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Smartphone-Based Non-Destructive Testing of Nigerian-Grown Ceiba pentandra Wood's Flexural Properties: A Low-Cost Alternative

Akıllı Telefon Tabanlı Tahribatsız Muayene Yaklaşımının Geliştirilmesi: Ahşabın Eğilme Özelliklerinin Tahmini için Düşük Maliyetli Bir Alternatif

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Abstract

Despite the wide exploration of non-destructive testing (NDT) methods their application to tropical species are underexplored; validating and expanding these methods for tropical woods is essential for accuracy and reliability. This study investigated the accuracy of two android applications (Sound Monitor FFTwave®, Version 1.9and Resonance Vibration Analysis® applications) and the effect of two test configurations (cantilever and simply supported) in predicting the flexural properties of *Ceiba pentandra,* a lightweight timber species, widely available in Nigeria, characterized by low density, thin cell walls, and high porosity, Transverse and longitudinal vibration techniques were employed. An apparatus was developed and used to simply support the wood samples. Samples were incited with a hammer and a smartphone was used to capture the resonant frequencies. The procedure was repeated in cantilever configuration with one end of sample clamped to a bench vice. A three-point static bending test was also conducted. Simple linear regressions were performed at 0.05 significance level to establish relationships and for calibrations between the static and dynamic flexural properties. Linear regression revealed moderate to strong positive correlations (0.5-0.79), with the Resonance Vibration Analysis® app surpassing in predicting static MOE in cantilever configuration. Similar trends were noted for static MOR prediction, confirming smartphone's potential for wood's flexural properties prediction. Potential for enhanced relationships exists through smartphone-enabled accelerometer integration to counter damping effects during vibration. The accuracy of this technique depends on the test configuration, end conditions, moisture content of lumber, and can be influenced negatively by vibrations and sounds from external sources.

Öz

Ahşap için Tahribatsız Muayene (NDT) alanındaki ilerlemelere rağmen, tropikal türler üzerine yapılan araştırmalar sınırlıdır; bu yöntemlerin tropikal ağaçlar için doğrulanması ve geliştirilmesi, doğruluk ve güvenilirlik açısından önemlidir. Bu çalışma, iki Android uygulamasının (Sound Monitor FFTwave® ve Resonance Vibration Analysis®) doğruluğunu ve iki deney düzeneğinin (ankastre ve basit mesnetli) etkisini, *Ceiba pentandra*'nın eğilme özelliklerinin tahmininde enine ve boyuna titreşim teknikleri kullanarak incelemiştir. Ahşap numunelerini basit mesnetli olarak desteklemek için bir düzenek geliştirilmiş ve kullanılmıştır. Numuneler bir çekiçle uyarılmış ve rezonans frekansları bir akıllı telefon ile kaydedilmiştir. Aynı işlem, numunenin bir ucunun mengeneye sabitlendiği ankastre düzende tekrarlanmıştır. Ayrıca üç noktalı statik eğilme deneyi yapılmıştır. Statik ve dinamik eğilme özellikleri arasındaki ilişkileri belirlemek ve kalibrasyon yapmak için %5 anlamlılık düzeyinde basit doğrusal regresyon analizleri gerçekleştirilmiştir. Doğrusal regresyon, orta ile güçlü arasında değişen pozitif korelasyonlar (0.5–0.79) göstermiş; Resonance Vibration Analysis® uygulaması, ankastre düzende statik MOE'nin tahmininde daha iyi performans sergilemiştir. Statik MOR tahmini için de benzer eğilimler gözlenmiş, bu da akıllı telefonların ahşabın eğilme özelliklerini tahmin etmedeki potansiyelini doğrulamıştır. Titreşim sırasında sönümleme etkilerini azaltmak için akıllı telefon tabanlı ivmeölçer entegrasyonu ile ilişkilerin daha da iyileştirilebileceği öngörülmektedir. Bu tekniğin doğruluğu, deney düzeneğine, uç koşullarına, kerestenin nem içeriğine bağlıdır ve dış kaynaklı titreşimler ile seslerden olumsuz etkilenebilir.

INTRODUCTION

Wood has been utilized by humanity for several applications, ranging from structural, functional and industrial to decorative uses, etc., making it one of the oldest and prevalent materials in human history. Precise wood mechanical property testing plays a vital role in determining its ability to meet structural requirements and for diverse other applications (Bucur, 2023). Traditionally, wood material testing is carried out using destructive methods. However, in recent years there has been advocacy for a transition to the use of Non-Destructive Test (NDT) techniques which offer the advantage of assessing a material's mechanical and physical properties without altering its end-use capabilities (Ross et al., 2023). NDT thus makes possible and facilitates in-situ performance evaluations and defect detection of wooden structural members.

Among the various NDT methods, acoustic methods, encompassing both sonic and ultrasonic methods, have emerged as particularly effective for measuring the Young's modulus of wood in standing trees, logs, lumber, and small-clear specimens (Wang, 2013; Gil-Moreno, 2018). The sonic technique involves propagating audible sound waves with frequencies typically falling within the range of 20 Hz to 20 kHz, while the ultrasonic methods involve using sound waves exceeding 20 kHz, making them imperceptible to the human ear (Tallavo et al., 2022). Acoustic techniques include vibration techniques, such as flexural, transverse, and longitudinal vibration tests, described in Cho (2007). Acoustic techniques do not only serve as alternative ways of predicting the stiffness of wood but has also been used to estimate other wood characteristics, including tracheid length, microfibril angle in the S2 layer, and chemical composition of cell walls to an extent (Chauhan & Aggarwal, 2011). All these methods, however, involve making contact with the specimen. Conversely, the non-contact NDT methods such as optical techniques, thermography, and electromagnetic testing do not require physical contact with the specimen (Tao et al., 2020). These non-contact methods offer distinct advantages in certain scenarios, as they enable inspection without direct interaction with the material, minimizing potential damage, providing increased accessibility to hard-to-reach areas, and eliminating the need for the processing test samples (Hassani & Dackermann, 2023).

