Assessment of the Application of a SMART THUMPER™ as a Low-cost and Portable Device Used for Stiffness Estimation of Timber Products

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Non-destructive evaluation methods for timber stiffness are gaining increased interest as an alternative to static testing since they can be fast, cost-effective, and transportable, as well as non-destructive. The objective of this study was to evaluate the accuracy and limitations of a newly developed smartphone application (SMART THUMPER™) for the non-destructive evaluation of timber stiffness properties. The study determined the effect of the length, density (species), and cross-section sizes of the timber samples on the stiffness results. The results were compared to beam identification by non-destructive grading (BING©), an existing commercial non-destructive testing technology for evaluating the mechanical quality of wood and other materials. It was found that the application can be used to reliably estimate the stiffness of various timber products with a resonance frequency value below 2000 Hz. Frequencies greater than 2000 Hz were found to induce errors due to the smartphone microphone, which is engineered to acquire a lower frequency range. A reliability matrix providing an indication of the accuracy of SMART THUMPER™ estimation was presented, which may also prove useful in selecting appropriate sample lengths prior to testing. The sample length or dimensions can be manipulated to lower the frequency, and hence, to improve the results.

Keywords: Non-destructive evaluation; Dynamic MOE; Timber products; Acoustic measurement; Stiffness estimation

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INTRODUCTION

The modulus of elasticity (MOE), *i.e.*, stiffness, is one of the most important mechanical properties of wood. Along with governing its serviceability performance when used in a structure, the MOE is also a key parameter in determining the structural grade of timber (Kumar *et al.* 2021). Whilst minimum strength properties are also required for different grades of timber, these are typically accounted for during processing through established correlations with MOE for the species in question, or through visual identification and exclusion for large, discrete defects. The market value of a structural sawn board is directly linked to its structural grade.

The standard test method to determine the MOE of timber in Australia is the static bending test, according to AS/NZS standard 4063.1 (2010). Predicting the MOE of timber has become a crucial issue in the operational value chain and received considerable attention in recent years in terms of grading and presorting (Brashaw *et al.* 2009; Aro *et al.*

2016; Nistal França *et al.* 2019). However, non-destructive techniques (NDT) to characterise wood and other materials are gaining popularity due to being non-destructive, comparatively faster, and not necessarily confined to a laboratory (Faircloth *et al.* 2021). Assessment of mechnical properties using vibration and other NDTs have a long history in the wood products industry (Hearmon 1946, 1958; James 1961; Falk *et al.* 1990; Halabe *et al.* 1997). Ross *et al.* (1998) described a wide range of non-destructive assessment technologies and their use for evaluating various wood products. Of the available technologies, ultrasound, transverse vibration, longitudinal vibration, X-ray, and stress wave have been well investigated and have been adopted by industries in various scales (Simpson and Wang 2001; Yang *et al.* 2002; Brashaw *et al.* 2009; Nistal França *et al.* 2019). Some other methods involve radiography, impulse excitation technique, electromagnetic testing, near infrared, and magnetic resonance (Baillères *et al.* 2009). Schimleck *et al.* (2002) calibrated near-infrared (NIR) to characterise a number of physical properties including density, MOE, micro fibril angle, and modulus of rupture (MOR) on small clear samples of *Eucalyptus delegatensis* and *Pinus radiata.* The MOE and density are the main parameters that describe the wave propagation in materials. Therefore, the MOE can be calculated by using the stress wave velocity measurement (Steiger 1996; Bucur 2003; Baillères *et al.* 2009). Some commercial NTD methods such as Hitman ST300 (Fibre-gen, Christchurch, New Zealand), Metriguard 7200 High Capacity Lumber Tester (HCLT, Metriguard Inc., Pullman, WA), E-computer Model 340 (Metriguard Inc.), portable Timber Grader MTG (Brookhuis Micro-Electronics), portable Lumber Grader PLG (Fakopp, Sopron, Hungary), and STIG grading machine (Slovenia) are already available for measuring mechanical properties of timber (Baltrušaitis *et al.* 2009; Baillères *et al.* 2012; Paradis *et al.* 2013; Yang *et al.* 2015; Fortuna *et al.* 2018; Llana *et al.* 2020). However, the most convenient method for measuring MOE non-destructively with high precision is the vibration method by measuring natural frequencies in different modes (longitudinal, flexion, or torsional) and the geometry and boundary conditions (Brancheriau and Baillères 2002; Arriaga *et al.* 2014).

Beam identification by non-destructive grading (BING©) is one such commercial, non-destructive testing technology developed by the agricultural research for development, France (CIRAD) for evaluating the mechanical quality of wood and other materials (Paradis *et al.* 2017). In addition, BING© allows for the determination of bending (transverse) and compression (longitudinal) MOE of a timber beam *via* analysis of the natural vibration spectrum. This technique is also known as the resonance method, as it allows the determination of the resonance frequencies of a beam from its response to an impact (Baillères *et al.* 2009). Furthermore, BING© can provide a good estimation (R^2 = 0.91) of the mechanical properties of a timber when compared with the standard static bending test (Baillères *et al.* 2019). However, the BING© system requires relatively expensive and complicated hardware and software, and a computer, thus limiting is portability.

A newly developed smartphone application called SMART THUMPER™ aims to provide a low-cost and effective alternative for the dynamic measurement of the stiffness of timber. The application was developed by Mississippi State University's Department of Sustainable Bioproducts (Timberbiz 2019). Since it is a smartphone application, this approach has the potential to be an easy-to-use, low-cost, and portable means of obtaining indicative stiffness properties of timber, which will make it readily available to a wider community (Timberbiz 2019).

The SMART THUMPER™ application uses a well-established and published relationship to calculate the MOE in the longitudinal direction from natural frequencies of soundwave, density, and dimension of the sample expressed as Eq. 1,

$$E_L = 4\rho L^2 (f_{L,n}/n)^2 \tag{1}$$

where ρ is the density (kg/m^3), L is the length (m), $f_{L,n}$ is the n^{th} longitudinal mode frequency, and n refers to the mode number (1, 2, 3, *etc.*). The application uses the first mode, *i.e.*, $n = 1$. The application calculates density based on the mass and dimension input by user.

However, the feasibility, accuracy, and limitations of the SMART THUMPER™ application in terms of measuring the indicative stiffness of timber needs to be identified and understood for different timber species and sample conditions to support wider adoption. The objective of this study was to conduct a detailed analysis of the accuracy and limitations of the SMART THUMPER™ application, which included the effects of the sample length, density (species), and cross-section size on the results.

EXPERIMENTAL

The experimental plan is summarized in Table 1. Prior to testing, all samples were stored in a conditioning chamber set to a temperature of 20 °C and a relative humidity of 65% until the equilibrium moisture content was reached. The samples were then tested using the SMART THUMPER™ and the BING© system, respectively. The test results were compared using the data analysis method described below. The stiffness results estimated for the same samples of wood using BING© were adopted as a baseline. The Pearson correlations and coefficients of variation (COV) between the stiffness values estimated *via* BING© and SMART THUMPER™ systems were presented for various species (density), board lengths, and cross-section sizes of the tested timber samples.

