Dynamic Young's Modulus and Moisture Content of Tropical Wood Species across Sap, Median, and Internal Wood Regions

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The dynamic Young's modulus (E_d) and moisture content (MC) were determined for two tropical wood species, *Gymnacranthera eugenifolia* and *Sindora* sp. using the free-free vibration method. The wood species were tested at the sap, median, and internal regions. The dynamic Young's modulus was found to be linearly correlated to the radial distance, with E_d gradually increasing with respect to the reduction in radial distance to the centre of the wood. Linear correlation was observed between the radial distance and E_d, with E_d gradually decreasing with respect to the radial distance from the centre. For *Sindora* sp. and *Gymnacranthera eugenifolia*, E_d ranged from 0.8 to 2.4 GPa and 0.9 to 1.6 GPa, respectively. Moisture content in *Sindora* sp. displayed a broad range, from 10 to 20 wt.%, while *Gymnacranthera eugenifolia* displayed a narrower range from 8 to 15 wt.%. Free-free flexural vibration testing is a fast, inexpensive, and reliable method for determining E_d. However, further studies are needed to investigate the acoustic qualities of these woods, such as the speed of sound and damping within the wood.

Keywords: Dynamic Young's modulus; Free-free vibration; Moisture content

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INTRODUCTION

Wood is a natural material whose complex structure provides a wide variety of uses. Wood consists of fibrous tissue that makes up a tree system, with the major parts including stems, branches, and roots. Resonance analysis of transverse vibrations is a simple, inexpensive, and effective means of characterizing the elastic properties of wood materials (Brancheriau and Bailleres 2002). The objective of this study was to evaluate the dynamic Young's modulus (E_d) of two tropical wood species, namely *Gymnacranthera eugenifolia* and *Sindora* sp., through free-free vibration analysis. This vibration technique is among the non-destructive techniques (NDT) that are used for measuring acoustic properties. In wood experimentation, acoustic properties such as E_d of wood have adopted the usage of NDT for assessing elastic properties based on transverse vibration (Murphy 1997; Sedik 2010). The natural vibrational frequency, or resonance frequency, of a material is related to its stiffness against compression or bending (Leite *et al*. 2012). With wide industrial applications in grading wood quality, vibrational properties can also be used to assess a wood's suitability for use in musical instruments (Obataya *et al*. 2000). The angle between the cellulose fibrils and the longitudinal cell axis, the microfibril angle, MFA was found to be a critical factor in determining the physical and mechanical properties of wood (Cave 1997). Differences in MFA have a profound effect on the properties of wood, in particular its stiffness. The large MFA in juvenile wood confers low stiffness and gives the sapling the flexibility it needs to survive high winds without breaking (Barnett and Bonham 2004).

In addition to being used for construction, Malaysian tropical woods can be used for musical instruments and furniture, as well as firewood. Tropical woods are used to make traditional musical instruments such as the *sapeh* and the *gendang*, for example (Chong 2000). However, converting tropical woods into musical instruments has been difficult, as the techniques of making soundboard for traditional musical instruments are largely based on trial and error, with the results for one species not applicable to another for producing a final product. Thus, the databases of tropical woods are largely unexploited and remain a vast ocean of new discoveries for fellow researchers. In previous work by the authors, specific dynamic Young's modulus (E_d/γ), internal friction (Q^{-1}), and acoustic converting efficiency (ACE) of kayu malam wood (*D. maingayi*) were investigated for constructing the marimba instrument (Hamdan *et al.* 2018). The results were consistent with earlier finding on *Syzygium*, *Dialium*, *Gymnostoma*, and *Sindora* wood (Hamdan *et al.* 2016).

The effects of moisture content (MC) on the ultrasonic wave velocity, dynamic Young's modulus (DMOE), and the mobility of free water during desorption from a water-saturated condition were examined for the longitudinal, radial, and tangential directions of *Taiwania cryptomerioides* Hayata plantation lumber (Wang *et al.* 2002). In this paper, a scientific approach using a free-free vibration technique will be used to discover dynamic Young's Modulus and moisture content of tropical wood species across sap, median, and internal wood regions.