The use of portable devices such as smartphones, although sparsely researched, has shown to be a promising advancement in non-destructive testing, proving relatively effective in estimating the flexural property of wood. França et al. (2020) and Seale et al. (2021), have contributed to the use of portable devices in estimating the flexural properties of wood. For instance, Seale et al. (2021) compared the use of BING and a newly developed smartphone application (Smart Thumper®) for predicting the elastic moduli of southern pine lumber. They found the Smart Thumper application reliable for frequencies below 2000 Hz, with strong correlations between resonant frequencies measured by both methods. Additionally, there were strong correlations between the elastic moduli obtained by both methods along the lumber length, although correlations were weaker across different cross sections (Seale et al., 2021). This indicates the influence of anisotropy of wood on the accuracy of the technique, suggesting potential limitations in application to orthotropic materials, especially across the grain, where speed of sound is less (Frampton, 2019), highlighting the need for further studies.

Studies utilizing artificial neural networks (ANN) and stress wave methods further highlight the potential of advanced technologies in enhancing wood property evaluation (Atuanya et al., 2014; Madhoushi & Boskabadi, 2019). Also, a number of studies have combined and/or compared destructive and non-destructive techniques to evaluate wood behaviour (Chiu et al., 2012; Butt et al., 2022). Fathi et al. (2020) highlight a crucial limitation of existing ultrasonic methods, which tend to overestimate wood's flexural properties. In response, they introduced a machine learning-based model utilizing guided Lamb wave propagation to predict flexural properties of wood with varying moisture content, achieving higher accuracy than traditional methods.

Despite advancements in non-destructive testing (NDT) for wood, research on tropical wood species remains limited, with most studies focusing on species exotic to Nigeria. Developing and validating NDT techniques specifically for tropical woods is crucial for ensuring that the methods are reliable and accurate across diverse wood types. This underscores the need for targeted investigations to enhance property assessments and support sustainable practices in wood products engineering.

This study presents the development and validation of a smartphone-based NDT approach designed to predict the Modulus of Elasticity (MOE) of wood. The primary objective was to assess the feasibility and accuracy of a smartphone-based NDT techniques in predicting wood flexural properties. The study probed into the possibility of harnessing the inbuilt hardware within smartphones and selected android applications to capture, analyse and determine the dynamic response of wood samples subjected to bending, establishing correlations with their static mechanical properties. This study endeavours to enhance the efficiency and accessibility of wood testing procedures within the timber industry by offering a cost-effective alternative to traditional NDT methods.

MATERIALS AND METHODS

Sample Collection and Preparation

The wood material used for this study was *Ceiba pentandra* popularly known by the Yorubas as *Àràbà*. The equipment used were: Electronic caliper (0.01 accuracy), Jinan Hensgrand Electronic Universal testing machine (WDW-50) - 50KN load capacity from China, kerro BL2001 Electronic compact scale (max load: 2000g, d = 0.1g), Samsung Galaxy A15 Android smartphone, VB-8206SD Vibration meter, fabricated apparatus (Figure 1) and a Wittime WT1039 electronic moisture meter.

The wood samples were obtained from Sango-Ota timber market, Ota, Ogun state, Nigeria. A log, free of defects, was selected and converted into 2 x 4 inches dimension lumbers, which were air-dried under a shed for three weeks until equilibrium moisture content was obtained. Three lumbers (from the outer sapwood, inner sapwood and heartwood) were carefully selected along the log height for processing into fifteen (15) samples, prepared to dimensions of 20 mm (Width) × 20 mm (Thickness) × 300 mm (Length) to ensure even distribution, making a total of 45 samples. This sample size was necessary for reliability of data. The moisture contents of the air-dried samples were determined as per ASTM D4442-16 (2016). The air-dry densities and specific gravities of the wood were determined in accordance with ASTM D2395-17 (2017) as shown in Equation 1.

$$\rho = \frac{M}{V} \quad (1)$$

Where: ρ is the density (kg/m^3), M is the mass of the wood sample (kg), and V is the volume of the wood (m^3).

NDT Test Procedures

The NDT techniques employed was developed, making reference to previous studies, but replacing NDT testing devices with a smartphone where necessary. In this study, a similar approach to that reported by Han et al. (2006). Yin et al. (2010) and França et al. (2015) was employed. However, a smartphone was used instead of transducers, accelerometers and microphones as reported in some of the aforementioned studies.

The first setup was similar to that of a simply supported beam (Figure 1). The samples were supported on a knife edge support at one end, and a roller support on the other end, which simulates the static bending strength test end conditions. As such, each piece was permitted to vibrate in an approximately unrestrained manner. The knife edge and roller support were padded with a damping material. An apparatus was fabricated for this purpose (Figure 1). The underlayment was made with a damping material to restrict sounds and vibration form external sources, such as the table on which it is placed, from interfering with the sounds and vibrations of the specimens. The apparatus had a slot in which a hammer could be fixed, which was free to fall from known heights. A protractor was situated at the slot which measures the angle at which the hammer was raised from which the height of fall (5cm).

