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EVALUATION OF DYNAMIC ELASTIC PROPERTIES OF *BAMBUSA BAMBOS* AT THREE DIFFERENT STAGES OF ITS LIFE CYCLE BY ELASTOSONIC TECHNIQUE

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Commercially important *Bambusa bambos* culms from three stages of its life cycle viz., before, during and after flowering were selected for determining strength properties using non-destructive and destructive techniques. The aim was to evaluate the dynamic modulus of elasticity (MOE_d) of bamboo strips subjected to impulse excitation using elastosonic technique and correlate with the corresponding static flexural parameters (modulus of elasticity-MOE_s and modulus of rupture-MOR) calculated from three-point static bending tests. Detailed statistical analysis was carried out to find relationships among flexural parameters with MOE_d and specific gravity. Linear regression was observed between dynamic MOE_d and static MOE_s with coefficient of determination (R^2) in the range of 0.64 to 0.88. The flexural strength (MOR) of bamboo from all three stages was also found to be linearly correlated with MOE_d with high R^2 values. Similarly, strength parameters (Y) from present study were found to follow power regression equations with specific gravity (X) of the form: $Y=mX^n$. Results confirmed that strength-specific gravity relations and resonance-based elastosonic technique can be successfully employed for rapid and reliable evaluation of stiffness and strength parameters of bamboo in strip forms which are mostly used in producing bamboo-based composite products.

Keywords: Culms, bamboo strips, density, modulus of elasticity, modulus of rupture, strength properties

INTRODUCTION

Bamboos are woody monocots belonging to the Poaceae family with versatility and fast growth rate. In India, bamboos have a wide range of distribution and are found in many types of moist tropical forests as well as in certain drier regions. In India, there are more than hundred bamboo species, out of which about 15–20 have been identified as potential species having commercial importance (Salam & Pongen 2008, Baksy 2013). *Bambusa bambos,* commonly known as Indian Thorny bamboo, is one such important species showing best growth in moist deciduous forests up to an altitude of 1000–1200 m. This bamboo is generally found throughout the country and more common in Central and South India. Potential applications of *B. bambos* include raw material for pulp and paper, panel products, building and construction (thatching and roofing), handicrafts etc.

Flowering in bamboos is unique and generally unpredictable phenomenon which may appear only once in a lifetime. *Bambusa bambos* flowers gregariously at long intervals varying from 30 to 45 years and die soon after fruiting and seedling. After flowering, bamboo produces a large quantity of seeds, which also become source of food for many predators. In post-flowering regime, different bamboos show different types of mortality behavior and there may be certain anatomical, histo-chemical and physiological changes in bamboo related to gregarious flowering (Garg et al. 1998, Sharma 1994, Songkram 1996). Smart & Amrhein (1985) studied collapse/disorganisation of lumen in mature xylem cells as a function of lignifications. Garg et al. (1998) found that total carbohydrates and reducing sugar have increased during flowering and reduced significantly thereafter. It was also observed that subsequent to flowering, lignin increased significantly by about 40% in the dead bamboo. As a result, huge amount of bamboo material becomes available for usage during and after flowering phenomena.

Studies on fiber characteristics and density of *B. bambos* and *Dendrocalmus strictus* are reported by Sharma et al. (2014a). Although, some variation in density was observed, fibre characteristics remained almost identical. It was concluded that these two species can be used for manufacturing panel products either individually or mixed with each other. Kumar & Bhat (2014) reported their studies on distribution of tissue proportion and its influence on density in culms of *B. bambos* selected from outer, mid and inner portions of culm wall taken from base, mid and top portions. Age was found to be another important factor influencing density. The results showed that anatomical and physical properties varied in relation to different portions of culm wall, height levels and age of culm. It was reported that anatomical properties such as percentage of tissues proportions may influence physical properties which were found to vary up to a particular age of culm and then the change was stabilised. Sharma et al. (2014b) reported their studies of various physical and mechanical properties on two bamboo species, namely *B. bambos* and *D. strictus* to find the suitability as dunnage pallets. Based on properties, both species were found suitable for dunnage pallets. It was also envisaged that *B. bambos* may be preferred over *D. strictus* due to its higher culm diameter.