Trials 1 to 6 were conducted using 4 different short length sawn timber boards (4 hardwoods and 1 softwood), and a section of softwood plywood representing an engineered wood product (EWP), to investigate the effect of density (species) and sample length. The hardwoods assessed were mature native forest spotted gum (*Corymbia citriodora*), blackbutt (*Eucalyptus pilularis* Sm), jarrah (*Eucalyptus marginata* D. Don ex Sm.), and messmate (*Eucalyptus obliqua* L'Herit.). The softwood was a southern pine, which is the dominant plantation softwood growing in Queensland, which is typically *Pinus elliottii* (PEE), *Pinus caribaea* (PCH), or a hybrid between these two species (PEE) X (PCH). All samples in trial 1 to 6 were cut to a length of 1.2 m, machined to a cross-section as specified in Table 1, and numbered for identification. The MOE estimations were collected at a length of 1.2 m, with the samples then iteratively docked to 1.1 m, 1.0 m, and 0.8 m, and tested at each decrement.

Trial 7 further investigated the sensitivity of the stiffness results for long length boards. Five softwood boards were used, and the lengths were progressively reduced (4.8 m, 4.5 m, 4.2 m, 3.7 m, 3.2 m, 2.7 m, 2.2 m, 1.7 m, and 1.2 m) and the MOE was estimated at each length decrement. Similar tests were completed on 5 hardwood boards for 5 different lengths (4.8 m, 4.2 m, 3.2 m, 2.2 m, 1.2 m).

Trial 8 was similar to Trial 7, *i.e.*, longer softwood pine; however, it included 5 long length sawn hardwood (spotted gum) boards tested at various lengths (4.8 m, 4.2 m, 3.2 m, 2.2 m, and 1.2 m).

Table 1. Experimental Plan and Sample Description

Trial No.	Test Objective	Sample		Length (m)*	Average Air-Dry Density (kg/m³)***	Cross Section (mm x mm)**	Number of Samples
1	Effect of density (species) and short lengths	Sawn hardwood	Spotted gum	1.2, 1.1, 1.0, 0.8	1124	80 x 18	40
2			Blackbutt	1.2, 1.1, 1.0, 0.8	938	80 x 18	40
3			Jarrah	1.2, 1.1, 1.0, 0.8	902	80 x 18	40
4			Messmate	1.2, 1.1, 1.0, 0.8	706	80 x 18	40
5		Sawn softwood	Southern pine	1.2, 1.1, 1.0, 0.8	683	88 x 35	40
6		Softwood plywood	Plywood	1.2, 1.1, 1.0, 0.8	516	80 x 18	40
7	Effect of long lengths	Sawn softwood	Pine	4.8, 4.5, 4.2, 3.7, 3.2, 2.7,2.2, 1.7,1.2	667	88 x 35	5
8		Sawn hardwood	Spotted gum	4.8, 4.2, 3.2, 2.2, 1.2	1142	95 x 19	5
9	Veneer	Softwood rotary veneer	Southern pine	1.0	596	3 x 100	40
10	Effect of cross-section sizes	Sawn softwood	Southern pine	1.2	667	88 x 35, 88 x 30, 80 x 30, 80 x 25, 80 x 20	5

* Multiple values indicate that the length of all individual boards were reduced and tested at each decrement.

** Multiple values indicate that the cross section of all individual boards were reduced and tested at each decrement.

***average air-dry density was calculated by the air dry mass/air dry volume

Trial 9 investigated the applicability of the application on veneer. Forty southern pine rotary veneer samples measuring 3 mm thick by 100 mm wide and 1 m long were tested.

Trial 10 investigated the effect of different cross-section sizes. Southern pine sawn boards of a constant length (1.2 m) and reducing cross-section sizes (88 mm x 35 mm, 88 mm x 30 mm, 80 mm x 30 mm, 80 mm x 25 mm, and 80 mm x 20 mm) were tested.

BING© Testing

The BING© system consists of a microphone, an acquisition card (Pico Technology), two elastic supports, and a hand-held hammer (Fig. 1). The dimensions and mass of the samples were measured with digital callipers and a weight scale, respectively. The sample was placed on the two elastic supports to ensure free vibration, before an impulse was generated by hitting one end of the sample with the hammer, and the acoustic sensor (Sennheiser K6) recorded the induced vibrations at the other end. The BING© software allowed the automatic detection of resonance frequencies and the computation of the results. The samples were tested using the compression (longitudinal) mode.

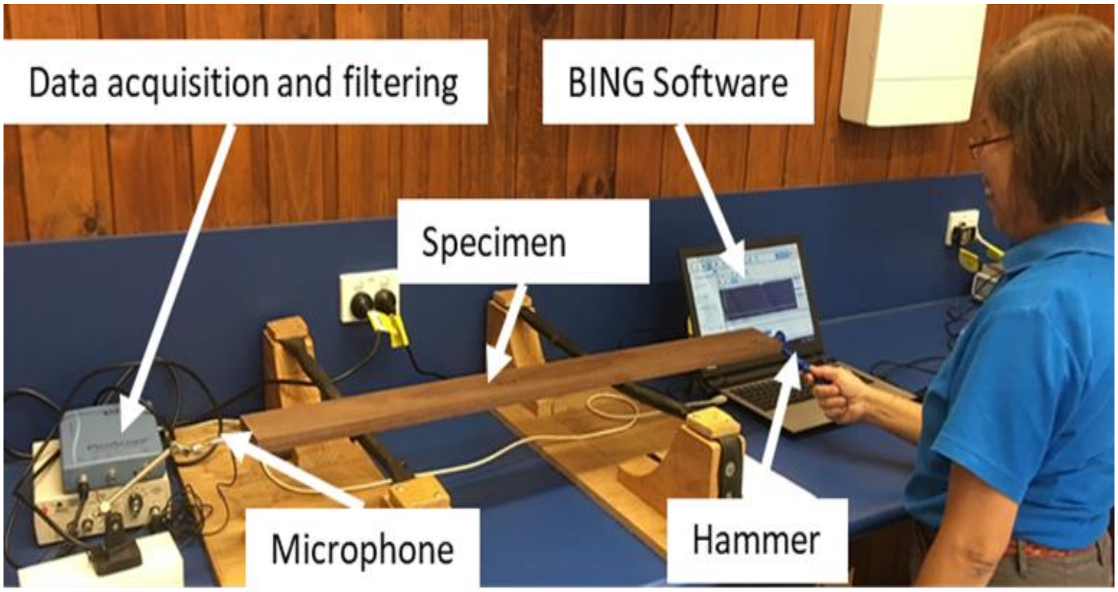

Fig. 1. The BING© test configuration for measuring the stiffness of a timber board

SMART THUMPER™ Testing

As the SMART THUMPER™ uses the same principles as BING©, the test configuration was similar (Fig. 2).

