreases gradually. In a study on radial variation of anatomical characteristics in plantation grown Nedun tree revealed that values for the vessel diameter, from wood at the bark side were higher than those at the pith[8]. They also reported that the vessel frequency gradually decreased from pith to bark. In addition, vessel element length was almost constant from pith to bark tissue. However, with a few exceptions, in our study most of the anatomical features increased from pith towards bark side. Similar trend of increasing anatomical properties from inner wood to outer wood of *Tectona grandis* were observed[20]. The above comparison also reveals that 29 year old plantation grown *Swietenia macrophylla* was having lower specific gravity (oven dry) and Modulus of rupture (Static bending) than the trees investigated in our study which are however of far higher age viz., 88 years. Interestingly however, shrinkage values were higher for our samples[12].

Correlation analysis revealed the interdependence of anatomical properties in *S. macrophylla* (table 5).

Table-1
Variation in physical properties of *Swietenia macrophylla* along the radial direction

Radial positions	**Pith**	**Middle**	**Periphery**	**Mean**
Moisture content green to oven dry (%)	25.10^{c}(8.78)	30.88^{b} (11.47)	35.64^{a}(15.79)	30.54
Moisture content from air dry to oven dry (%)	55.02^{b} (9.00)	57.56^{b} (12.12)	74.51^{a}(13.80)	62.36
Specific gravity				
$SPG_{(g)}$	1.00^{b} (0.14)	1.04 ^{a}(0.25)	1.4^{a} (0.19)	1.03
$SPG_{(a.d)}$	0.62^{b} (0.05)	0.69^{a} (0.11)	0.69^{a} (0.09)	0.67
$SPG_{(o.d.)}$	0.51^{b} (0.02)	0.55^{a} (0.07)	0.52^{b} (0.04)	0.53
Radial shrinkage (%)				
$RS_{(g-a.d.)}$	0.42^{a} (0.16)	0.60^{a}(0.22)	0.46^{a} (0.11)	0.49
$RS_{(a.d-o.d.)}$	2.93^{a} (0.43)	3.31 ^{a} (0.21)	2.95 ^{a} (0.32)	3.06
$RS_{(g-o.d.)}$	3.36 ^{a} (0.52)	3.95^{a} (0.53)	3.42^{a} (0.53)	3.58
Tangential shrinkage (%)				
$TS_{(g-a.d.)}$	4.54 ^{a} (0.30)	4.44 ^{a} (0.23)	4.66 ^{a} (0.43)	4.55
$TS_{(a.d-o.d.)}$	4.15^{a} (0.76)	4.39^{a} (0.51)	3.87^{a} (0.54)	4.14
$TS_{(g-o.d.)}$	4.55^{a} (0.94)	4.85^{a} (0.57)	4.48^{a} (0.33)	4.63

Note: Values with same superscript within a row are not significantly different, values given in paranthesis are the standard deviations, g- Green a.d- Air dry o.d. - Oven dry.

Table-2
Mechanical properties of *Swietenia macrophylla* along the radial direction

	Mechanical properties	Green	Air- dry
1	**Compressive strength perpendicular to grain** (MPa)		
	a) $CS_{at\ LP}$	84.1	93.0
	b) $CS_{at\ 2.5\ mm}$	128.7	141.0
	c) MOE	6520.4	7896.0
2	**Compressive strength parallel to grain** (MPa)		
	a) $CS_{at\ LP}$	283.7	313.7
	b) $CS_{at\ ML}$	379.5	411.6
	c) MOE	28608.1	35826.4
3	**Static bending test** (MPa)		
	a) MOR	654.6	751.2
	b) ML	127.0	142.0
	c) $HS_{at\ ML}$	23.5	26.8
	d) $HS_{at\ LP}$	15.4	18.7
	e) $FS_{at\ LP}$	429.3	525.5
	f) MOE	65429.9	71236.9

Table- 3
Anatomical properties of *Swietenia macrophylla along* the radial direction