The non-destructive testing (NDT) techniques are being developed as rapid, reliable and cost effective methods to evaluate certain important mechanical and physical parameters of lignocellulosic materials such as strength, stiffness, moisture content, amount of deterioration etc (Yang et al. 2013). These properties are taken into consideration while deciding the quality, grade as well as appropriate end-use applications of various woody materials (Del Menezzi et al. 2014, Pellerin & Ross 2002, Ross 2015). A wide range of NDT and evaluation techniques and tools as applied to wood and wood products are summarised by Ross (2015). Applications of these NDT techniques depend on the kind of information required such as quality of wood structures, stiffness and strength for grading purpose (Bucur 1995, Teles et al. 2010). The vibrational properties of wood are evaluated to determine longitudinal Young's modulus through non-destructive testing. Similarly, the stress wave method was recently used to measure the dynamic modulus of elasticity of heat treated eucalypt wood (Garcia et al. 2012). Non-destructive elastosonic technique is one of the quick and reliable assessment tools to evaluate efficiently the dynamic elastic parameters of bamboo. Although, a few studies have been carried out for assessing physical and mechanical properties of a few bamboo species (Rao et al. 2009, Shukla et al. 1988), not much research work is reported on the evaluation of elastic parameters of *B. bamboo* during different stages of their life cycle using NDT technique. In view of above, it was felt necessary to study various quality parameters of *B. bambos* obtained from before, during and after flowering stages.

MATERIALS AND METHODS

Five culms each of *B. bambos* from three different stage namely, before flowering (BF), during flowering (DF) and after flowering (AF) were collected from three clumps each from Somwarpet forest range, Kushalnagar, Karnataka, India. Morphological properties like inter-nodal length, girth, culm diameter, culm wall thickness and culm lumen diameter were measured with metric scale and digital calipers. Specimens from selected internodes of bamboo culms were used to measure certain physical properties such as moisture content, density and specific gravity following the standard procedures (Anonymous 1976) as described below.

Moisture content

Specimens of the size 2.0 × 2.0 cm^2 with full wall thickness from the sound portion of split bamboo were selected for determining the moisture content (MC). The specimens were weighed using a digital balance with an accuracy of 0.001 g and kept in a hot air-oven to dry at 103 ± 2 °C for more than 24 hours. Subsequently, the dried specimens were cooled in a desiccator and oven-dry weight was measured. Moisture content of each specimen was determined from the following equation:

$$MC\,(\%) = \left(\frac{W_1 - W_0}{W_0}\right) \times 100 \qquad (1)$$

where W_1 = initial weight of specimen (g), W_0 = oven-dry weight of specimen (g).

Density and specific gravity

Specimens of the size 2.0×2.0 cm^2 from the sound portion of split bamboo were taken for determining the density and specific gravity. The specimens were weighed and dimensions were measured and volume of each specimen was calculated. The specimens were weighed (W_1) and kept in a hot-air oven to dry at 103 ± 2 °C for more than 24 hours. Subsequently, oven-dry weight (W_0) of specimens was measured. Density and specific gravity (SG) was determined from the following equation:

$$\text{Density} = (W_1/V) \tag{2a}$$

$$\text{SG} = (W_0/V) \tag{2b}$$

where W_1 = initial weight of specimen (g), W_0 = oven-dry weight of specimen (g), V = volume of specimen (cm^3).

Flexural properties (static bending test)

The width and depth of split bamboo specimens were taken respectively as twice and equal to the thickness. The length of the specimen was 14 times the depth plus 5 cm. The specimens were free from any defect like crack, crookedness, etc. The flexural specimen were tested from inter-node only and treated as rectangular in cross-section. The specimen was kept horizontally on two parallel rollers of about 2 cm diameter spaced at a distance centre to centre of 14 times the depth of the specimen. The skin surface of the specimen was on bottom surface. The load was applied through a roller at the centre of specimen continuously at uniform speed of 0.00025 l^2 h^{-1} per minute till failure (Anonymous 1976). The flexural parameters (MOR and MOE_s) were determined using following equations:

$$\text{MOR} = (3 \times P' \times l)/(2 \times b \times h^2) \tag{3a}$$

$$MOE_s = (P \times l^3)/(4 \times b \times h^3 D) \tag{3b}$$

where P = load at proportional limit (N), D = deflection at proportional limit (mm), P' = maximum load (N), b = width (mm), h = depth (mm) and l = span (mm).

