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VARIATION OF STRESS WAVE VELOCITY, WOOD DENSITY AND STATIC BENDING STRENGTH OF 22-YEAR-OLD PLANTED *TECTONA GRANDIS* TREES IN NORTHWEST VIETNAM

Van Duong D[1,2]* & Kanninen M[3]

[1] *Centre of Crop Research for Adaptation to Climate Change, Thai Nguyen University of Agriculture and Forestry, Thai Nguyen, Vietnam*
[2] *Faculty of Forestry, Thai Nguyen University of Agriculture and Forestry, Thai Nguyen, Vietnam*
[3] *Viikki Tropical Resources Institute (VITRI), Department of Forest Sciences, University of Helsinki, Finland*

**duongvandoan@tuaf.edu.vn*

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We studied stress wave velocity and wood properties at different radial and axial levels of 22-year-old planted *Tectona grandis* trees growing in Northwest Vietnam. We measured stress wave velocity of logs (SWV_L) and small clear specimens (SWV_S) obtained from the logs. In addition, we measured air-dry density (AD), modulus of rupture (MOR), and modulus of elasticity (MOE) at 12% moisture content. Within tree, radial position was not a source of variation of stress wave and wood properties, except for MOR. In contrast, the longitudinal variation was highly significant and the most important of variation in SWV_S and MOE. There was statistically significant (0.1% level) but weak correlation (r = 0.36) between AD and MOE, while strong correlation was found between AD and MOR (r = 0.67). The increase of SWV_L and SWV_S may result in significant increase in dynamic modulus elasticity of log (E_L) and MOE, respectively. These results suggest that the stress wave technique could be applied for grading or segregation of the stiffness of timber in teak.

Keywords: MOE, MOR, stress wave velocity, *Tectona grandis*, wood density

INTRODUCTION

Teak (*Tectona grandis*) is one of the most important valuable hardwoods in the world due to its attractive characteristics such as brightness in color, easy to cut, and high natural resistance (Wanneng et al. 2014, Kollert & Kleine 2017). Teak wood has been widely used in furniture and carvings, as well as in construction work such as ship and vehicle body building (Perez & Kanninen 2003, Perez 2005, Amoah & Inyong 2019). Teak grows naturally in India, Myanmar, Laos and Thailand (Hidayati et al. 2013). It was first introduced to Vietnam in early 20th century, and it adapted well to a wide range of site conditions (Trieu et al. 2022). In Vietnam, teak plantations cover about 6600 ha located mainly in Central Highland, Northwest, and Southeast. Approximately 50% of the total teak forest area in Vietnam was established during 1993–2010 under the 327 Program (1993–1998) and the 661 Program (1998–2010) (FORMIS 2017). Research on teak in Vietnam had focused mainly on improving phenotypic features, silvicultural techniques, or pest and disease resistance (Hoang & Nguyen 1996, Bao et al. 1998). There is little information available on the radial and axial variation in wood properties of teak, such as wood density and static bending strength, which determine suitability for high-quality timber production.

Wood properties within a tree vary from the center outward and from the base of the tree to its top, in which variation along the radial direction is the best known and most studied within-tree variability in wood (Zobel & van Buijtenen 1989). An ability to estimate the proportion of fit-for-purpose wood properties in a tree or log is necessary for optimal utilisation of each product group. Three crucial properties of solid wood, namely air-dry density (AD), modulus of rupture (MOR), and modulus of elasticity

(MOE), are functions of the performance of timber when used in construction. Current measurement standards require destructive sampling and careful sample preparation and testing. Measurement of wood density and static bending strength is expensive and time consuming, making it impossible to collect the desired number of samples in time and in budget (Van Duong et al. 2022, Schimleck et al. 2018). Therefore, nondestructive evaluation technology has contributed considerably towards reducing these limitations and shown promise for predicting the mechanical properties of wood materials including standing trees, logs or small clear specimens (Ishiguri et al. 2007, Wang et al. 2013, Van Duong et al. 2023b).

The aim of this study was to examine the variation in stress wave velocity, wood density and static bending strength within the stem of 22-year-old planted teak (*Tectona grandis*). We also studied the possibility for predicting the mechanical properties of teak wood using stress wave method to provide wood processing strategies based on wood quality.