EXPERIMENTAL

Two tropical wood species were chosen for this study, namely *Gymnacranthera eugenifolia* and *Sindora* sp. with density 580 kg/m^3 and 521 kg/m^3 respectively. Diameter at breast height (DBH) for *Gymnacranthera eugenifolia* and *Sindora* sp. are 40 cm and 76 cm. *Gymnacranthera eugenifolia* sapwood thickness is about 1 to 2 cm only, and *Sindora* sp. sapwood thickness is about 10 cm. These species were chosen due to their ready availability and were harvested at the foothills of Mount Pueh, in Kuching, Sarawak, Malaysia. Only one tree from each species was used, as within-species variation was not specifically studied. This study targeted sap wood, median wood, and internal wood. Each tree was cut into various bolts of 1.2 m and subsequently quarter sawn to produce planks of 10 cm thickness. These planks were left to air dry in a room at 60% relative humidity and an ambient temperature of 25 °C for a month prior to testing. The planks were shredded and divided into 3 sections, namely sap, median, and internal wood. For each section, the wood samples were fabricated to produce 20 replicates of 340 mm (L) × 20 mm (T) × 10 mm (R) for the free-free vibration test. All samples were left in a convection oven for 24 hours at 103 °C.

The determination of the dynamic Young's modulus **(**E_d**)** was performed using the free-free flexural vibration test, as shown in Fig. 1. The wood sample was held with A-A thread according to the first mode of vibration. The wood sample, with an iron plate glued at one end, was set up facing the electromagnetic driver, while the microphone was placed at the centre of the wood sample. The data acquisition analyzer was done using a Pico Scope computer software (Pico Technology, 3000 series, Eaton Socon, UK) used to view and analyze the time signals from Pico Scope oscilloscopes (Pico Technology, 3000 series, Eaton Socon, UK)) and data loggers for real time signal acquisition. Pico Scope software enables analysis using Fast Fourier transform (FFT), a spectrum analyzer, voltage-based triggers, and the ability to save/load waveforms to a disk. The frequency was varied to identify the resonant, or natural frequency of the wood, and E_d was calculated from the natural frequency using the following equation (Hearmon 1958),

$$E_d=4\pi^2 f^2 l^2 A\rho / I(m_n)^4 \quad (1)$$

where $I = bd^3/12$, d is the beam depth, b is the beam width, l is the beam length, f is the natural frequency of the specimen, ρ is the density, A is the cross-sectional area, and n = 1 for the first mode of vibration, with m_1 = 4.730.

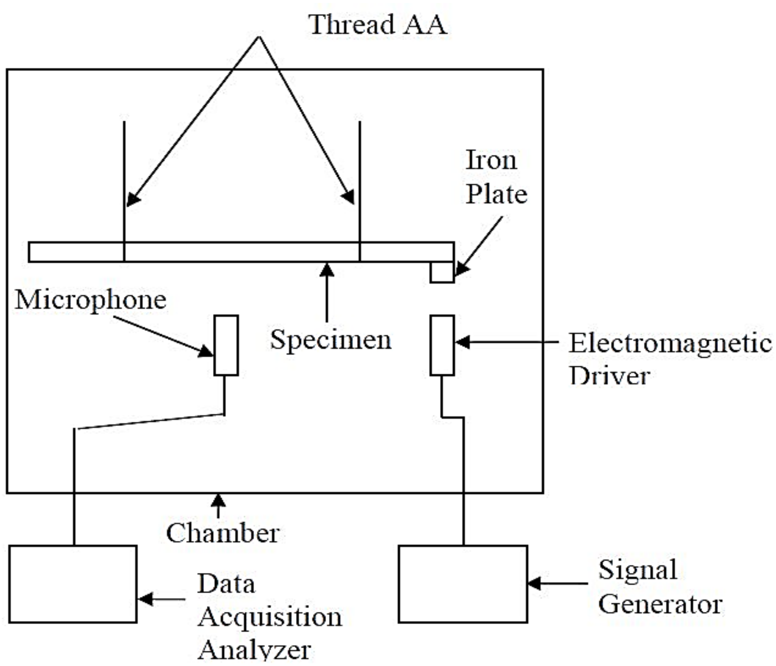

Fig. 1. Free-free flexural vibration system

The moisture content of the wood was determined according to ASTM D4442 (2016). Before oven drying, the wood samples were weighed, recorded as initial weight, W_i. Ten samples from the sap, median, and internal wood of each wood species were left in the convention oven at 103 °C for 24 h. After 24 h, the wood samples were again weighed, recorded as final weight, W_f. Moisture content (MC) for each wood species was calculated using the following equation:

$$MC=[(W_f-W_i)/ W_i]x100\% \quad (2)$$

However, further studies are needed to investigate the acoustic qualities of these woods, such as the speed of sound and damping within the wood.

RESULTS AND DISCUSSION

Figures 2 and 3 show E_d of *Sindora* sp. and *Gymnacranthera eugenifolia* wood in the sap, median, and internal wood regions. Overall, *Sindora* sp. and *Gymnacranthera eugenifolia* wood species showed E_d values from 0.8 to 2.4 GPa and 0.9 to 1.6 GPa, respectively. In general, E_d for both species gradually increased with the wood regions from the sapwood (outer) to the internal wood (inner). The average E_d of *Sindora* sp. wood in the sap, median, and internal wood regions was 1.01, 1.59, and 2.04 GPa, respectively, while the average E_d for *Gymnacranthera eugenifolia* wood was 1.04, 1.33, and 1.41 GPa, respectively.

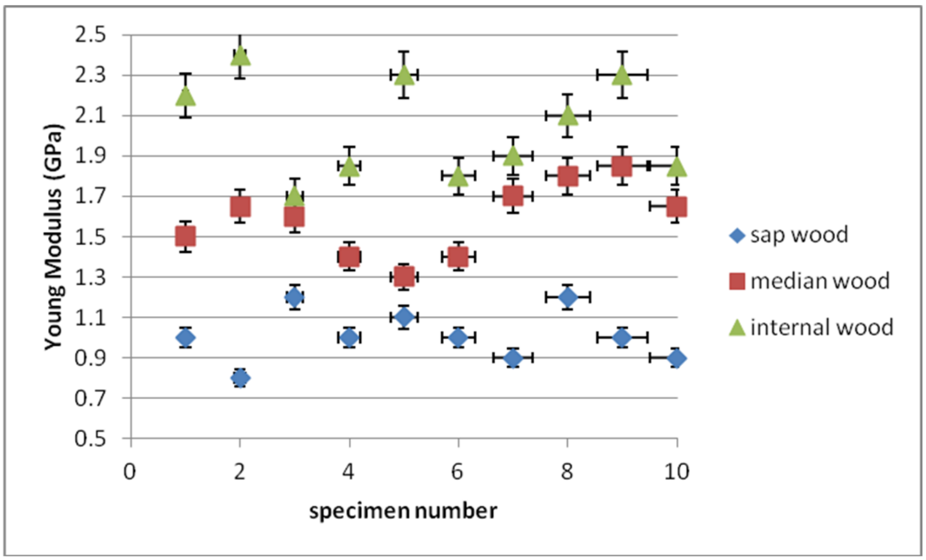

Fig. 2. Dynamic Young's modulus of *Sindora* sp. wood in the sap, median, and internal wood regions