Radial positions	Pith	Middle	Periphery	Mean
Vessel area ***	22500^{c} (1864)	31487^{b} (8127)	45242^{a} (9591)	33076
Vessel diameter*	139.4^{b} (5.3)	155.3^{b} (25.9)	207.9^{a} (12.3)	167.6
Vessel frequency**	7^{a}(0.97)	6^{a} (0.66)	7_{a}(28.926)	6
Vessel length *	102.23^{a} (25.12)	123.21^{a} (30.08)	106.81^{a} (18.57)	102.23
Ray height*	467.6^{b} (46.9)	539.9^{a}(71.9)	539.4^{a} (66.3)	515.6
Ray width*	45.0^{b} (14.4)	71.7^{a} (9.5)	78.2^{a} (14.2)	64.9
Ray frequency **	15.7^{a} (2.4)	11.7^{b} (1.2)	11.2^{b} (1.9)	12.9
Fibre length*	1298.9^{b}(118.3)	1297.4^{b} (80.3)	1337.0^{a} (196.2)	1311.1
Fibre wall thickness*	1.91^{b} (0.74)	2.12^{a} (0.94)	1.71^{c}(0.25)	1.9
Fibre lumen diameter*	13.1^{a} (2.0)	13.5^{a} (3.3)	11.8^{a} (1.9)	12.8
Fibre diameter*	21.4^{a} (2.8)	20.5^{a} (2.9)	19.3^{a} (2.7)	20.4
Ray per cent	26.64^{a} (6.63)	33.16^{a} (5.17)	31.81a (9.36)	30.5
Vessel per cent	7.1^{a} (1.6)	6.1^{a} (0.8)	5.5^{a} (1.3)	6.24
Parenchyma per cent	26.6^{a} (8.2)	22.5^{a} (5.9)	24.6^{a} (7.6)	24.54
Fibre per cent	54.01^{a} (10.96)	49.56^{a} (5.39)	51.79^{a} (7.11)	51.8

Note: The values with same superscript within a row are homogenous; Values given in paranthesis are the standard deviations, *µm, ** rays/ mm^2, ***$µm^2$

The correlation between anatomical properties and physic-mechanical properties also were worked out (table 6). In *S. macrophylla*, none of the anatomical characters were correlated with specific gravity. However, correlation analysis revealed that the oven dry specific gravity was positively correlated with $CS_{at\ ML\ and}$ MOE in compression parallel to grain at dry condition. With respect to static bending test, oven dry specific gravity was found to be positively correlated with $MOR_{(d)}$. Vessel diameter was positively correlated with the MOE (g) in compression parallel to grain, whereas it was found to be negatively correlated with ML at green condition in static bending test. The ray frequency was negatively correlated with ML (d) and ray percentage with HS at ML (g) in static bending test. Fibre percent showed negative correlation with ML (d) in the static bending test. A close relation among many wood physical, mechanical and anatomical properties has been reported[21-26].

Regression equations connecting mechanical properties and physical and anatomical properties in *Swietenia macrophylla* are given in table 7. The linear regression equations recorded a higher r^2 value and they can be used for the reliable prediction.

Table-4
Comparison of wood properties of *Swietenia macrophylla* with teak, natural grown *Pterocarpus dalbergioides* , and plantation grown *S. macrophylla*

Wood properties	*Swietenia macrophylla* (present study)	Plantation grown *Swietenia macrophylla*[12]	*Tectona grandis*[9]	Natural grown *P. dalbergioides*[10]
Specific gravity (oven dry)	0.526	0.435	0.604	0.644
Moisture content (oven dry, %)	30.54	-	76.6	8.3
Radial shrinkage (%)	3.58	2.2	2.30	3.3
Tangential shrinkage (%) (green to oven dry)	4.63	1.4	4.80	4.4
Static bending				
i. Fibre stress at limit of proportionality (kg/cm^2)	535.91	-	651.00	659.44
ii. Modulus of rupture (kg/cm^2)	766.01	611.82	959.00	1069.37
iii. Modulus of elasticity(Kg/cm^2)	72641.44	94833.60	119600	125220.39
Compression parallel to grain				
i. compressive stress at limit of proportionality (kg/cm^2)	319.94	-	376.00	-
ii. Maximum crushing stress(kg/cm^2)	419.65	-	532.00	644.05
iii. Modulus of elasticity (kg/cm^2)	36532.81	-	137400	-
Compression perpendicular to grain				
i. Compressive stress at limit of proportionality (kg/cm^2)	94.77	-	101.00	172.23

Table-5
Correlation analysis among wood anatomical properties in *Swietenia macrophylla*