Dynamic elastic properties (elastosonic technique)

An elastosonic test apparatus was used for accurately detecting, measuring and analysing the fundamental resonant frequency of a vibrating free-free rectangular bamboo beam. It consists of an impulser, a suitable pickup transducer to convert the mechanical vibration into an electrical signal, an electronic system (consisting of a signal conditioner/amplifier, a signal analyser, and a frequency readout device), and a support system. The exciting impulse which is a Teflon ball of diameter ~14 mm fixed to an end of a polymer rod is imparted by lightly striking the specimen with a suitable implement. This device has most of its mass concentrated at the point of impact and has mass sufficient to induce a measurable vibration, but not so large as to displace specimen.

Signal pickup and electronic system

Signal detection is done by means of a non-contact transducer which is an acoustic microphone to measure the vibration. Small sensor was embedded on a rectangular block made of sound insulating material, two adjustable 'O' rings of polyurethane are provided for supporting test samples. The frequency range of the transducer from 100 Hz to 50 kHz was sufficient to measure the expected frequencies of the bamboo specimens.

The electronic system consists of a signal conditioner/amplifier, signal analyser, and a frequency readout device. The system has accuracy and precision sufficient to measure the frequencies to an accuracy of 0.1%. The signal conditioner/amplifier was suitable to power the transducer and provide an appropriate amplified signal to the signal analyser. With the digital storage oscilloscope, a Fast Fourier Transform (FFT) signal analysis system is used for analysing and identifying the fundamental resonant frequency.

Computation of dynamic Young's modulus

Dynamic Young's modulus or modulus of elasticity (MOE_d) is computed from fundamental resonant frequency, dimensions and mass of a rectangular bar using equation (Anonymous 2005):

$$MOE_d = [0.9465 \times (m \times f_f^2/b)\times(L^3)/t^3)\times T_1] \quad (4)$$

where MOE_d = dynamic Young's modulus (Pa), m = mass of the bar (g), b = width of the bar (mm), L = length (mm), t = thickness of bamboo strip (mm), f_f = fundamental resonant frequency of specimen in flexure (Hz), T_1 = correction factor for fundamental flexural mode to account for finite thickness of bar and Poisson's ratio. If L/t ≥ 20, the correction factor T_1 can be simplified to the following (Anonymous 2005):

$$T_1 = [1.000 + 6.585 \times(t/L)^2] \quad (5)$$

where L = length (mm), t = thickness of the split bamboo specimen (mm).

RESULTS AND DISCUSSION

Table 1 shows the average values of certain physical and mechanical properties such as moisture content, density, specific gravity, flexural modulus of rupture (MOR), modulus of elasticity (MOE_s), dynamic modulus of elasticity (MOE_d) and maximum compressive strength parallel to grain (MCS) of split *B. bambos* tested in three different stages of its life cycle (before, during and after flowering). The standard deviations of different parameters are also listed in the same table along with the average values. It may be seen from this table that the moisture content of the bamboo from the BF and DF stages was found to be quite high in the range of 71.5–109.5% signifying the green condition. However, the bamboo specimens from the AF stage exhibited significantly lower amount of moisture content in the range of air-dry values (8.7–15.1%). After flowering, the bamboo starts drying which leads to further degradation and finally die (Panda 2011). However, the bio-chemical mechanism of bamboo flowering and dying phenomenon is not yet understood completely. The average value of density at test in the AF stage was found to be significantly lower (0.678 g/cm^3) compared to BF and DF stages (1.11 and 1.19 g/cm^3 respectively). Similarly, specific gravity in the AF stage was 17.3% and 16.3% lower compared to BF and DF stages respectively. The amount of variations in the density and standard specific gravity of *B. bambos* in three stages may be attributed partly to the moisture content as well as availability of starch, proteins and lipid in culms detected during histo-chemical studies. The starch grains were observed near epidermis, middle and inside culm wall in before and during flowering stages. Mild reaction was also observed in the culms from both these stages tested for total proteins. However, no starch grains could be observed across the wall thickness or along the height of the culm in the AF stage. A decreasing trend in the availability of total proteins and no reaction for lipid from base to top were observed.