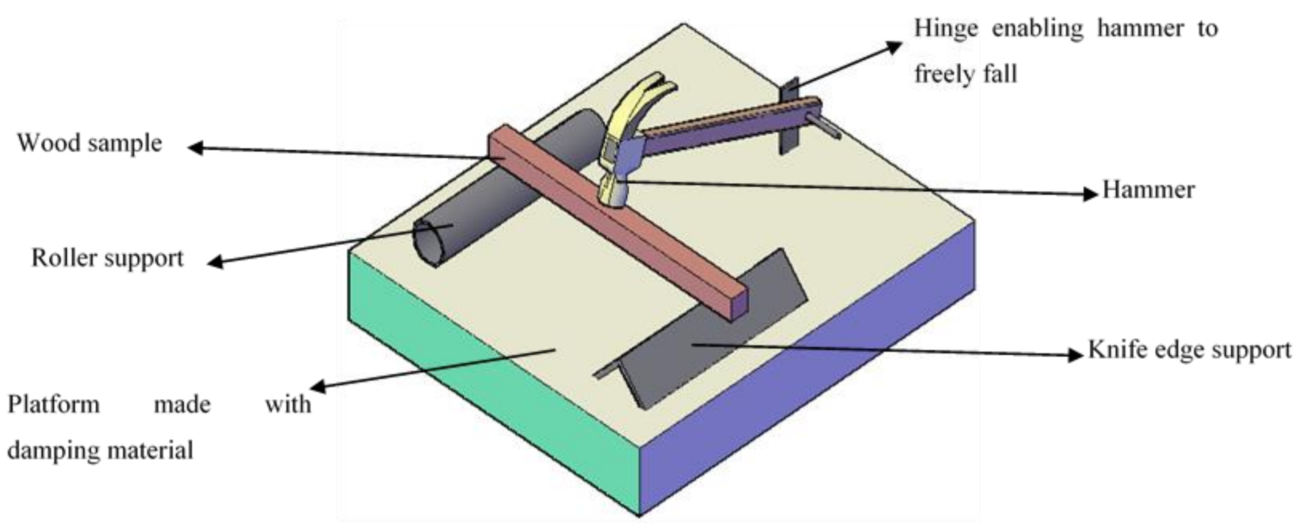


Figure 1. 3D model of fabricated apparatus

The second setup was in a cantilever configuration. The specimen was fixed at one end using a bench vice; the testing device (smartphone or vibration meter) was attached to the specimen using a rubber band. Then specimen was gently tapped five times at an interval of 15 seconds at the free end as shown in Plate 2. Samsung Galaxy A15 Android smart phone, enabled with Sound Monitor FFTwave®, version 1.9 and Resonance Vibration Analysis®, version 2.2.0 applications, which were downloaded from Google Play Store, was used as testing device in the experiment. The Sound Monitor FFTwave® app's spectrum analyser could detect sound frequencies ranging from 20Hz to 20KHz and perform Fast Fourier transformation (FFT) through which the resonant frequencies were detected. While the Resonance Vibration Analysis® app was used to measure the frequency (Hz) of vibration whenever the wood samples were incited with a hammer. Figures 2 and 3 are screenshots of the Sound Monitor FFTwave® and Resonance Vibration Analysis® apps respectively. Both applications were used to encompass complementary smartphone-based approaches due to their differing data acquisition methods. FFT Wave performs frequency analysis of acoustic signals (sounds) using Fast Fourier Transform, while the Resonance app measures the specimen's response via direct-contact vibration.

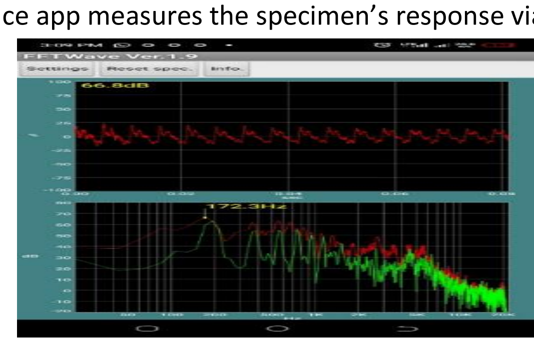


Figure 3. Sound Monitor FFTwave®, version 1.9

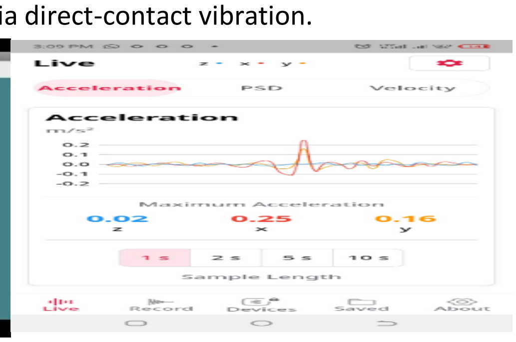


Figure 2. Resonance Vibration Analysis®, version 2.2.0

Vibration from external sources was not taken into consideration. However, all windows and doors were closed and fans were switched off and a calibration procedure was performed in the applications, prior to measurement to minimize the influence of ambient noise and ensure reliable signal acquisition.

Figures 4a and 4b show the Transverse vibration test setups procedure using the Sound Monitor FFTwave® app and the Resonance app respectively. As shown in the Plates 1a and 1b, transverse vibration test was carried out on the samples with the use of a fabricated apparatus and a smartphone. The specimens were incited by gently tapping around the center of the span (along the transverse direction) with a hammer as per ASTM E 1876 (2015). Resonance Vibration Analysis® app and was used to measure the resonant frequency from vibration (Hz). Sound Monitor FFTwave® app was used to measure the resonant frequency from sound (Hz). The resonant frequencies for the longitudinal vibration, carried out in cantilever configuration (Figure 5) were similarly captured using the Resonance Vibration Analysis® and Sound Monitor FFTwave® apps. During the test, special care was taken to ensure that the vibration was horizontal because vertical vibration had the potential to vibrate in an additional mode, which could have deviated the determined frequency.