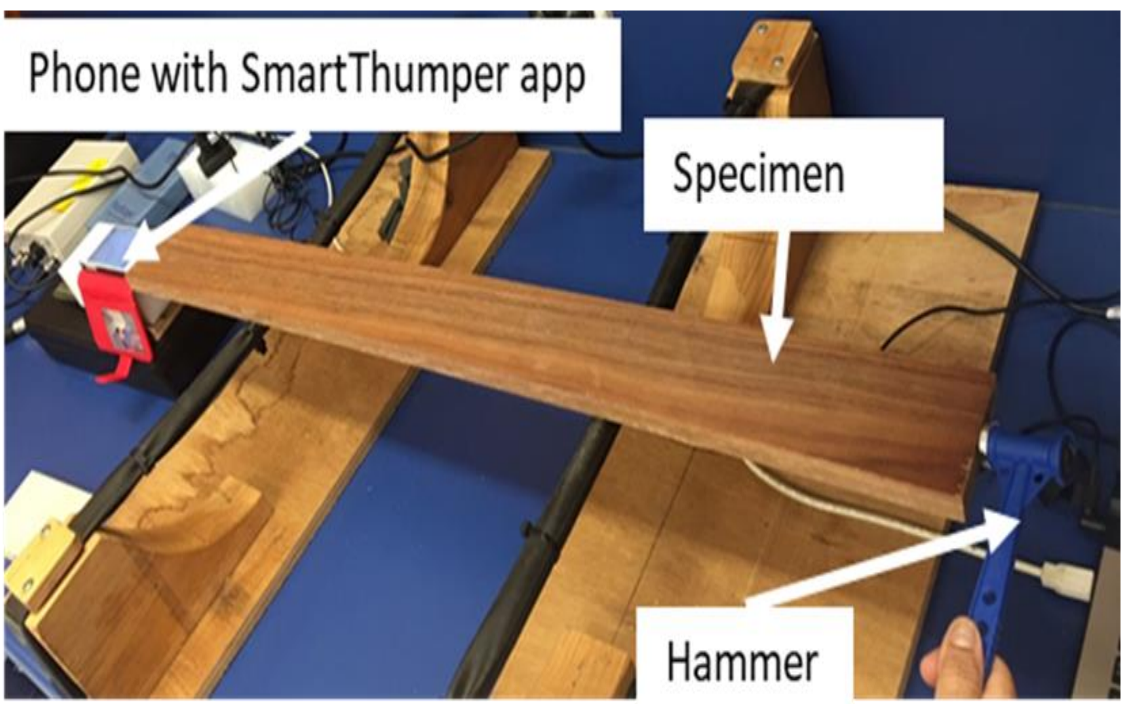

Fig. 2. Test configuration for the SMART THUMPER™ application

The specimen was placed on two elastic bands, equidistance apart, and hit with a small hammer on one end. A smartphone (iPhone 5s) with the SMART THUMPER™ application was placed with its microphone directed toward the opposite end of the sample. The specimen number, species, dimensions, and weight of the sample were entered into the SMART THUMPER™ application. Once struck by the hammer, the MOE and resonance frequency of the sample were calculated and displayed by the application. The testing was performed using the soundwave test (longitudinal) option on the app.

Data Analysis Method

Correlation matrix

The correlation matrices between the MOE values collected from the *SMART THUMPER™* application and the BING© system were calculated using R-studio (R-Studio, Boston, MA), an integrated development environment for R. The correlation matrices were developed using the 'psych' package in R-studio (Cran.R-project 2019). The correlation matrices showed the bivariate scatter plots below the diagonal, histograms on the diagonal, and the Pearson correlation above the diagonal.

Coefficient of variations (COV)

The coefficient of variation (COV), or relative standard deviation (RSD), is a dispersion of data points in a data series around the mean. It is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from one another. In this study, the COVs were calculated between the MOE of the same specimens for various lengths or cross-sections measured *via* BING© and SMART THUMPER™ systems. The coefficient of variations (COVs) were calculated by the ratio of the standard deviation to the mean using an Excel spreadsheet (version 2016, Microsoft, Redmond, WA).

Linear regression

The linear regression analyses were conducted between the variables obtained from BING© and SMART THUMPER™ using Microsoft Excel. The regression analyses were evaluated by their coefficient of determination, *i.e.*, R^2, and slope of the regression line.

RESULTS AND DISCUSSION

Effect of Density

The effect of density on MOE estimated by the SMARTTHUMPER™ app was investigated on the 1.2 m length of 4 hardwoods and 1 softwood samples (test 1 to 5) as shown in Table 1. The density of these samples varies between 539 kg/m^3 to 1242 kg/m^3.

Figure 3 shows a strong positive correlation (R^2=0.97) between BING© and SMART THUMPER™ MOEs, indicating that the SMART THUMPER™ application can estimate the MOE of timber with various densities. The application measures frequency and then calculates the MOE from the frequency and density according to Eq. 1. The density in the app is calculated from the input data of mass and dimension input data provided by users. Therefore, the density was not expected to affect the final MOE estimation by the applications if the frequency measurement was correct. More detail of frequency measurement by the app at various timber densities is discussed in the next section.

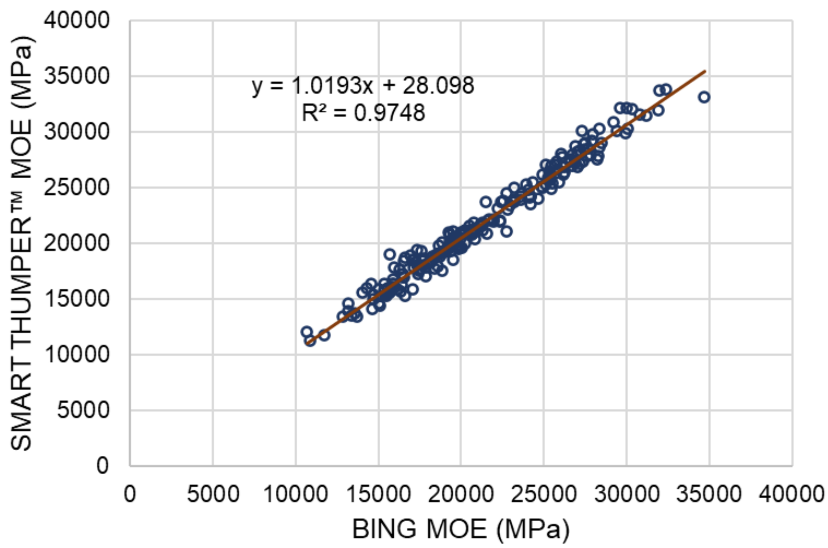

Fig. 3. Correlation between the BING© and SMART THUMPER™ MOEs of timber with various densities

Effect of Board Length

This section discusses the effect of length on MOE estimation by the SMART THUMPER™ as described in Table 1. The investigations included hardwood, softwood and plywood of various shorter lengths (0.8 m to 1.2 m) and longer lengths hardwoods and softwoods.