Average values of static bending strength (flexural MOR) and stiffness (MOE_s) parameters along with standard deviations are also listed in Table 1. It may be seen that no significant difference was shown in MOR and MOE_s between BF and DF stages. Due to higher moisture contents, the MOR values in DF and BF stages were 8.5% and 7.0% lower compared to AF stage respectively. Similarly, split bamboo from AF stage showed static bending MOE_s values higher by about 8.2% and 4.0% in comparison to those obtained in DF and BF stages respectively. The

Table 1 Average physical and mechanical properties of split *Bambusa bambos* in three different stages of its life cycle

Properties	Before flowering	During flowering	After flowering
Moisture content (%)	80.97 ± 9.43	96.97 ± 12.53	11.89 ± 3.22
Density at test (g cm^3)	1.11 ± 0.18	1.19 ± 0.11	0.678 ± .075
Specific gravity (OD wt./vol. at test)	0.619 ± 0.098	0.612 ± 0.090	0.512 ± 0.045
Flexural parameters (static bending):			
Modulus of rupture MOR (MPa)	110.14 ± 22.32	111.84 ± 26.64	120.30 ± 22.51
Modulus of elasticity MOE_s (GPa)	12.13 ± 2.70	12.63 ± 3.44	13.13 ± 4.29
Dynamic modulus of elasticity MOE_d (GPa)	13.56 ± 3.36	13.84 ± 3.72	14.30 ± 5.30
Max. compressive strength parallel to grain MCS (MPa)	38.65 ± 6.31	32.65 ± 6.80	44.44 ± 10.61