The dynamic Modulus of Elasticity (E_L) was derived through the longitudinal vibration method (E_L) (Figure 3) was computed using Eqn. 2., as reported by Kumar et al. (2021).

The formula used to calculate the longitudinal Modulus of Elasticity (EL) is:

$$E_L = 4\rho L^2 \left(\frac{f_{L,n}}{n}\right)^2 \quad (2)$$

Where: E_L is the longitudinal Modulus of Elasticity; ρ is the density of the material $(\mathrm{kg/m^3})$; L is the length of the sample (m); $f_{L,n}$ is the n -th longitudinal mode frequency; n is the mode number.

Simplification for the First Mode $(n = 1)$

Since the application uses the first mode $(n = 1)$, the formula simplifies to:

$$E_L = 4\rho L^2 f_{L,1}^2 \quad (3)$$

The dynamic Modulus of Elasticity, derived through the transverse vibration method (E_T) was computed using Eqn. 4 (Ross et al., 2023)

$$E_T = \frac{f_r^2 \times W \times L^3}{2.46 \times I \times g} \quad (4)$$

where: E_T is the dynamic Modulus of Elasticity (GPa), F_r is the resonant frequency (Hz), W is the weight of the sample, (kg), L is the beam span (m), I is the moment of inertia (m^4), and g is the acceleration due to gravity (9.8 ms^{-2}).

For the longitudinal vibration, the dynamic Modulus of Elasticity, derived through the transverse vibration method (E_L) was computed using Eqn. 5 (Turk, 2008; Loh et al., 2022). From Euler–Bernoulli beam theory for a fixed–free (cantilever) beam:

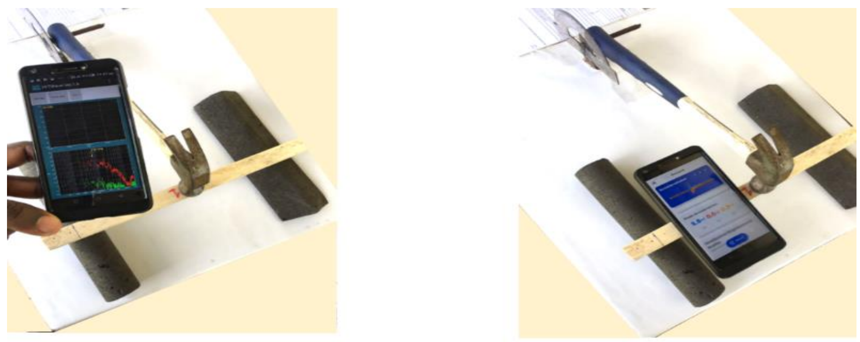
<u>*Natural frequency:*</u>

$$f_n = \frac{K_n}{2\pi}\sqrt{\frac{EI}{\rho A L^4}} \quad (5)$$

Rearranged for dynamic modulus:

$$E_d = \frac{\rho A L^4}{I}\left(\frac{2\pi f_n}{K_n}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ (6)}$$

Where: E_d = dynamic modulus of elasticity; f_n = natural frequency (Hz); K_n = mode constant (1.875^2 - 3.52 for 1st mode); L = free length (m); I = moment of inertia (m^4); A = cross-sectional area (m^2); ρ = density (kg/m^3)



(a) (b)

Figure 4. Transverse vibration setup using the FFTwave® app (a) and the Resonance app (b)

(a) (b)

Figure 5. Longitudinal vibration test (cantilever configuration)
(a) Using the resonance application, (b) Using the FFTwave application

Static Bending Test

The same samples used for the dynamic (non-destructive) tests were taken for flexural test on a universal testing machine. A 3-point bending test was conducted on a 50 kN Jinan Hensgrand Electronic Universal testing machine (WDW-50) at a loading rate of 0.11mm/sec from which the mechanical properties such as moduli of rupture (MOR) and elasticity (MOE) were evaluated (Figure 6). The clear wood samples were processed to 20 mm × 20 mm × 300 mm dimensions. All the specimens were subjected to a 3-point bending test until the limit of proportionality was reached. Unlike in the dynamic test, the static bending test was conducted using only a simply supported configuration; the cantilever configuration was not employed.

Figure 6. A sample undergoing flexural test in a UTM

The MOE and MOR were then estimated using Equation 5 and Equation 6 respectively, as per ASTM D4761-19.

$$MOE = \frac{P'L^3}{4\Delta' bd^3} \quad (5)$$

$$MOR = \frac{3PL}{2bd^2} \quad (6)$$

Where:

MOE is the modulus of elasticity (N/mm^2); P' is the load at the proportionality limit (N); *P* is the static bending maximum load; *L* is the length of the span (mm); Δ' is the centre deflection at the proportionality limit load (mm); *b* is the width of the sample (mm), and *d* is the thickness (depth) of the sample (mm).

The relationships between the static and dynamic Moduli of Elasticity (MOE) and the correlation between the static Modulus of Rupture (MOR) and dynamic MOE were analyzed. Linear regression analysis based on the Pearson correlation coefficient was used, with a significance level (α) of 0.05. Fitted regression models for each relationship were derived, and the coefficients of determination (R^2) were noted for each relationship. Also, other statistical tools including coefficient of variation (COV) were used to analyze and discus the data.