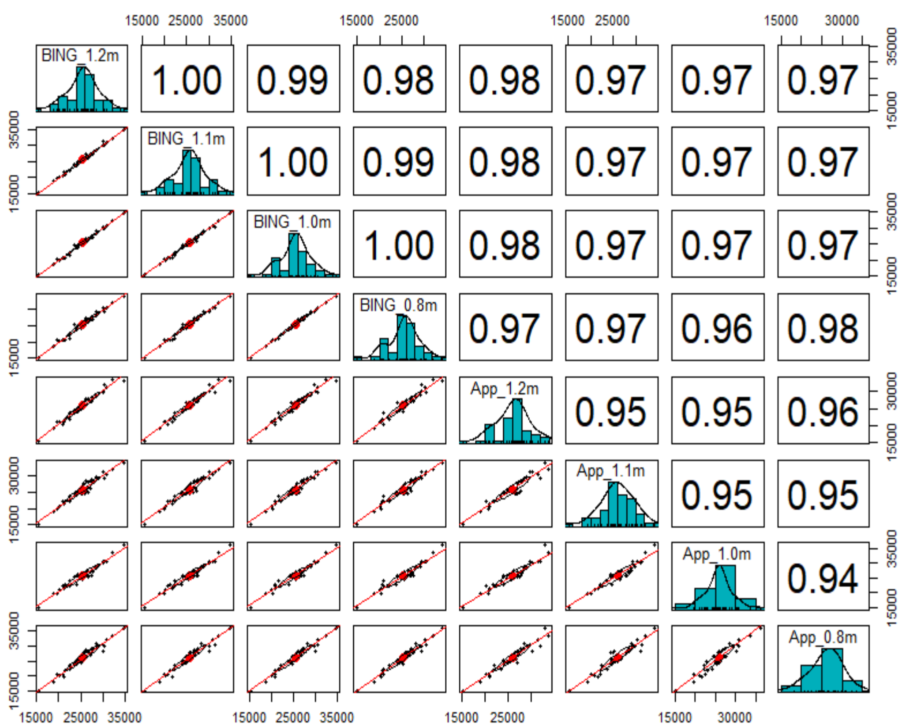

Fig. 4. Correlation matrix between the BING© and SMART THUMPER™ MOEs in MPa showing the Pearson correlation, histogram, and scatterplot with linear model for sawn blackbutt timber

Blackbutt (Trial 2)

Figure 4 shows the scatter plots below the diagonal along with the linear fit line, the histograms on the diagonal, and the Pearson correlation above the diagonal between the MOE estimated *via* BING© and the SMART THUMPER™ app at different lengths for sawn blackbutt timber. Overall, a strong correlation exists among the BING© results (r = 0.98 to 1.00), between the BING© vs the SMART THUMPER™ results (r = 0.96 to 0.98), and among the SMART THUMPER™ results (r = 0.94 to 0.96) for the various lengths tested. The scatter plots and linear regression line below the histograms show positive correlations without outliers.

The mean COVs for the 30 sawn blackbutt samples were 1.03% and 3.20% for BING© and SMART THUMPER™, respectively, which indicated that the SMART THUMPER™ had greater variation in MOE estimation of a single sample measured at different lengths (Table 2).

Table 2. COV Values of the BING© and SMART THUMPER™ MOEs for the Sawn Blackbutt Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	3.31	5.62
Minimum	0.06	0.96
Average	1.03	3.20

The histograms for the SMART THUMPER™ app data (as shown in Fig. 4) show fewer group segregations, classes, or bins in terms of the MOE for 1.0 m and 0.8 m long boards compared to the 1.2 m and 1.1 m long boards. Further investigation revealed that the frequency obtained from the SMART THUMPER™ app for the 1.0 m and 0.8 m samples had a discrete cluster of some frequency values, *i.e.*, had the same frequencies for a number of samples, (Fig. 5a).

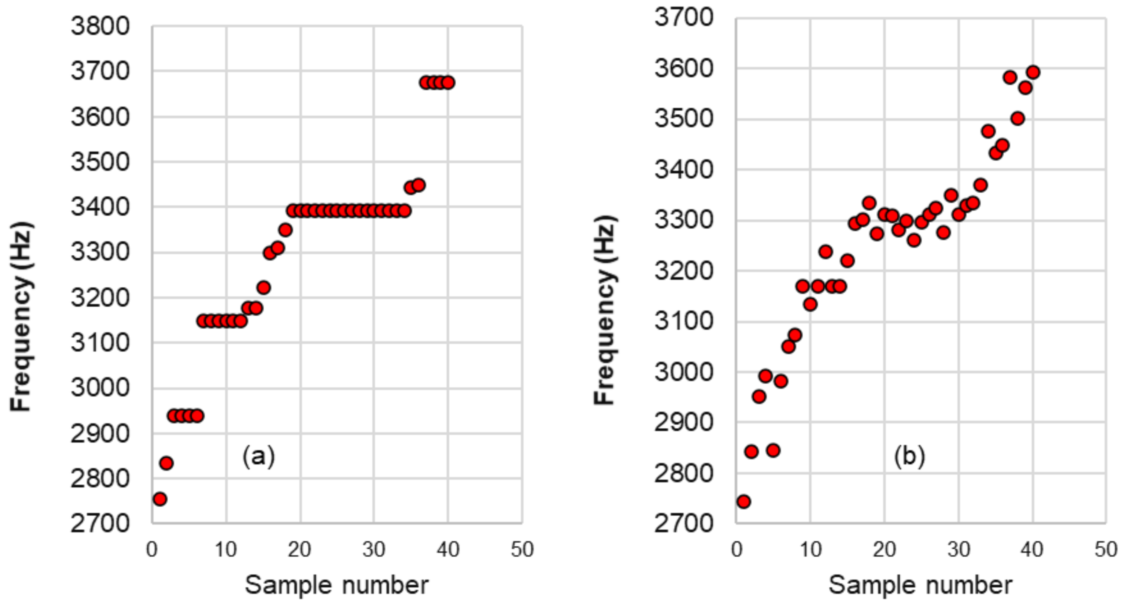

Fig. 5. Frequency values for the 0.8 m Blackbutt sample obtained from a) SMART THUMPER™ and b) BING©

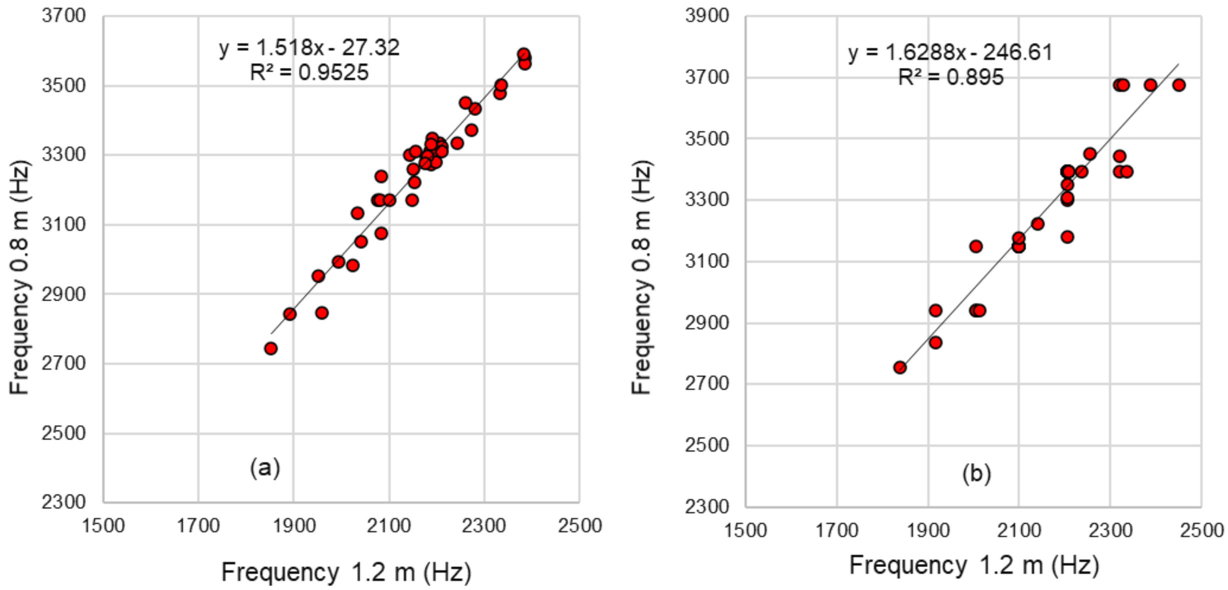

Fig. 6. Correlation between frequency for the 1.2 m and 0.8 m samples obtained from a) BING© and b) SMART THUMPER™