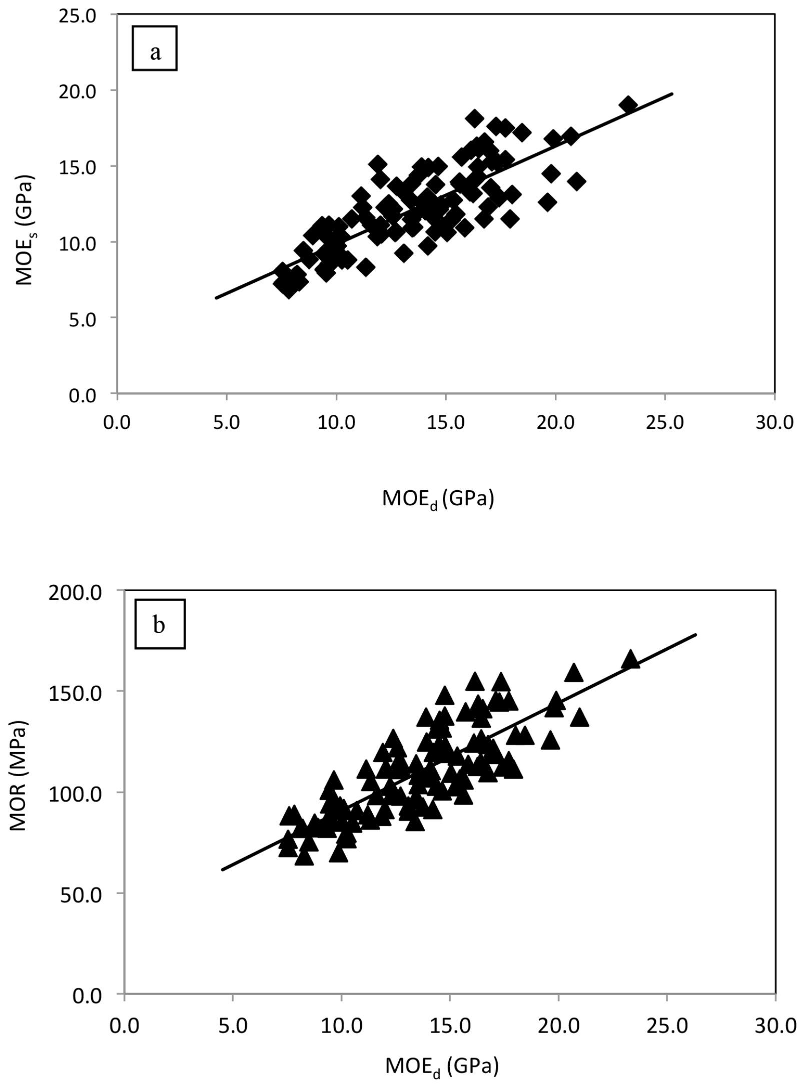

Figure 1 Relations between dynamic modulus of elasticity (MOE_d) and static modulus of elasticity (MOE_s) (a) and dynamic modulus of elasticity (MOE_d) and static modulus of rupture (MOR) (b) in before flowering (BF) stage of *Bambusa bambos*

average maximum compressive strength parallel to grain (MCS) value of split bamboo in AF stage was also found to be higher by 13.0% and 26.5% compared to values of culms in BF and DF stages respectively. Average MOE_d values determined by the elastosonic NDT technique were found to be higher by 11.8, 9.6 and 8.9% than corresponding MOE_s in BF, DF and AF stages respectively. The comparison between different physical and mechanical properties of three groups exhibited that most of the properties were not significantly different between BF and DF stages. However, certain properties of bamboo from AF stage were found to be significantly greater compared to other two stages due to large difference in moisture values.

The data between dynamic MOE_d was plotted against static MOE_s and MOR for all three stages of bamboo namely, BF, DF, AF and shown in Figures 1(a,b), 2(a,b) and 3(a,b) respectively. The linear regression equation of the form: $y = ax + b$ fitted between MOE_d and MOE_s of bamboo strips for BF, DF and AF stages with fitting parameters (a and b) are listed in Table 2. Similarly, MOE_d and MOR values were regressed and linear regression equation of the form: $y = px + q$ along with fitting parameters (p and q) are also shown in the same table for split bamboo from all the three stages. The linear models: $MOE_s = a + b \times MOE_d$ for different stages of bamboo life cycle were found to be statistically significant at high level ($p < 0.001$) and the coefficients of determination (R^2)

Table 2 Linear regression equations between dynamic modulus of elasticity (MOE_d) with static modulus of elasticity (MOE_s) and modulus of rupture (MOR), their fitting parameters and coefficients of determination for split *Bambusa bambos*

Stages of bamboo	Regression equations fitting parameters	$MOE_s = a + b \times MOE_d$		R^2 (R^2_{adj})	$MOR = p + q \times MOE_d$		R^2 (R^2_{adj})
		a	b		p	q	
Before flowering	Value ± SE	3.36 ± 0.64	0.65 ± 0.05	0.64 (0.64)	37.48 ± 5.32	5.34 ± 0.38	0.65 (0.65)
During flowering	Value ± SE	-0.42 ± 0.77	0.87 ± 0.05	0.83 (0.82)	22.05 ± 8.44	6.00 ± 0.55	0.65 (0.65)
After flowering	Value ± SE	2.34 ± 0.42	0.80 ± 0.03	0.88 (0.88)	69.23 ± 3.28	3.66 ± 0.22	0.71 (0.70)