Statistical Analysis

To determine the relationship between static and dynamic MOE, static and dynamic values collected for the samples under study were used for linear regression analysis in excel, using a Equation 7:

$$Y=\beta_0+\beta_1 X+\epsilon \quad (7)$$

Where: Y represents the predicted value of Dynamic MOE; X represents the value of Static MOE; β_0 is the intercept; β_1 is the slope coefficient; ϵ represents the error term. The regression analysis was performed using Microsoft Excel, using a single-variable linear regression analysis (α = 0.05) technique. The coefficient of determination (R^2) was noted for each relationship.

RESULTS AND DISCUSSION

The mean values of the flexural property tests for both static and dynamic tests are summarized in Table 1. Generally, the margin between the static and dynamic test result Elastic Moduli was notably high, especially in the longitudinal vibration tests. The cantilever setup imposes specific boundary conditions on the wood specimen, with one end fixed and the other free.

Table 1. Evaluated properties

		Mean	Median	SD	Minimum	Maximum	COV (%)
MOE (Transverse Vibration) (N/mm²)	**Sound Monitor FFTwave®**	9819.84	9226.59	1792.68	8143.56	13143.58	18.26
	Resonance Vibration Analysis®	11602.77	17053.88	7115.42	2417.11	18082.99	61.33
MOE (Longitudinal Vibration) (N/mm²)	**Sound Monitor FFTwave®**	46.41	39.25	18.29	32.24	82.57	39.41
	Resonance Vibration Analysis®	611.70	49.58	734.21	21.23	1808.09	120.03
Static Tests	**MOE (N/mm²)**	1839.73	1791.64	230.63	1513.33	2217.08	12.54
	MOR (N/mm²)	27.85	27.62	2.98	23.84	32.34	10.69
Physical Properties	**MC (%)**	15.14	15.30	0.93	13.90	16.40	6.12
	Overall Density (kg/m³)	405.11	416.40	25.62	360.69	430.73	6.32
	Density (Sapwood) (kg/m³)	392.02	391.80	18.75	360.69	410.20	4.78
	Density (Heartwood) (kg/m³)	418.20	420.10	9.85	402.50	430.73	2.35

The static Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) of the specimens are consistent with values reported in previous studies. For instance, the MOE and MOR of *Ceiba pentandra* reported by Iyiola and Olufemi (2016), were 1694 N/mm² and 28.58 N/mm².

Although this configuration simulates certain real-world scenarios, it may not fully represent the actual conditions the wood experiences in its intended use. This disparity between testing and real-world conditions could affect the relevance and applicability of the results. The accuracy and reliability of measurements in a cantilever setup are highly sensitive to the experimental setup and conditions.

Variations in mounting techniques, loading procedures, and environmental factors can introduce variability and uncertainty into the results. Despite these challenges, the cantilever configuration remains a valuable tool for studying certain aspects of wood behaviour and characterizing its mechanical properties. However, researchers and practitioners should carefully consider the limitations and potential biases associated with this testing method and complement it with other approaches, such as bending tests with different boundary conditions, to obtain a comprehensive understanding of wood performance. However, the margin between static and dynamic result is not unusual because although dynamic Young's Moduli are sometimes close to static Young's Moduli, they have been reported to be significantly higher than static MOEs in a number of studies (Divos & Toshinari, 2005; Guan et al., 2015). In such cases, where the margin is wide, regression equations from the correlations between the static and dynamic Moduli of elasticity may be useful, as modification factors, to bridge the gap, especially when the correlation is strong. However, Fathi et al. (2020) who observed a similar trend inferred that the variation might have been as a result of possible infinitesimal internal stresses and deformations inflicted by static loading, especially during the MOR test which is more susceptible to such deformations. This could have made the results obtained from the three-point bending test lesser. Similarly, Görgün (2026) outlined that dynamic modulus of elasticity obtained from acoustic methods correlate better with static MOE than with static MOR, due to computation discrepancies arising from computation. The author noted that while MOR is based on the maximum (breaking) load and neglects deflection, MOE depends on load–deflection behaviour within the elastic region, which results in differing slope relationships in the load–deflection curve.

The coefficients of variation for the dynamic Modulus of Elasticity (MOE) were notably higher than those of the dynamic tests in certain observations. This was particularly evident in the longitudinal vibration test using the Resonance Vibration Analysis® method, as compared to the coefficients of variation for the static MOE. This variability could be attributed to factors such as the sensitivity of the accelerometer, sample heterogeneity or environmental influences.

Relationship Between Static and Dynamic MOE in Both Configurations

Figures 7 through 10 show the relationships between the static Young's Moduli and the dynamic Young's Moduli obtained using the mobile applications (Sound Monitor FFTwave® apps and Resonance Vibration Analysis®) in the simply supported and cantilever configurations, representing the transverse and longitudinal vibration techniques, respectively.

The correlation strengths were mostly moderate to relatively strong positive correlations (0.5-0.79), as indicated by the coefficient of determination (R^2), with the exception of the correlation between the dynamic MOE predicted using the Sound Monitor FFTwave® app in the transverse vibration configuration (simply supported) and the static MOE, which was only relatively weak ($R^2 = 0.47$). This demonstrates that the resonance app in cantilever form (longitudinal vibration) was the best predictor of the static MOE. The resonance app works by vibration while the Sound Monitor FFTwave® works by analysing sound, processing the resonant frequency via a Fast Fourier transform.