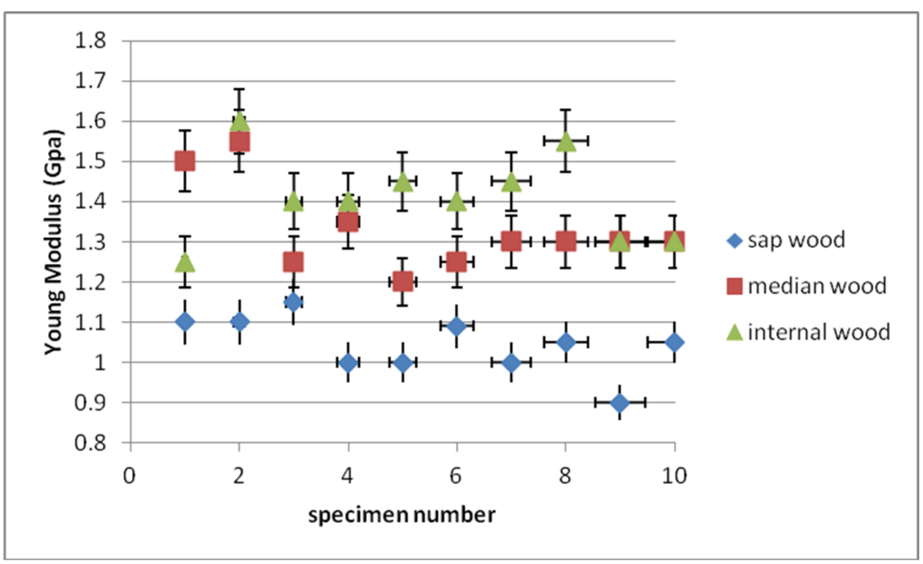

Fig. 3. Dynamic Young's modulus of *Gymnacranthera eugenifolia* wood in the sap, median, and internal wood regions

The modulus of elasticity of a wood species is largely determined by the angle of microfibrils in the S_2 layer of its fibers (Leite *et al*. 2012). The variations in E_d of the two species are the result of many influences, including moisture, which yields wood with widely varying characteristics. The dynamic Young's modulus is an intrinsic characteristic of materials and is determined by the bonding forces among atoms. Sapwood has weaker bonding forces than median wood and internal wood, which results in the lowest E_d. In term of strength and durability, sapwood is much weaker because sapwood contains living cells. The cell walls are thin and permeable that make it weak in term of strength. Heartwood contained dead cells. The cell walls are thicker, lignified, and contain extractives. Extractives give darker color to heartwood.

Figures 4 and 5 show the MC of *Sindora* sp. and *Gymnacranthera eugenifolia* wood at three radial distances: in the sap, median, and internal wood regions.

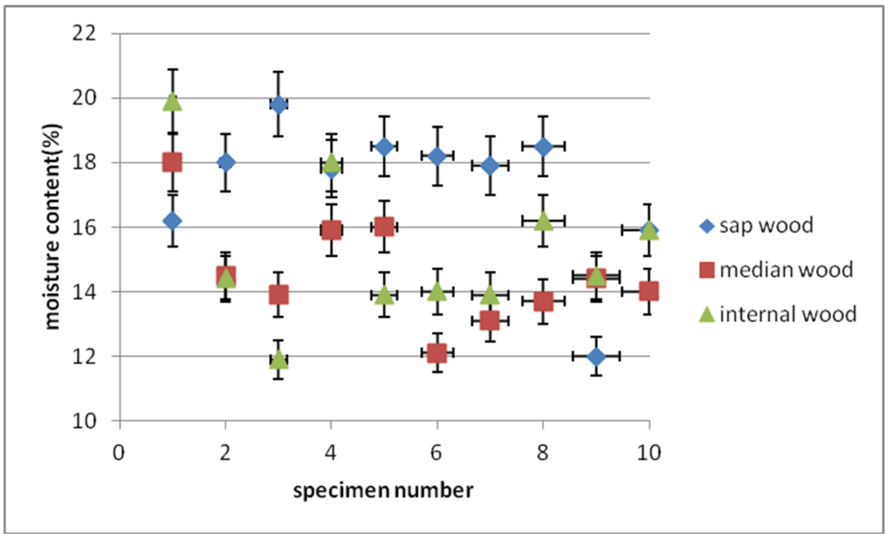

Fig. 4. Moisture content of *Sindora* sp. wood in the sap, median, and internal wood regions