SE = Standard error

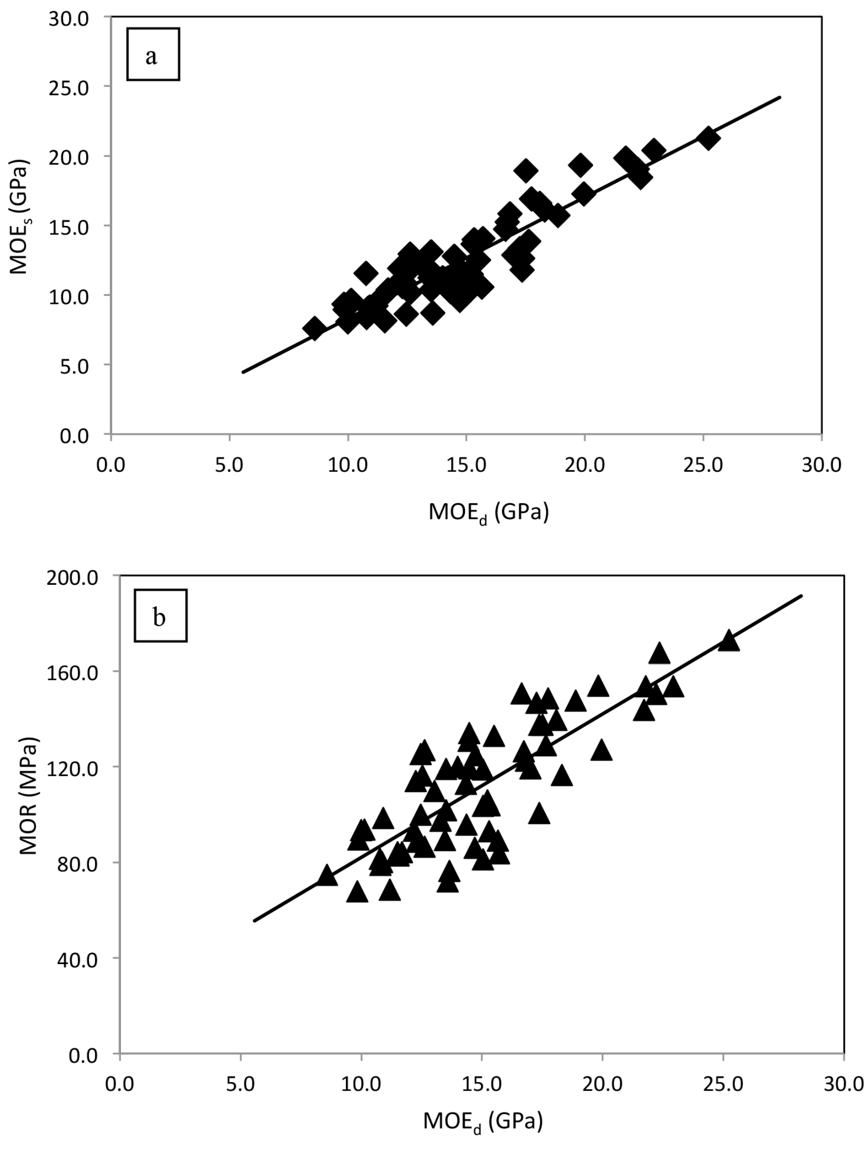

Figure 2 Relations between dynamic modulus of elasticity (MOE_d) and static modulus of elasticity (MOE_s) (a) and dynamic modulus of elasticity (MOE_d) and static modulus of rupture (MOR) (b) in during flowering (DF) stage of *Bambusa bambos*

varied in the range from 0.64 to 0.88. Similarly, linear models between MOR and MOE_d: MOR = p + q × MOE_d for different stages of bamboo life cycle were also found to be statistically significant ($p < 0.001$) with R^2 values varied from 0.65 to 0.71. The models fitted to the mechanical properties presented better predictability when MOE_d was used as independent variable. The mean R^2 value, considering all models between MOE_d and MOE_s of different stages of bamboo was about 0.78, while models fitted between MOE_d and MOR presented a mean R^2 of 0.67. It can be inferred that the stages of bamboo did not affect the linear regression of the results, and certainly provided high predictability of the models as depicted in equations (6a–c).

BF stage: $MOE_s = 3.36 + (0.65 \times MOE_d)$
$MOR = 37.48 + (5.34 \times MOE_d)$ (6a)

DF stage: $MOE_s = -0.42 + (0.87 \times MOE_d)$
$MOR = 22.05 + (6.00 \times MOE_d)$ (6b)

AF stage: $MOE_s = 2.34 + (0.80 \times MOE_d)$
$MOR = 69.23 + (3.66 \times MOE_d)$ (6c)

where MOE_s = static modular of elasticity, MOE_d = dynamic modular of elasticity, MOR = modular of rupture.