MATERIALS AND METHODS

Trees and test samples

Wood samples of *Tectona grandis* trees were obtained from the forest stands planted in 2000 under 661 program of Vietnamese Government in Chieng Hac commune, Yen Chau district, Son La province, Vietnam (E00201558 and N02326952). The diameter at breast height (DBH) of 83 trees growing at the site was measured in October 2022 to select standard trees. Five trees with a stem diameter close to the average DBH of 83 trees were selected for the present study. The tree stems were straight, had normal branching and showed absence of disease or pest symptoms. The five trees were felled and total tree height measured. The north and south sides of each tree were marked before felling. Characteristics of the test trees were indicated in Table 1 as described by Van Duong et al. (2023a).

From each tree, 50-cm-long logs were taken at different height levels (0.3, 1.3, 2.3, 3.3, 4.3 and 5.3 m heights from above the ground) with the aim of obtaining representative samples for the examination of axial variation in wood properties. A total of 30 logs were obtained from the five selected trees, and the weight and volume of logs were measured to calculate the green density (GD). Each log was first evaluated using the longitudinal stress wave technique (Fakopp Microsecond Timer, Fakopp Enterprise Bt., Hungary) to obtain a stress wave velocity for the log (SWV_L) within 24 hours of felling (Van Duong & Schimleck 2022). Figure 1 shows the experimental setup for stress wave measurement of the logs. Start and stop transducers were attached at the middle position from pith to bark (transverse face) on each side of log. The stress wave transmission time was measured five times through a hammer impact on the start transducer. The SWV_L (m s^{-1}) of a log was determined by dividing log length by the average stress wave transmission time. Green weight and dimensions of logs, including bark, were measured by a portable electric balance and diameter tape, and a tape measure, respectively. Dynamic modulus elasticity of log E_L (GPa) was calculated as:

$$E_L = GD.SWV_L^2 \qquad (1)$$

where E_L is the dynamic modulus elasticity of log (GPa), GD is green density of log (kg m^{-3}), and SWV_L is stress wave velocity of log (m s^{-1}).

After measuring E_L, these logs were dried in a room at ambient conditions for approximately 4

Table 1 Characteristics of the five test trees

Test tree no.	Diameter at breast height (cm)	Total tree height (m)
1	22.3	19.6
2	17.8	16.3
3	22.1	19.8
4	17.8	17.3
5	20.4	16.8

weeks without humidity control. From each log, small clear specimens with nominal dimensions of 20 × 20 × 320 mm^3 (radial × tangential × longitudinal) were carefully taken at 10, 50, and 90% of the radial length from pith on both sides (north and south) for strength testing (Figure 1). The total number of small clear wood specimens from 30 logs was 180 (six specimens for each log). These were then dried in a controlled environment at about 65% relative humidity and 20 °C to reach an equilibrium moisture content of about 12%.

Before the bending tests were conducted, air-dry density (AD) of the specimens which is the mass of each small clear specimen per volume, is measured and expressed in g cm^{-3}. Figure 1 also shows the experimental setup for stress wave measurement of the specimens using a Fakopp Microsecond Timer. Longitudinal stress wave time was measured for each specimen and used to calculate stress wave velocity of small clear specimen (SWV_S) by dividing specimen length by propagation time. The procedure measured bending mechanical properties perpendicular to the grain and was assessed in accordance with Japanese Industrial Standards (JIS Z2101:1994, 2000) using a universal testing machine (INSTRON 5569/USA). The length of the span and the load speed were 240 mm and 5 mm min^{-1}, respectively.

Data analysis

The variation in stress wave velocity and wood properties within stem was statistically evaluated using R software (R Core Team 2020). The difference among the radial and height positions within stem were examined by one-way analysis of variance (ANOVA) followed by Tukey's HSD test with the level of significant differences at $P < 0.05$ (n = 180).