This clustering, or rounding, of the frequency values could be due to limitations of the app, or the frequency response of the smartphone and requires further investigation. However, this problem did not appear in the BING© results (Fig. 5b). This indicated that BING© measures the frequency more precisely at higher frequencies than the SMART THUMPER™ app and subsequently provided a more accurate MOE estimation. This is further evidenced by the coefficient of determination (R^2) between frequencies for the 1.2 m and 0.8 m samples obtained from the BING© and SMART THUMPER™ systems (Fig. 6). The R^2 values for the 1.2 m and 0.8 m samples were 0.9525 and 0.895 for the BING© and SMART THUMPER™ systems, respectively.

Jarrah (Trial 3)

The correlations between BING© MOE estimation were between 0.98 and 0.99, whereas the correlations for SMART THUMPER™ were between 0.92 to 0.98 for varying lengths of sawn jarrah (Fig. 7). The correlation between BING© and SMART THUMPER™ MOE ranged from 0.94 to 0.98 for all board lengths. The minimum value (0.94) occurred in the 1.2 m and 0.8 m length samples, due to differences in the precision of the frequency measurements, as shown previously.

Similar to sawn blackbutt, the COVs for the SMART THUMPER™ system were higher than the COVs for the BING© system. The average COVs were 1.35% and 3.17% for BING© and SMART THUMPER™, respectively (as shown in Table 3).

Table 3. COV Values of the BING© and SMART THUMPER™ Systems for the Jarrah Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	4.47	6.32
Minimum	0.26	0.41
Average	1.35	3.17

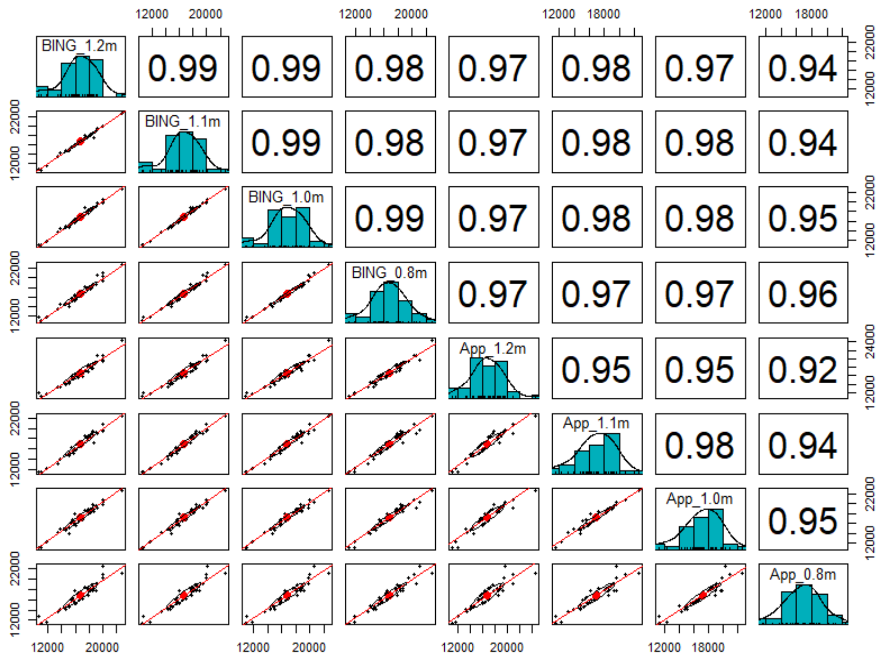

Fig. 7. Correlation matrix between the BING© and SMART THUMPER™ MOEs showing the Pearson correlation, histogram, and scatterplot with a linear model for sawn jarrah timber

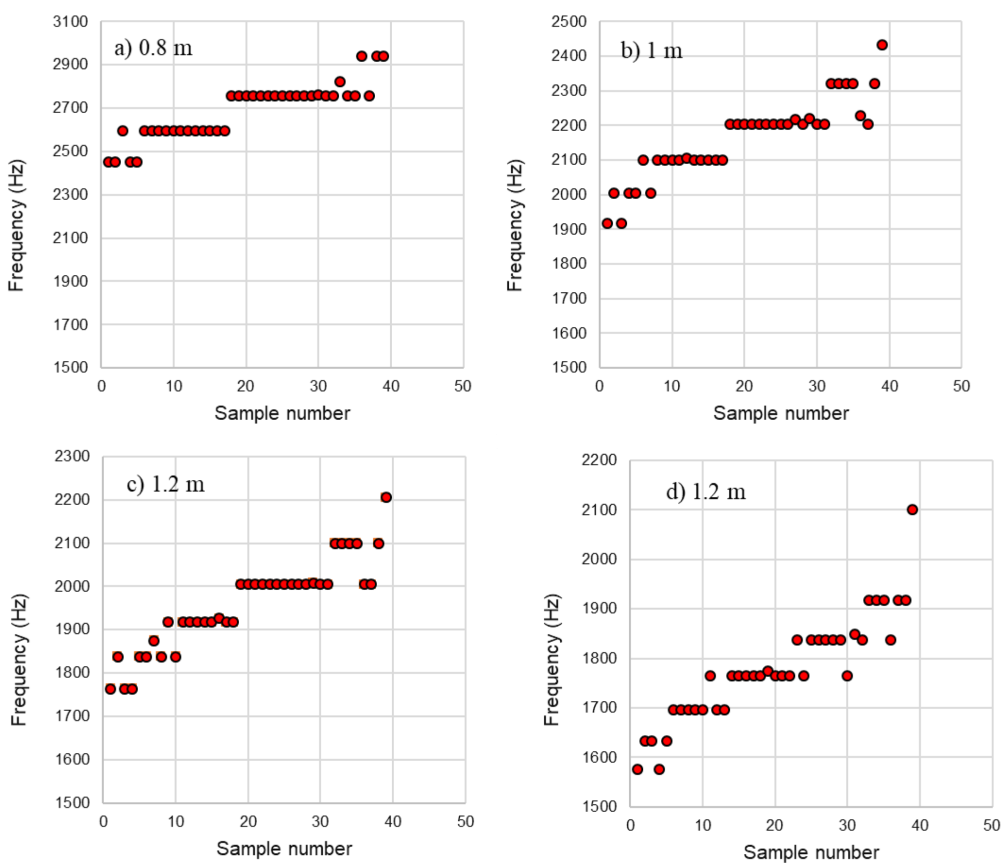

Fig. 8. Frequencies obtained from various lengths (0.8 m to 1.2 m) of jarrah samples using the SMART THUMPER™ application

The frequencies for all sawn jarrah samples at various lengths are shown in Fig. 8. The clustering, or rounding, of the frequency values becomes noticeable as the frequencies increase due to the sample length decreasing.