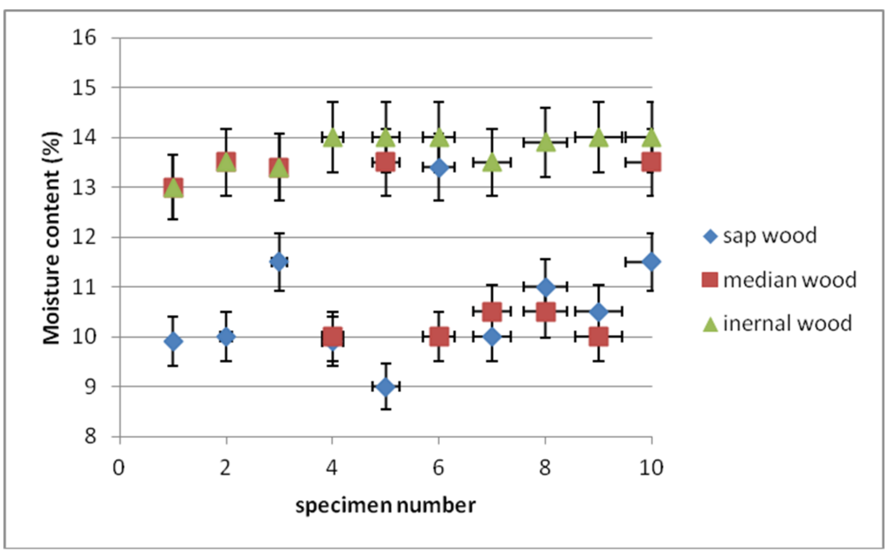

Fig. 5. Moisture content of *Gymnacranthera eugenifolia* wood in the sap, median, and internal wood regions

Sindora sp. displayed a broad range of moisture values, from 12 to 20 wt. %, while *Gymnacranthera eugenifolia* displayed a narrower MC range, from 9 to 14 wt.%. Because median wood and internal wood are considered as the heartwood region, the sapwood of *Sindora* sp. showed higher MC than the heartwood of *Sindora* sp. In contrast, the sapwood of *Gymnacranthera eugenifolia* showed lower MC than the heartwood. This finding is consistent with Rowell (2005). A relationship between MC and vibrational properties is very prominent because wood is a viscoelastic material, in which the vibrational properties are highly dependent on the elasticity within the cell wall. MC affects E_d, which alters the sound velocity within the wood. Higher MC in *Sindora* sp. results in lower sound quality compared to *Gymnacranthera eugenifolia*.

Figures 6 and 7 show the dynamic Young's modulus versus MC of *Sindora* sp. and *Gymnacranthera eugenifolia* along 3 radial directions, sap, median, and internal wood.

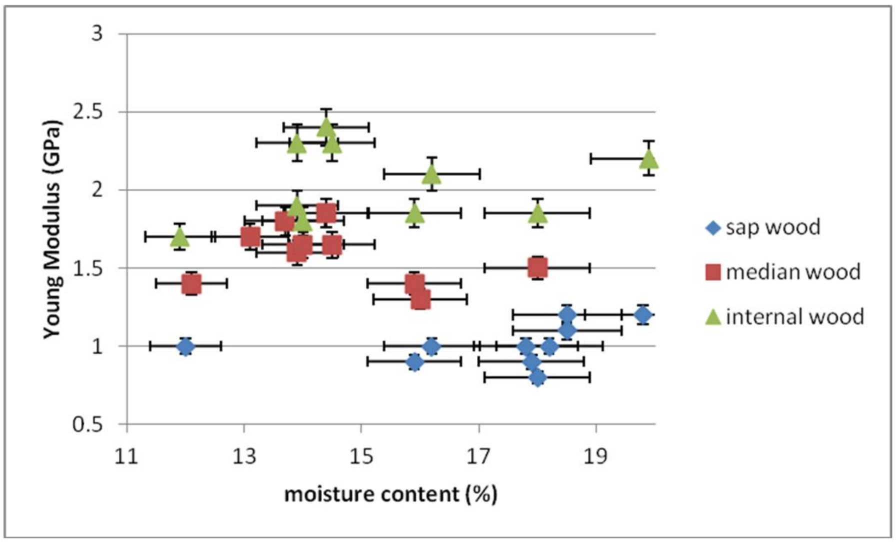

Fig. 6. Dynamic Young's modulus versus moisture content of *Sindora* sp. wood in the sap, median, and internal wood regions