To clarify the variation of SWV_S, AD, MOR and MOE among radial directions, stem heights and individual trees, the variance component model of linear mixed was used based on the following equation:

$$Y_{ijk} = \mu + R_i + H_j + T_k + (RT)_{ik} + (HT)_{jk} + e_{ijk} \quad (2)$$

where Y_{ijk} is the observation in the ijk^{th} tree, μ is the intercept of the model, R_i and H_j are fixed effects of radial direction and stem height, respectively, T_k is the random effect of tree, $(RT)_{ik}$ is the interaction between tree and radial position effect, $(HT)_{jk}$ is the interaction between tree and stem height effect, and e_{ijk} is the random error term.

RESULTS AND DISCUSSION

Log properties

Green density (GD), stress wave velocity (SWV_L), and dynamic modulus elasticity (E_L) of logs from different height positions of five sample trees are shown in Table 2. There was a significant ($P < 0.05$) difference in the log properties observed among height levels. The GD decreased from the bottom to middle sections and increased in the top section, whereas the mean SWV_L and E_L values were the lowest at 0.3 and 1.3 m above the ground and then gradually increased to the upper logs. Until now, there have been no reports of evaluating wood quality of teak log using nondestructive method. For the first time, we have experimentally confirmed the values of

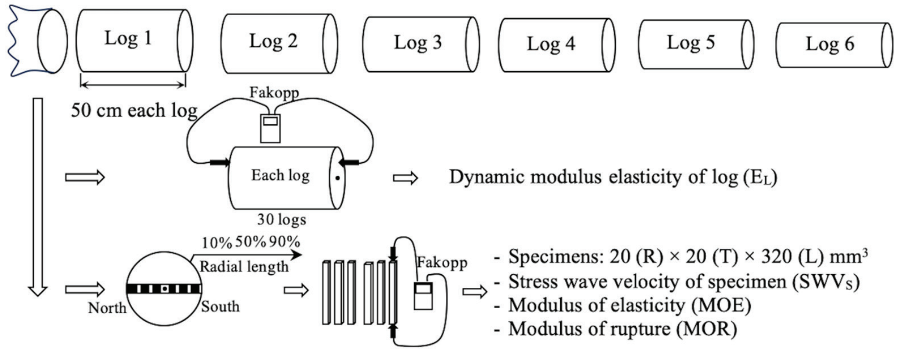

Figure 1 Illustration of experiment procedures

SWV$_{L}$ and E$_{L}$ measurements in teak logs. The SWV$_{L}$ values obtained in this study (Table 2) were slightly higher than stress wave velocity measured on standing trees for 24-year-old teak planted in Indonesia (Hidayati et al. 2013).

No clear relationship ($P > 0.05$) could be established between GD and E$_{L}$, while a significant positive relationship ($r = 0.89$; $P < 0.001$) between SWV$_{L}$ and E$_{L}$ of logs was observed as shown in Figure 3. Ishiguri et al. (2007) reported that there was a significant positive relationship ($R^2 = 0.51$) between SWV$_{L}$ and E$_{L}$ of *Paraserianthes falcataria* planted in Indonesia. In addition, Van Duong and Schimleck (2022) reported that logs with high stress wave grades produced high-grade lumbers for Eucalyptus clones in Vietnam. Our results are similar to their results. This implies that stress wave velocities can be applied for segregation of mechanical properties of logs in teak.

Radial and longitudinal variations

The mean and standard deviation values of SWV$_{S}$, AD, MOR and MOE for each radial position and stem height of the sampled teak

Table 2 Average values of the log properties of five sample trees

Height position	*n*	GD (g cm^{-3})	SWV$_{L}$ (m s^{-1})	E$_{L}$ (GPa)
0.3	5	1.02 ± 0.05^{a}	3623 ± 263^{b}	13.40 ± 1.85^{ab}
1.3	5	0.93 ± 0.08^{ab}	3705 ± 169^{ab}	12.79 ± 1.75^{b}
2.3	5	0.87 ± 0.02^{b}	4023 ± 178^{ab}	14.13 ± 1.50^{ab}
3.3	5	0.93 ± 0.05^{ab}	4068 ± 260^{ab}	15.50 ± 2.45^{ab}
4.3	5	0.98 ± 0.06^{ab}	4040 ± 286^{ab}	15.96 ± 2.07^{ab}
5.3	5	0.96 ± 0.06^{ab}	4110 ± 163^{a}	16.22 ± 1.63^{a}
Mean	30	0.95 ± 0.07	3928 ± 297	14.67 ± 2.18

n = number of log, GD = green density of log, SWV$_{L}$ = stress wave velocity of log, E$_{L}$ = the dynamic modulus elasticity of log