The rounding of the frequencies to discrete values, as obtained *via* the SMART THUMPER™ system, can also be clearly seen in the scatter plots between the BING© and SMART THUMPER™ frequencies for the 1.2 m and 0.8 m samples (Fig. 9). Figure 9 shows that for shorter samples the frequency obtained from the SMART THUMPER™ system clustered in four major groups, whereas there were more than four groups for the 1.2 m samples. This indicated that the SMART THUMPER™ app may not provide accurate results for shorter samples that require higher frequencies, *i.e.*, greater than approximately 2000 Hz.

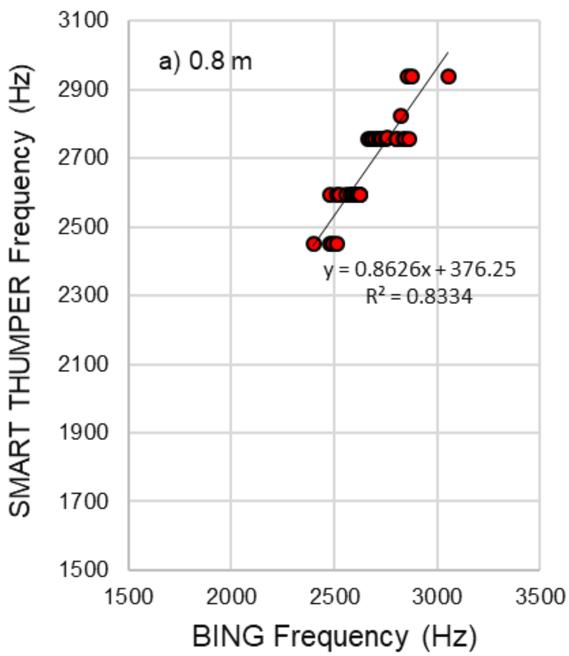

Fig. 9. The linear regression between the frequencies obtained *via* the SMART THUMPER™ and BING© systems for a) 0.8 m and b) 1.2 m sawn jarrah samples

Spotted gum (Trial 1)

Of the sawn timber included in this study, the sawn spotted gum had the highest air-dry density, *i.e.*, an average of 1124 kg/m^3. Although it was a denser wood, the correlations between the BING and SMART THUMPER™ systems were strong (r = 0.87 to 1). The correlation between the BING© and SMART THUMPER™ MOEs were 0.97, 0.97, 0.94, and 0.95 for the 1.2 m, 1.1 m, 1.0 m, and 0.8 m samples, respectively (Fig. 10).

The correlation between the BING© and SMART THUMPER™ system frequencies between the 1.2 m and 0.8 m samples for spotted gum and messmate provided similar results to the sawn jarrah and blackbutt samples. Therefore, these results are not shown for the spotted gum and messmate samples.

The average COVs were 0.93% and 3.06% for the BING© and SMART THUMPER™ systems, respectively (Table 4).

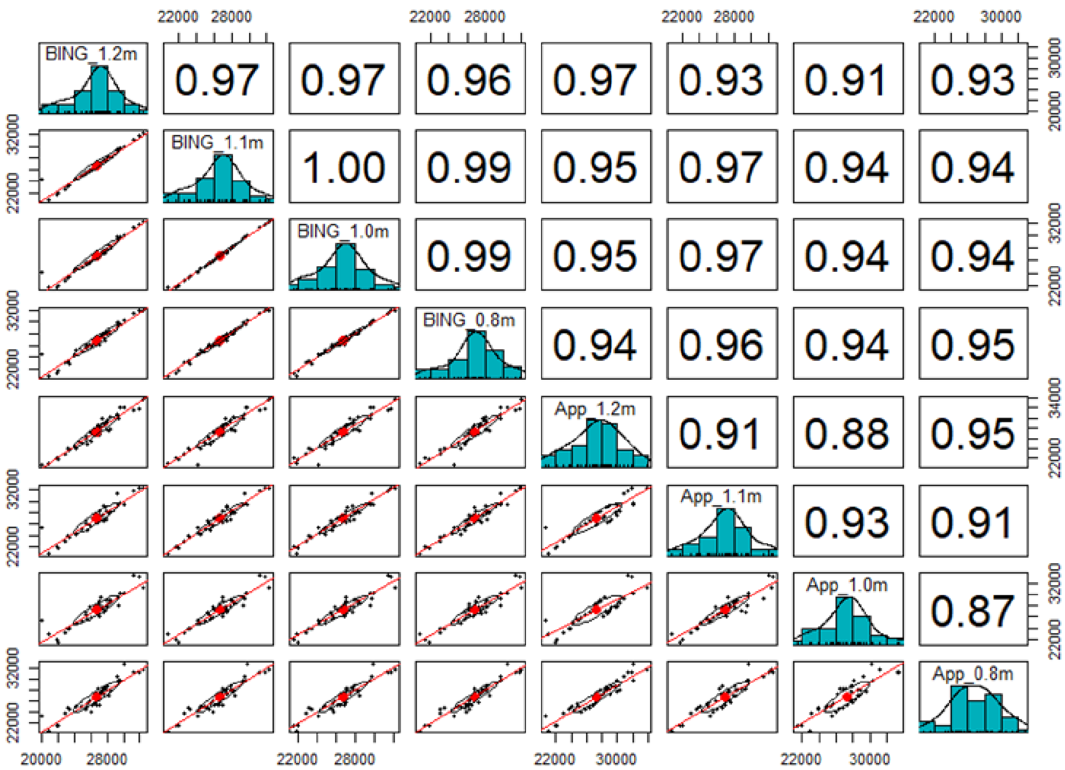

Fig. 10. Correlation matrix between the BING© and SMART THUMPER™ MOEs showing the Pearson correlation, histogram, and scatterplot with a linear model for sawn spotted gum

Table 4. COV Values of the BING© and SMART THUMPER™ Systems for the Spotted Gum Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	9.35	9.25
Minimum	0.13	0.79
Average	0.93	3.06

Messmate (Trial 4)

The messmate samples had the lowest density among the hardwoods investigated in this study. The correlation matrix shown in Fig. 11 shows a strong correlation between the BING© MOEs (0.98 to 1), between the BING© and SMART THUMPER™ MOEs (0.95 to 0.99), and between the SMART THUMPER™ MOEs (0.94 to 0.97). The histograms show better normal distributions than other solid wood species tested, even for the shorter length samples. Therefore, it can be concluded that the SMART THUMPER™ app can provide a good estimation of MOE for a range of solid hardwoods with varying densities.

In contrast to all other COV results, the maximum COV for the BING© system was higher than the SMART THUMPER™ COV. However, the average COV was 3.34% for SMART THUMPER™ system and 1.77% for the BING© system.