Experimental data on different mechanical properties such as MOE_d, MOE_s, MOR and MCS were regressed with specific gravity in the form:

$$Y = mX^n \quad (7)$$

where Y = given mechanical property, X = specific gravity and 'm' and 'n' = fitting parameters of the power equation.

The regression equations for the split bamboo from three different stages of flowering B. bambos along with fitting parameters, the error in these fitting parameters and coefficients of determinations are given in Table 3. The error value of regression parameters (m and n) of power equations between mechanical properties and specific gravity was observed to be small as listed in Table 3. Similarly, R^2 value for all the regression equations was quite high and found to vary in the range 0.61–0.78. As expected, for all the mechanical properties tested, the fitting parameters (m and n) corresponding to air-dried AF stage were greater than BF and DF stages having higher amount of moisture contents. The correlation between different strength properties measured using non-destructive and conventional techniques as well as regression equations between mechanical properties and specific gravity may be used for rapid estimation of the different property of split bamboos of given specific gravity. These models may generally be employed for material development, characterisation, design data generation as well as quality control purposes during usage of split bamboos for different applications specially

Table 3 Regression equations of dynamic modular of elasticity (MOE_d), static modular of elasticity (MOE_s), modular of rupture (MOR) and maximum compressive strength (MCS) with specific gravity (SG) along with fitting parameters and coefficients of determinations for split *Bambusa bambos*

Regression equations	Fitting parameters	Before flowering	During flowering	After flowering
		Value ± SE	Value ± SE	Value ± SE
$MOE_d = m1 \times (SG)^{n1}$	*m1*	34.21 ± 1.45	30.07 ± 1.36	37.57 ± 1.80
	n1	1.78 ± 0.09	1.41 ± 0.09	1.57 ± 0.08
	R^2	0.78	0.77	0.72
$MOE_s = m2 \times (SG)^{n2}$	*m2*	22.66 ± 0.97	28.28 ± 1.41	40.81 ± 2.21
	n2	1.19 ± 0.09	1.61 ± 0.11	1.63 ± 0.09
	R^2	0.62	0.77	0.71
$MOR = m3 \times (SG)^{n3}$	*m3*	199.43 ± 8.28	220.63 ± 10.56	245.28 ± 11.52
	n3	1.07 ± 0.08	1.27 ± 0.10	1.41 ± 0.07
	R^2	0.61	0.72	0.70
$MCS = m4 \times (SG)^{n4}$	*m4*	66.31 ± 2.94	73.51 ± 4.01	103.12 ± 2.94
	n4	1.16 ± 0.10	1.40 ± 0.01	1.22 ± 0.04
	R^2	0.70	0.74	0.73