(a) (b) (c) (d)

Figure 2 The experimental procedures: 50-cm-long logs from five sampled trees (a), specimen cutting (b), static bending strength specimens (c), destructive testing (d)

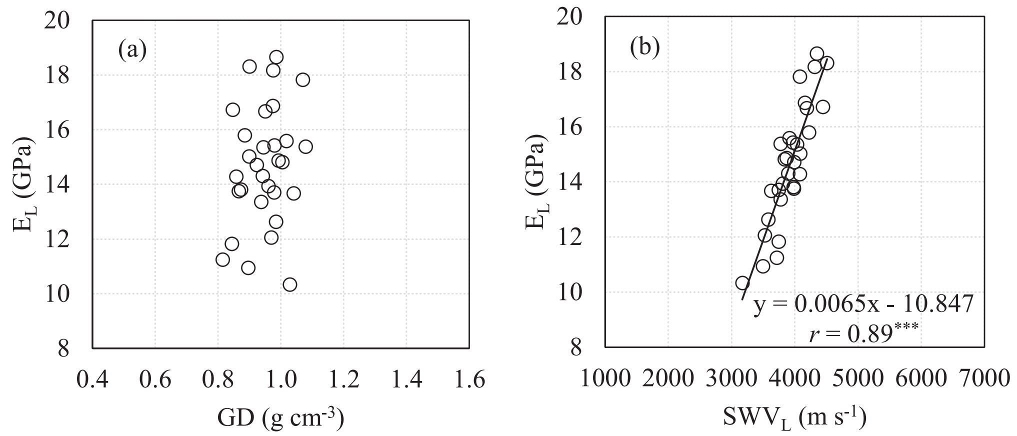

Figure 3 Relationship between (a) green density (GD) and dynamic modulus elasticity of log (E_L), and (b) stress wave velocity (SWV_L) and E_L

are given in Table 3. The overall SWV_S, AD, MOR and MOE were 4264 m s^{-1}, 0.66 g cm^{-3}, 104.53 MPa and 12.19 GPa, respectively (Table 3). The AD and MOE in this study are similar, but MOR is higher than values reported by Amoah and Inyong (2019) for teak planted in Ghana (respective values for AD, MOE and MOR were 0.67 g cm^{-3}, 12.24 GPa and 87 MPa, respectively).

Table 4 shows the results obtained for the analysis of variance (ANOVA) of SWV_S, AD, MOR and MOE, with regards to the statistical significance and proportion of explained variation for the difference sources of variation. Within tree, radial position was not a source of variation of SWV_S, AD and MOE, explaining only 4.75, 7.10 and 11.81% of the total variation, respectively. There was a significant radial variation in MOR with position, but contributed little (15.25%) to the total variation (Table 4). Several authors have also reported that the effect of the radial position on mechanical properties of teak wood was negligible (Bailleres & Durand 2000, Miranda et al. 2011). The radial pattern of AD in the present study is in agreement to that of a previous study which reported of a nearly constant specific gravity measured for each ring from pith to bark of the same sampled trees in the study (Van Duong et al. 2023a). Shinha et al. (2017) also reported that wood density of teak grown naturally in India decreased slightly in first few rings from pith outwards and then increased towards middle portion before declining towards the periphery in the radial direction.