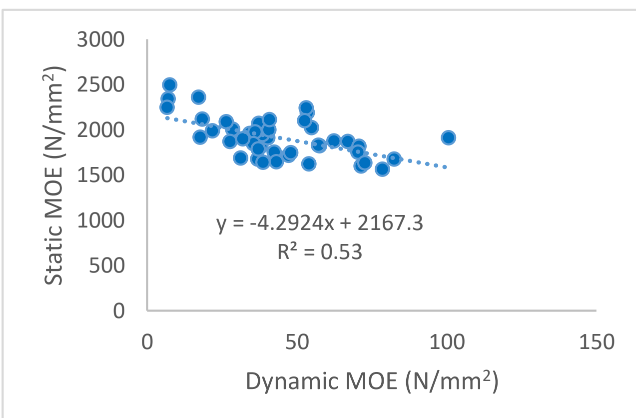


Figure 8. FFTwave app in longitudinal vibration

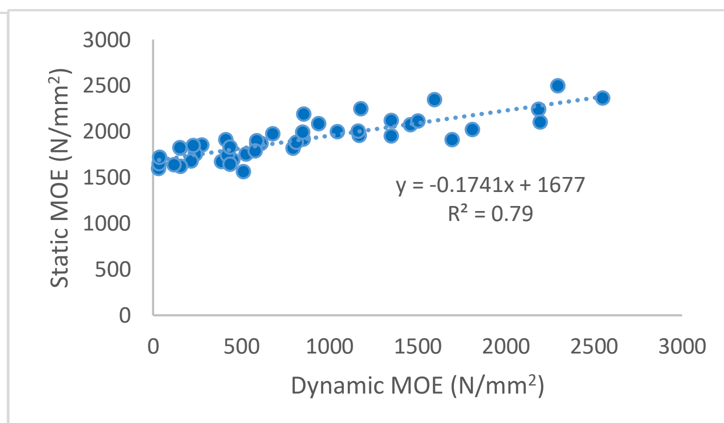


Figure 7. Resonance app in longitudinal vibration

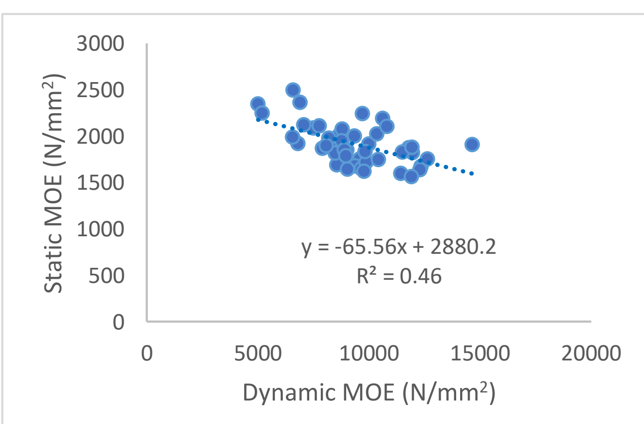


Figure 10. FFTwave app in transverse vibration

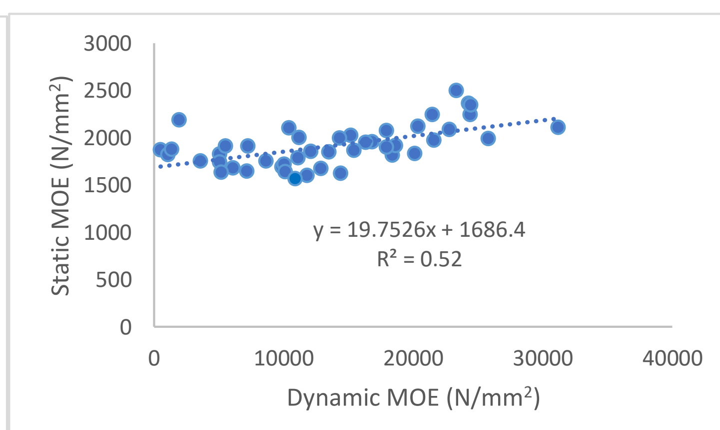


Figure 9. Resonance app in transverse vibration

Relationship Between Dynamic MOE and Static MOR

Figures 11–14 show the visual representation of the relationships between dynamic Young's moduli and static MOR.The R^2 indicated that the prediction strength ranged from moderate to relatively strong positive associations (0.51 - 0.83). The Resonance app stood out in predicting the the static Modulus of Rupture (MOR) from the dynamic Modulus of Elasticity with an R^2 of 0.79. This association was most evident when the resonance app was used in the cantilever configuration, which represents longitudinal vibration. This highlights the Resonance app's ability to provide good estimates of the static Modulus of Rupture when used in that configuration. It may even be possible to get stronger relationships between static and dynamic MOE using the Resonance app if by possibly manufacturing external accelerometers that work with smartphones, because placing the smartphone directly on the wood sample may have caused significant damping of the wood's vibration.