SE = standard error

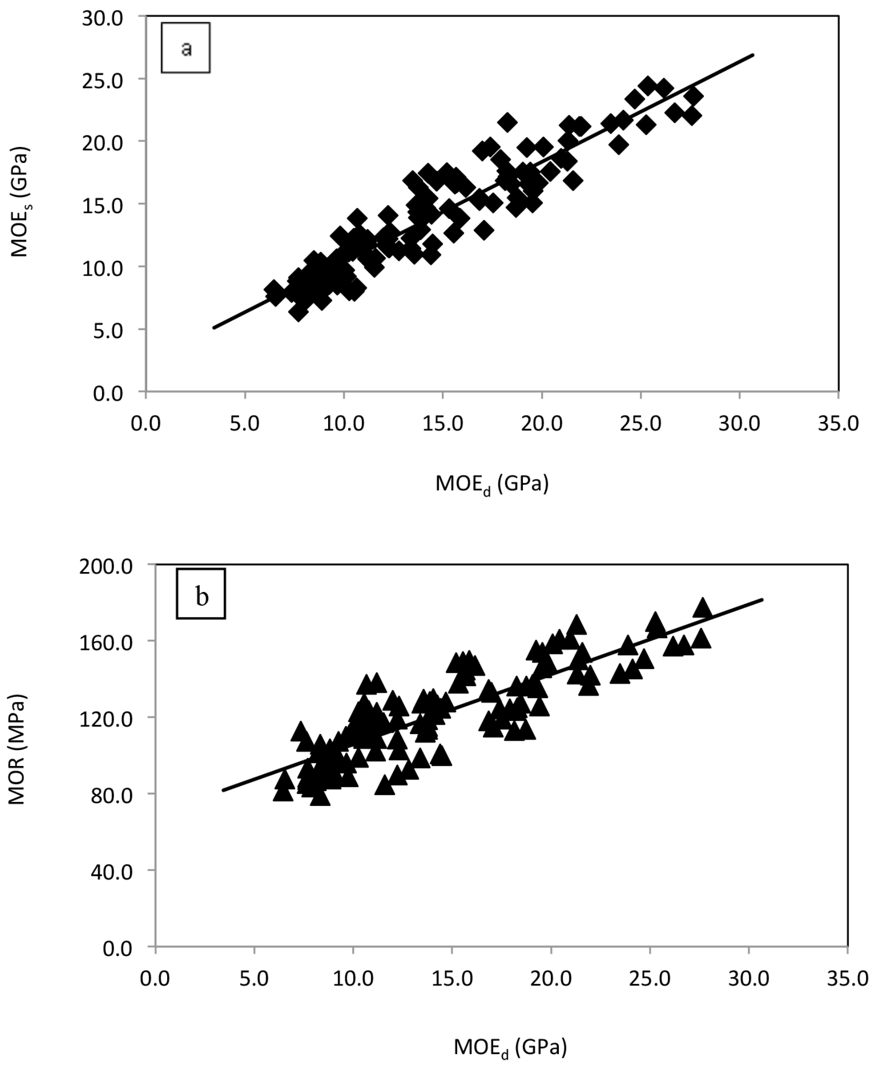

Figure 3 Relations between dynamic modular of elasticity (MOE$_d$) and static modular of elasticity (MOE$_s$) (a) and dynamic modular of elasticity (MOE$_d$) and static modular of rupture (MOR) (b) in after flowering (AF) stage of *Bambusa bambos*

high strength layered laminate composites for structural purposes (Verma & Chariar 2012).

Many researchers have discussed the dependence of mechanical properties of wood on its density (Haygreen & Bowyer 1989, Desch & Dinwoodie 1996). Most of the strength parameters such as modulus of rupture, modulus of elasticity, compressive strength parallel to grain, compressive strength perpendicular to grain etc. of wood were found to increase with increasing density values. Similarly, Shukla & Rajput (1989) also carried out extensive work on establishing the relationships of specific gravity with different physical and mechanical properties of a numerous Indian timber species. The computed relationships were found to be of the best fit form $S = a \times D^b$ for both green (wet) and dry conditions with high values of correlation coefficients (r) where S is a given mechanical property, D is the specific gravity and a, b are fitting parameters. These power equations were employed for providing statistically more reliable and versatile estimates of strength properties from specific gravity. However, it is to emphasise that the specific gravity-mechanical properties relationships work as guide to find some estimates and not a complete substitute of actual testing and evaluation of strength properties. Further studies are required on more number of bamboo species to make these models robust and applicable in the industrial conditions for quality control.

CONCLUSIONS

Most of the physical and mechanical parameters of split *B. bambos* were found to be higher in AF stage (air-dry) compared to BF and DF stages. The flexural parameters obtained from the static tests (MOE_s and MOR) were found to be linearly correlated with dynamic modulus of elasticity (MOE_d) with high values of coefficient of determination (R^2). Similarly, regression equations of the form: were obtained between different mechanical properties (MOE_d, MOE_s, MOR, MCS) and specific gravity (SG) of bamboo tested from three different stages with small error and high R^2 values. The non-destructive elastosonic technique as well as different regression equations between mechanical properties and specific gravity may be employed for rapid estimation of different strength parameters of split bamboo for material development, characterisation, design data generation as well as quality control purposes.

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