The longitudinal variation was highly significant and the most important within-tree source of variation in SWV_S and MOE,

Table 3 Stress wave and wood properties of *Tectona grandis* sampled

Variable	Description	*n*	SWV_S (m s^{-1})	AD (g cm^{-3})	MOR (MPa)	MOE (GPa)
Radial position from pith (%)	10	60	$4281^a \pm 254$	$0.65^a \pm 0.04$	$102.64^b \pm 11.70$	$12.26^a \pm 1.63$
	50	60	$4285^a \pm 266$	$0.67^a \pm 0.04$	$107.68^a \pm 9.27$	$12.51^a \pm 1.58$
	90	60	$4226^a \pm 227$	$0.65^a \pm 0.04$	$103.23^{ab} \pm 11.71$	$11.81^a \pm 1.83$
Height above the ground (m)	0.3	30	$3895^b \pm 243$	$0.68^a \pm 0.04$	$103.48^a \pm 9.73$	$10.55^b \pm 1.71$
	1.3	30	$4301^a \pm 162$	$0.65^{ab} \pm 0.04$	$105.60^a \pm 11.83$	$12.36^a \pm 1.03$
	2.3	30	$4288^a \pm 193$	$0.65^b \pm 0.04$	$100.24^a \pm 10.12$	$12.15^a \pm 1.64$
	3.3	30	$4319^a \pm 155$	$0.65^b \pm 0.04$	$103.68^a \pm 12.53$	$12.33^a \pm 1.89$
	4.3	30	$4361^a \pm 199$	$0.65^{ab} \pm 0.04$	$105.49^a \pm 11.40$	$12.59^a \pm 1.34$
	5.3	30	$4419^a \pm 133$	$0.66^{ab} \pm 0.04$	$108.62^a \pm 9.97$	$13.17^a \pm 1.35$
Mean		180	4264 ± 250	0.66 ± 0.04	104.52 ± 11.12	12.19 ± 1.70

Same letter associated with mean values indicate no significant differences among radial or height positions based on Tukey's HSD test at 5%; *n* = number of specimen sampled, SWVs = stress wave velocity of specimen, AD = air-dry density of specimen, MOR = modulus of rupture, MOE = modulus of elasticity accounting for 75.99 and 36.82% of the total variation, respectively. The results showed that the lowest SWV$_S$ and MOE were found in the bottom of tree and then increased up to 1.3 m height before being less or more stable at the top. The AD decreased from the bottom to the middle sections, and then increased in the top section. In contrast, the variation of MOR with height was very small and without statistical significance (Table 4). The most important and highly significant source of variation in teak wood properties was the tree (Table 4), explaining 81.64, 67.05 and 36.51% of the total variation of the respective AD, MOR and MOE values.

Relationship between wood density and mechanical properties

One of the most important wood properties is density, proven to be a useful and commonly considered as an indicator to predict wood quality due to its effect on strength, performance and the general quality of final products. Besides, it can be measured reasonably fast and cheaply (Zobel & van Buijtenen 1989).

Statistical analysis procedures were used to examine the relationships between the AD and mechanical properties in the small clear samples. The results obtained were presented in Figure 4. The AD had a significant linear relationship with both MOR and MOE, but weak correlation ($r = 0.36$) was found between AD and MOE (Figure 4b). The coefficient of correlation between AD and MOR is 0.67 (Figure 4a).

Relationship between stress wave velocity and mechanical properties

Figure 5 shows the relationships between the SWV$_S$ and the average MOE or MOR in static bending of small specimens. There was a relatively good correlation ($r = 0.69$; $P < 0.001$) between SWV$_S$ and MOE (Figure 5b), but no significant ($r = 0.12$; $P > 0.05$) correlation was found between SWV$_S$ and MOR (Figure 5a).

The results obtained in this study are in agreement to that obtained by Van Duong and

Table 4 Effects of radial position, height level and tree on stress wave velocity, wood density and static properties (MOR, MOE) of *Tectona grandis*

Source of variation	*df*	SWV$_S$		AD		MOR		MOE	
		p value	Var%	*p* value	Var%	*p* value	Var%	*p* value	Var%
Radial position (R)	2	0.352	4.75	0.087	7.10	0.024	15.25	0.076	11.81
Height level (H)	5	0.001	75.99	0.025	7.35	0.089	7.84	0.001	36.82
Tree (T)	4	0.194	6.86	0.001	81.64	0.001	67.05	0.001	36.51
R × T	8	0.436	1.34	0.048	1.41	0.116	3.39	0.029	4.10
H × T	20	0.001	9.73	0.001	1.79	0.005	4.41	0.001	9.91
Residuals	140		1.34		0.70		2.06		1.85