	VA	VD	VF	RH	RW	RF	FWT	FLD	FD	RP	VP	PP	FP
VA	1.00												
VD	0.91**	1.00											
VF	-0.11	0.04	1.00										
RH	0.28	0.25	-0.28	1.00									
RW	0.65**	0.58*	-0.23	0.70**	1.00								
RF	-0.56*	-0.49	0.75**	-0.64*	-0.57*	1.00							
FWT	-0.12	-0.02	-0.17	0.15	-0.09	-0.15	1.00						
FLD	-0.29	-0.44	0.05	0.38	0.06	0.08	-0.13	1.00					
FD	-0.25	-0.34	0.06	0.29	-0.07	0.07	0.17	0.84**	1.00				
RP	0.38	0.29	-0.58*	0.10	0.27	-0.56*	-0.01	-0.44	-0.46	1.00			
VP	-0.61*	-0.43	0.17	0.04	-0.31	0.32	0.58*	0.24	0.51	-0.42	1.00		
PP	-0.14	-0.01	0.31	0.19	0.02	0.16	0.46	0.14	0.41	-0.63*	0.45	1.00	
FP	-0.16	-0.18	0.52*	-0.20	-0.21	0.52*	-0.45	0.41	0.21	-0.82**	-0.05	0.14	1.00

Note: VA- vssel area, VD- vessel diameter, VF- vessel frequency RH- ray height RW- ray width RF- ray frequency FWT- fibre wall thickness FLD-Fibre lumen diameter FD: Fibre diameter RP- ray %, VP vessel % PP-parenchyma %, FP- Fibre %, *Significant at 5 % level, ** significant at 1 % level

Table- 6
Correlation analysis of different wood properties in *Swietenia macrophylla*

	Compression parallel to grain			Static bending test			
	ML(d)	**MOE(g)**	**MOE(d)**	**MOR(d)**	**ML(g)**	**ML(d)**	**HS at ML(g)**
VD	0.46	.927*	-0.137	-0.137	-.914*	-0.011	0.162
RF	-0.50	-0.031	-0.573	-0.571	-0.088	-.896*	0.458
RP	0.06	-0.277	0.03	0.03	0.213	0.049	-.954*
FP	-0.74	-0.453	-0.554	-0.552	0.319	-.939*	0.415
SG(O)	0.93*	0.329	.914*	.914*	-0.095	0.698	-0.147

* Significant at 5 % level

Table- 7
Regression equations showing the relationship between mechanical properties and anatomical properties in *Swietenia macrophylla*

Dependent variable	Independent variable (X)	Name of fitted equation	Fitted equation	R^2
CMPL_CS at ML(D)	Specific gravity	Linear	Y = -672.005 + 2084.857 X	0.86
STBD_HS atML(D)	Vessel diameter	Linear	Y = -2357.052 + 16.570 X	0.86
STBD_HS at LP(G)	Specific gravity	Linear	Y = -13.169 + 55.172 X	0.84
STBD_FS at LP(G)	Specific gravity	Linear	Y = -379.750 + 1561.336 X	0.84
STBD_FS at LP(D)	Vessel diameter	Linear	Y = 3351.520 – 19.144 X	0.84
MOE(g)	Ray frequency	Linear	Y = 97608.613 – 3776.214 X	0.80
MOE(g)	Ray frequency	Linear	Y = 103689.910 – 1055.14 X	0.88
MOE(D)	Ray %	Linear	Y = 72821.723 – 667.261 X	0.91

Conclusion

Overall it can be concluded big leaf mahogany is a good timber with and superior mechanical properties suitable for solid wood uses. Hence, this species has tremendous potential for popularisation in the state. The wood physical and anatomical properties showed radial variation and interrelationship was obvious among anatomical and physico-mechanical properties. Due to the decline in availability of teak and other timber species, introduction of indigenous and foreign exotics with superior timber quality needs to be undertaken. The Mahogany trees retained in the trial at Dhoni (Olavakkode) are over mature (88 years old at the time of felling) which even though has superior timber properties, particularly the dark reddish colouration and superior figure compared to those found in younger trees, harvesting mahogany at early ages (30 – 35 years), which is currently the practice in the state may not be detrimental to the timber quality particularly for furniture, sliced veneers, turnery, carving, mouldings and interior joinery. Extending rotation to higher ages can however result in good colour and figure which may help procure exponentially high prices for the old growth timber.

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