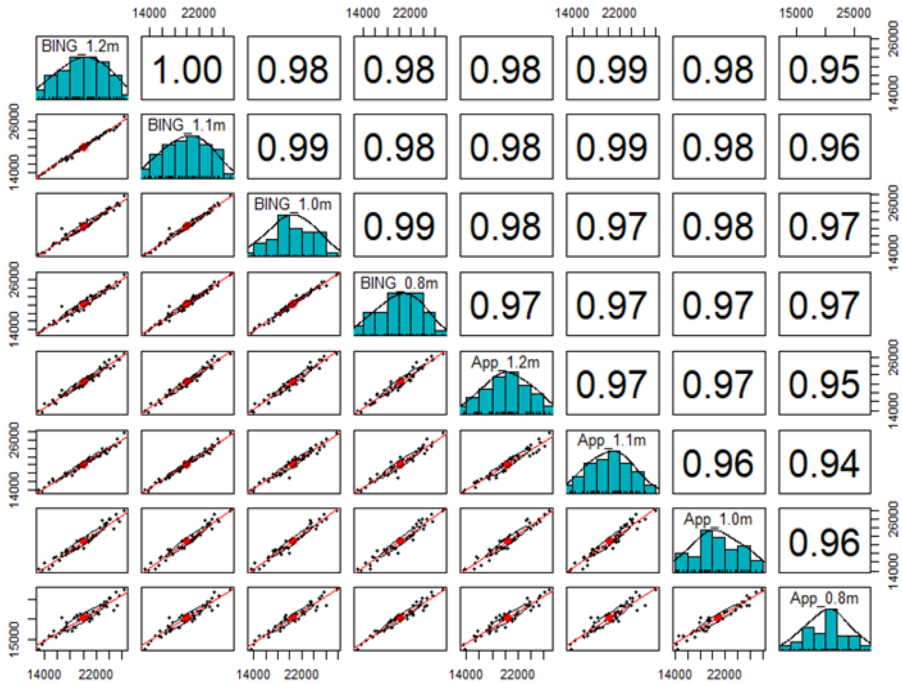

Fig. 11. Correlation matrix between the BING© and SMART THUMPER™ MOEs showing the Pearson correlation, histogram, and scatterplot with a linear model for messmate samples

Table 5. COV Values of the BING© and SMART THUMPER™ Systems for the Messmate Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	9.55	7.66
Minimum	0.32	0.64
Average	1.77	3.34

Southern pine (Trial 5)

The correlation matrix for the southern pine samples is shown in Fig. 12. The correlation varies from 0.85 to 0.99. In contrast to the blackbutt samples, the histogram for the shorter samples (1.1 m and below) shows more sample variation than the 1.2 m samples.

The average COVs were 1.80% and 4.03% for the BING© and SMART THUMPER™ systems, respectively.

Table 6. COV Values of the BING© and SMART THUMPER™ Systems for the Southern Pine Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	5.68	7.88
Minimum	0.18	1.84
Average	1.80	4.03

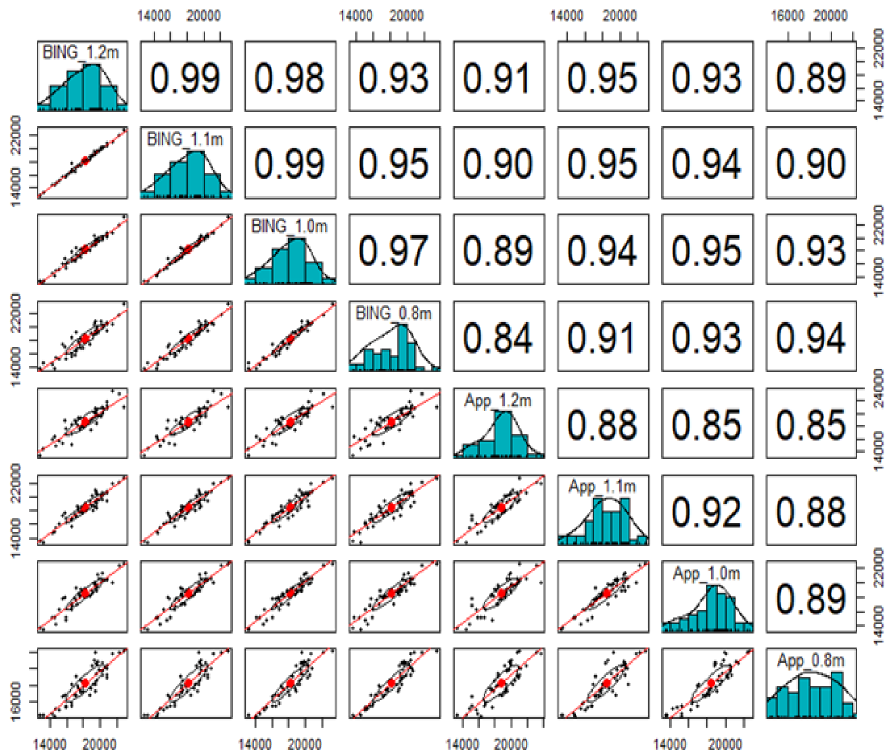

Fig. 12. Correlation matrix between the BING© and SMART THUMPER™ MOE showing the Pearson correlation, histogram, and scatterplot with a linear model for southern pine timber

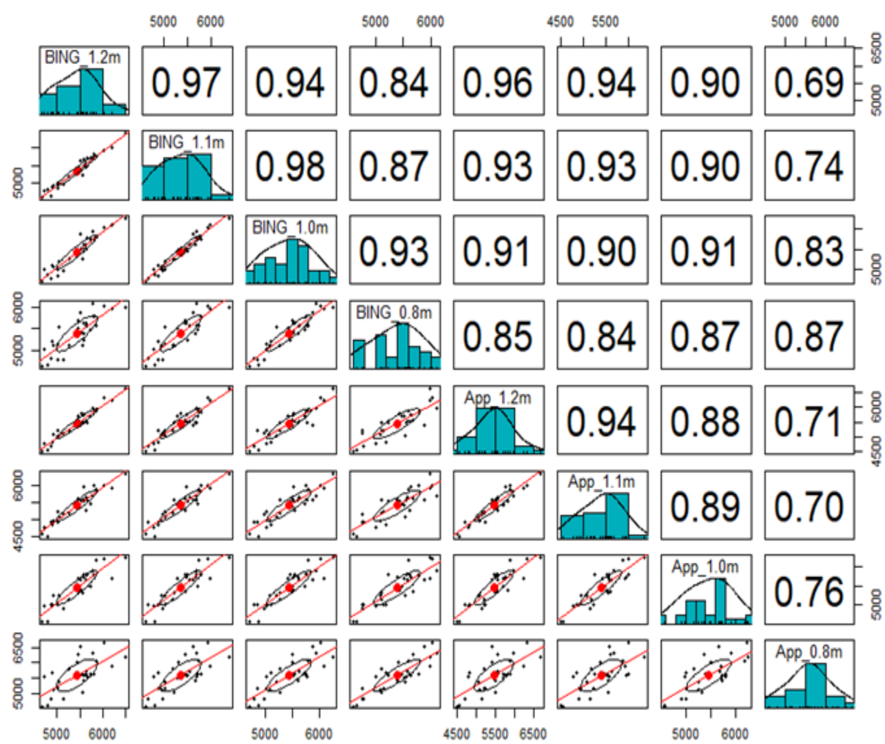

Fig. 13. Correlation matrix between the BING© and SMART THUMPER™ MOE showing the Pearson correlation, histogram, and scatterplot with a linear model for plywood samples

Plywood (Trial 6)

In addition to the solid timber tested above, plywood samples were assessed to investigate the suitability of measuring the MOE using the SMART THUMPER™ application. The correlation between the BING© and SMART THUMPER™ MOEs for various lengths ranged from 0.74 to 0.96. The correlation coefficient was comparatively lower than the solid woods tested with the lowest values (0.69) occurring in BING© 1.2 m samples and SMART THUMPER™ 0.8 m samples (Fig. 13). It is theorized that this could be due to the alternating grain direction between the plywood layers. The scatterplots show greater dispersion compared to the solid wood samples.