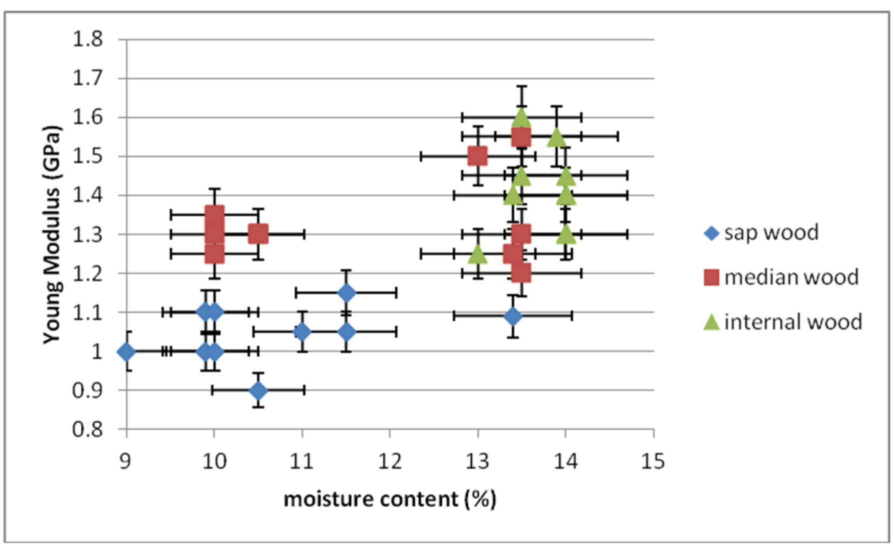

Fig. 7. Dynamic Young's modulus versus moisture content of *Gymnacranthera eugenifolia* wood in the sap, median, and internal wood regions

The dynamic Young's modulus was found to be linearly correlated to the radial distance, increasing with respect to the reduction in radial distance to the center of the wood. Tables 1 and 2 show the MC and dynamic Young's modulus (E_d) of *Sindora* sp. and *Gymnacranthera eugenifolia* along 3 radial directions, sap, median, and internal wood.

Table 1. MC and E_d of *Sindora* sp. along Sap, Median, and Internal Wood Regions

Sap wood		Median Wood		Internal wood	
MC	E_d	MC	E_d	MC	E_d
16.2	1	18	1.5	19.9	2.2
18	0.8	14.5	1.65	14.4	2.4
19.8	1.2	13.9	1.6	11.9	1.7
17.8	1	15.9	1.4	18	1.85
18.5	1.1	16	1.3	13.9	2.3
18.2	1	12.1	1.4	14	1.8
17.9	0.9	13.1	1.7	13.9	1.9
18.5	1.2	13.7	1.8	16.2	2.1
12	1	14.4	1.85	14.5	2.3
15.9	0.9	14	1.65	15.9	1.85

Table 2. MC and E_d of *Gymnacranthera eugenifolia* along Sap, Median, and Internal Wood Regions

Sap wood		Median Wood		Internal wood	
MC	E_d	MC	E_d	MC	E_d
9.9	1.1	13	1.5	13	1.25
10	1.1	13.5	1.55	13.5	1.6
11.5	1.15	13.4	1.25	13.4	1.4
9.9	1	10	1.35	14	1.4
9	1	13.5	1.2	14	1.45
13.4	1.09	10	1.25	14	1.4
10	1	10.5	1.3	13.5	1.45
11	1.05	10.5	1.3	13.9	1.55
10.5	0.9	10	1.3	14	1.3
11.5	1.05	13.5	1.3	14	1.3

CONCLUSIONS

1. Both wood species, *Sindora* sp. and *Gymnacranthera eugenifolia*, showed increasing E_d with respect to radial distance to the wood centre.
2. Determined from the free-free flexural vibration test, E_d had values from 0.8 to 2.4 GPa and 0.9 to 1.6 GPa for *Sindora* sp. and *Gymnacranthera eugenifolia*, respectively.
3. Moisture content in *Sindora* sp. displayed a broad range, from 12 to 20 wt. %, while *Gymnacranthera eugenifolia* displayed a narrower range, from 9 to 14 wt. %. *Sindora*

sp. had higher MC in the sap wood region than in the heartwood region, while *Gymnacranthera eugenifolia* showed the reverse.

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