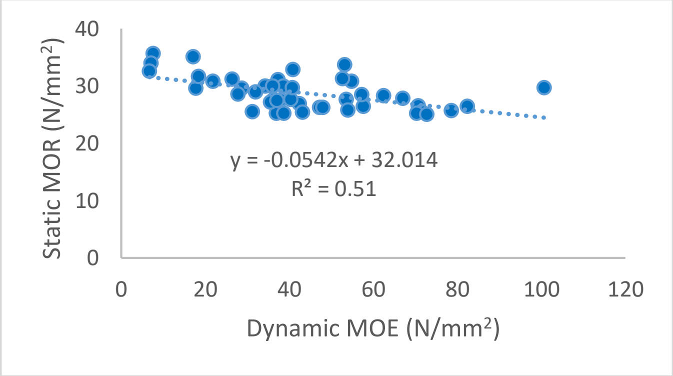


Figure 11. Resonance app in longitudinal vibration

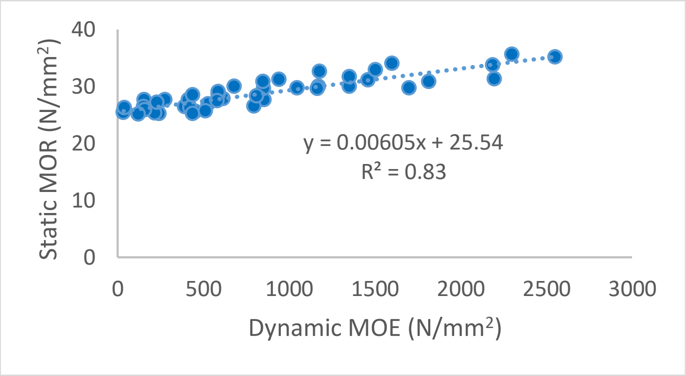


Figure12. FFTwave app in longitudinal vibration

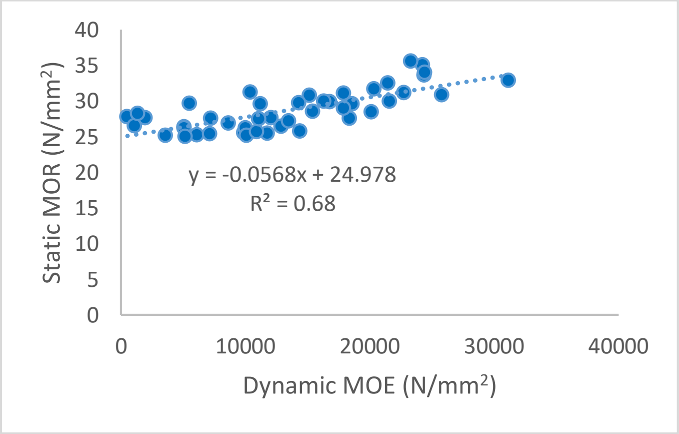


Figure 133. Resonance app in transverse vibration

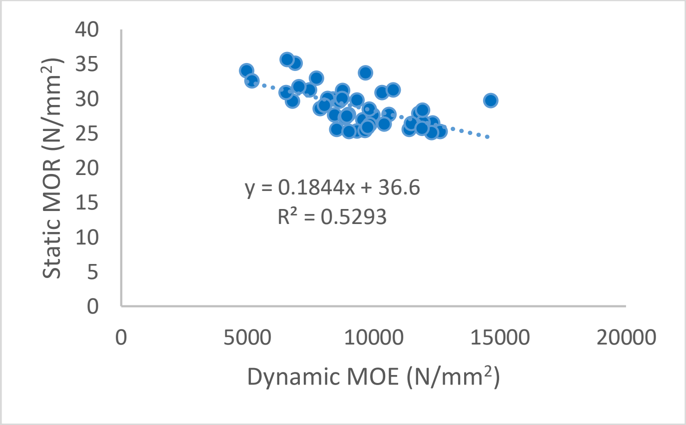


Figure 14. FFTwave app in transverse vibration

CONCLUSIONS

The following conclusions were drawn from the study:

The in-built accelerometers in smartphones are able to capture longitudinal vibration and may hold great potentials for stress grading of timber. Hence, smartphones may be used to collect useful data that may be useful for identifying very wood stick or very strong ones. However, the test configuration, end conditions and moisture contents in the wood lumen are major determining factors with respect to the accuracy of this technique. Although vibrations from external sources were not taken into consideration in this study, resonant frequency measured from vibration using Resonance Vibration

Analysis® app in the cantilever configuration via longitudinal vibration yielded the best association with static flexural properties compared to those measured from sound using the Sound Monitor FFTwave® app.

With the availability and affordability of smartphones, it can become an affordable NDT tool and can help in reducing the cost of wood material property evaluation. However, it is expedient to evaluate the potency of this approach across other density ranges. Also, further studies should focus on improving the test procedure and experimenting on large size lumber as well as conducting anatomical studies of the wood. Following a large number of observations for tropical woods, mobile apps should be developed based on algorithms derived from the experimental and analytical procedures.

REFERENCES

ASTM E 1876. (2015). *Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration*. ASTM, West Conshohoken. PA.

ASTM D4442-16. (2016). *Standard test methods for direct moisture content measurement of wood and wood-based materials*. ASTM International, West Conshohocken, PA, USA.

ASTM D2395-17. (2017). *Standard test methods for density and specific gravity (relative density) of wood and wood-based material.* ASTM International, West Conshohocken, PA, USA.

ASTM D4761-19. (2019) *Standard Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Materials.* ASTM International, West Conshohocken, PA.

Atuanya, C., Nwobi-Okoye, C., & Onukwuli, O. (2014). Predicting the mechanical properties of date palm wood fibre-recycled low density polyethylene composite using artificial neural network. *International Journal of Mechanical and Materials Engineering, 9*(1). https://doi.org/10.1186/s40712-014-0007-6

Bucur, V. (2023). A review on acoustics of wood as a tool for quality assessment. *Forests*, 14(8), 1545. https://doi.org/10.3390/f14081545

Butt, J., Bhaskar, R., & Mohaghegh, V. (2022). Non-destructive and destructive testing to analyse the effects of processing parameters on the tensile and flexural properties of fff-printed graphene-enhanced pla. *Journal of Composites Science, 6*(5), 148. https://doi.org/10.3390/jcs6050148

Chauhan, S.S., & Aggarwal, P. (2011). Segregation of Eucalyptus tereticornis sm. clones for properties relevant to solid wood products. Annals of Forest Science, 68, 511-521. https://doi.org/10.1007/s13595-011-0053-7

Chiu, C., Lin, C., & Yang, T. (2012). Application of nondestructive methods to evaluate mechanical properties of 32-year-old taiwan incense cedar *(Calocedrus formosana*) wood. *Bioresources,* 8(1). https://doi.org/10.15376/biores.8.1.688-700

Cho, C.L. (2007). Comparison of three methods for determining young. *Taiwan Forestry Science*, 22 (3), 297-306. ws.tfri.gov.tw/001/Upload/OldFile/files/07-96-22.pdf

Divos, F., & Toshinari, T. (2005). Relation between static and dynamic modulus of elasticity of wood= Kapcsolat a faanyag statikus és dinamikus rugalmassági modulusza között. *Acta Silvatica et Lignaria Hungarica*, *2005*(1), 105-110.