SWV$_S$ = stress wave velocity of specimen, AD = air-dry density of specimen, MOR = modulus of rupture, MOE = modulus of elasticity, *df* = degrees of freedom, Var = variance

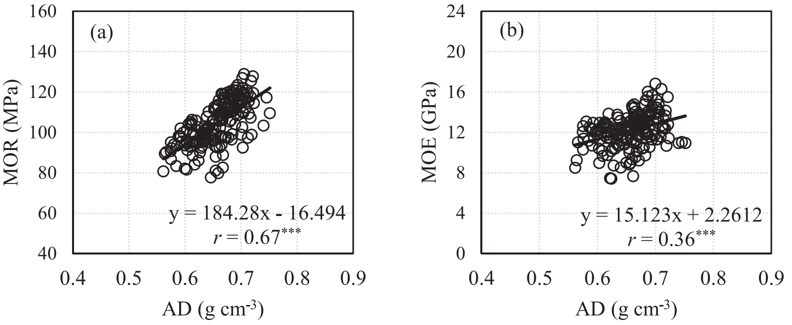

Figure 4 Relationship between air-dry density (AD) and static properties: (a) modulus of rupture (MOR) and (b) modulus of elasticity (MOE)

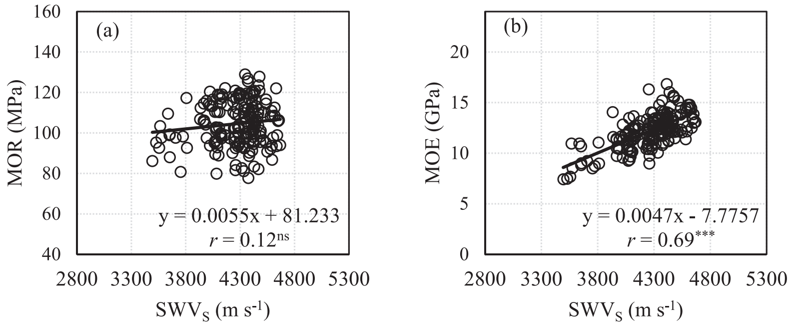

Figure 5 Relationship between the stress wave velocity of specimen (SWV_S) and static properties: (a) modulus of rupture (MOR) and (b) modulus of elasticity (MOE)

Ridley-Elllis (2021) who reported of a statistically significant relationship between SWV_S and MOE, but no significant relationship was obtained between the SWV_S and MOR for *Melia azedarach.* Stress wave velocity is not an intrinsic wood property. It is derived from wood density and modulus of elasticity in combination. In this study, the relationship between AD and MOE was significant but weak correlation (r = 0.36), therefore SWV_S had a significant positive correlation with MOE at the moisture content. This implies that stress wave velocity gives a good indication of stiffness in teak planted in Vietnam.

CONCLUSION

In this study, green density (GD), stress wave velocity (SWV_L) and dynamic modulus elasticity (E_L) of logs were evaluated for green logs, and stress wave velocity (SWV_S), air-dry density (AD), modulus of rupture (MOR) and modulus of elasticity (MOE) were evaluated for small clear specimens at 12% moisture content of teak planted in Northwest Vietnam. Within tree, radial position was not a source of variation of SWV_S, AD, MOR and MOE, explaining only 4.75, 7.10, 15.25 and 11.81% of the total variation, respectively. The longitudinal variation was highly significant and the most important within-tree source of variation in SWV_S and MOE. In contrast, the variation of AD and MOR with height was very small, corresponding to values of 7.35 and 7.84%. It is not useful for predicting strength of teak by stress wave technique when no correlation was found between SWV_S and MOR, while wood density is a good predictor of strength. As for the relationship between stress wave velocity measured both in logs and small clear specimens and mechanical properties, the increase in stress wave velocity may result in significant increases in E_L and MOE. This implies that stress wave technique could significantly enhance the precision of stiffness predictions for teak wood. In the future, the results obtained in this study may help practitioners of teak users to improve their grading and segregation procedures.

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