Fathi, H., Nasir, V., & Kazemirad, S. (2020). Prediction of the mechanical properties of wood using guided wave propagation and machine learning. *Construction and Building Materials*, 262, 120848. https://doi.org/10.1016/j.conbuildmat.2020.120848

Frampton, M.J. (2019). *Acoustic studies for the non-destructive testing of wood* (Doctoral dissertation, University of Canterbury). University of Canterbury. https://ir.canterbury.ac.nz/bitstreams/36cd83da-f338-47b9-b19e-17a040a6927b/download

França, F.J.N., Seale, R.D., Franca, T.S.F.A., & Shmulsky, R. (2015). Assessing southern pine 2× 4 lumber quality use a portable device. In *Proceedings of the 19th International Nondestructive Testing and Evaluation of Wood Symposium, Rio de Janeiro, Brazil* (pp. 22-25).

França, F.J.N., França, T.S.F.A., Seale, R.D., & Shmulsky, R. (2020). Nondestructive evaluation of 2 by 8 and 2 by 10 southern pine dimensional lumber. *Forest Products Journal*, *70*(1), 79-87. https://doi.org/10.13073/FPJ-D-19-00051

Gil-Moreno, D. (2018). Potential of noble fir, Norway spruce, western red cedar and western hemlock grown for timber production in Great Britain. Extended abstract. *International Wood Products Journal*, *9*(4), 200-200. https://doi.org/10.1080/20426445.2018.1546283

Görgün, H.V. (2026). Predicting flexural properties of thermo–vacuum-treated wood using non-destructive tests. *Applied Sciences*, *16*(6), 3030. https://doi.org/10.1080/20426445.2018.1546283

Guan, C., Zhang, H., Zhou, L., & Wang, X. (2015). Dynamic determination of modulus of elasticity of full-size wood composite panels using a vibration method. *Construction and Building Materials*, *100*, 201-206. https://doi.org/10.1016/j.conbuildmat.2015.10.008

Han, G., Wu, Q., & Wang, X. (2006). Stress-wave velocity of wood-based panels: effect of moisture, product type, and material direction. *Forest Products Journal. (Jan. 2006)* 56(1), 28-33.

Hassani, S., & Dackermann, U. (2023). A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. *Sensors*, *23*(4), 2204. https://doi.org/10.3390/s23042204

Iyiola, E.A., & Olufemi, B. (2016). Physical and mechanical properties of torrefied Ceiba pentandra wood. *Pro Ligno*, *12*(3).

Kumar, C., Redman, A., Leggate, W., McGavin, R.L., & Dakin, T. (2021). Assessment of the application of a SMART THUMPER™ as a low-cost and portable device used for stiffness estimation of timber products. *BioResources*, *16*(3), 5838-5861.

Loh, T.B., Wu, Y., Goh, S.H., Kong, K.H., Goh, K.L., & Chong, J.J. (2022). An integrated approach for the determination of young's modulus of a cantilever beam using finite element analysis and the digital image correlation (DIC) technique.

Electronics, 11(18), 2826. https://doi.org/10.3390/electronics11182826

Madhoushi, M., & Boskabadi, Z. (2019). Relationship between the dynamic and static modulus of elasticity in standing trees and sawn lumbers of paulownia fortune planted in Iran. *Maderas Ciencia Y Tecnología, 21*(4), 461-470. https://doi.org/10.4067/s0718-221x2019005000104

Ross, R.J., Wang, X., & Senalik, C.A. (2023). Nondestructive evaluation of wood products. In *Springer Handbook of Wood Science and Technology* (pp. 991-1017). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-81315-4_19

Seale, R.D., Shmulsky, R., & Jose Nistal França, F. (2021). Non-destructive lumber and engineered pine products research in the Gulf South US 2005–2020. *Forests, 12*(1), 91. https://doi.org/10.3390/f12010091

Tallavo, F.J., Pandey, M.D., Cascante, G., & Lara, C.A. (2022). Ultrasonic and acoustic pulse velocity methods for nondestructive detection of early decay in wood poles. *Canadian Journal of Civil Engineering*, *49*(6), 1059-1068. https://doi.org/10.1139/cjce-2020-0658

Tao, Y.H., Fitzgerald, A.J., & Wallace, V.P. (2020). Non-contact, non-destructive testing in various industrial sectors with terahertz technology. *Sensors*, *20*(3), 712. https://doi.org/10.3390/s20030712

Turk, C. (2008). *Cantilever-beam dynamic modulus for wood composite products: apparatus* (Vol. 308). US Department of Agriculture, Forest Service, Forest Products Laboratory.

Wang, X. (2013). Stress wave e-rating of structural timber—Size and moisture content effects. *In: USDA Forest Service, Forest Products Laboratory, General Technical Report, FPL-GTR-226 226*: 38-46. https://research.fs.usda.gov/download/treesearch/46413.pdf

Yin, Y., Nagao, H., Liu, X., & Nakai, T. (2010). Mechanical properties assessment of Cunninghamia lanceolata plantation wood with three acoustic-based non-destructive methods. *Journal of Wood Science*, *56*(1), 33-40. https://doi.org/10.1007/s10086-009-1067-8