The average COVs were 2.08% and 3.57% for the BING© and SMART THUMPER™ systems, respectively. The average COV for the BING© system (2.08%), which was higher than the solid wood COV, infers that the BING© results also had higher variation in the plywood samples.

Table 7. COV Values of the BING© and SMART THUMPER™ Systems for the Plywood Samples

Values	BING© COV (%)	SMART THUMPER™ COV (%)
Maximum	4.51	8.57
Minimum	0.38	0.94
Average	2.08	3.57

Longer length southern pine (Trial 7)

Five longer length southern pine samples were tested to assess the SMART THUMPER™ application in terms of typical industrial length boards. These five individual boards were tested at their full length (4.8 m), and then the lengths of the boards were iteratively reduced and tested at 4.5 m, 4.2 m, 3.7 m, 3.2 m, 2.7 m, 2.2 m, and 1.7 m. The COVs for the five long length pine boards, calculated for each board tested at various lengths, are presented in Table 8.

Table 8. COV Values of the BING© and SMART THUMPER™ Systems for the Longer Southern Pine Samples

Sample number	BING© COV (%)	SMART THUMPER™ COV (%)
1	1.62	3.03
2	1.99	2.95
3	2.97	3.56
4	2.10	3.39
5	3.50	3.65

For the long length pine samples (1.7 m to 4.8 m), the regression analysis between the BING© and SMART THUMPER™ frequencies showed strong correlation (R^2 = 0.9991) and minimal bias (slope = 0.9807) (as shown in Fig. 13).

However, the correlation between the BING© MOE and the SMART THUMPER™ MOE, when considering all boards at varying test lengths, was slightly lower than the other samples (R^2 = 0.658). This lower R^2 could be due to a combination of knots in the samples, varying sample lengths, and the low number of samples.

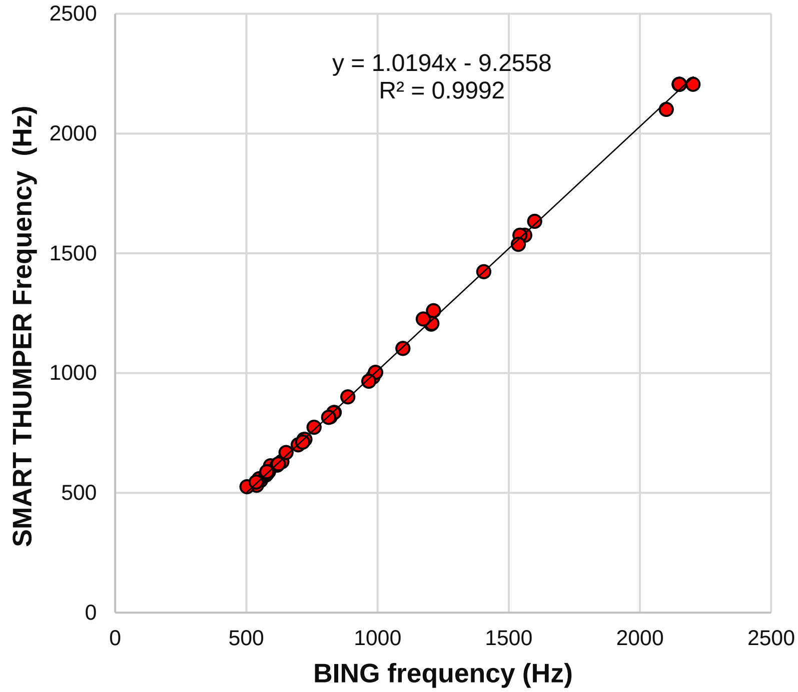

Fig. 14. Regression between the BING© and SMART THUMPER™ frequencies for longer length southern pine samples

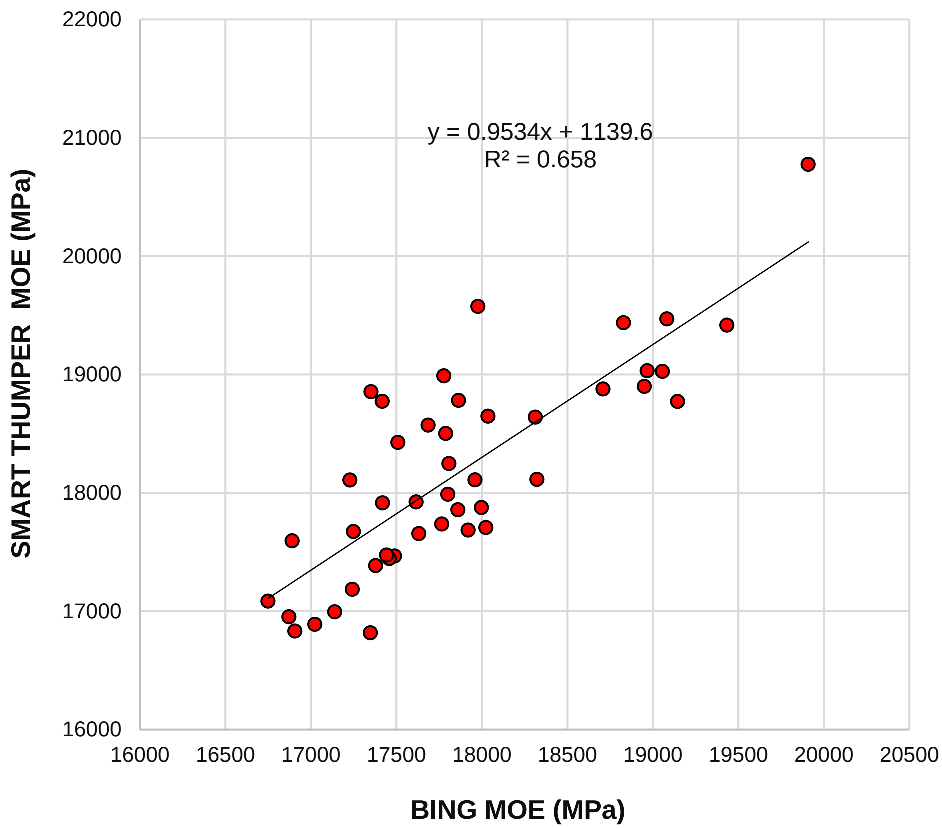

Fig. 15. Regression between the BING© and SMART THUMPER™ MOEs for longer length southern pine samples

Longer length hardwoods (Trial 8)

The long length hardwood (spotted gum) timber boards were also tested similarly to the longer pine boards. The regression line shows a strong correlation (R^2 = 0.96 and slope = 1.022) between the BING© MOE and SMART THUMPER™ frequencies and much better correlations between the MOEs (R^2 = 0.9205 and slope =1.065) than the longer softwood boards (as shown in Fig. 15 and Fig. 16). This could be due to more uniform properties and a lower number of knots in the hardwood boards.

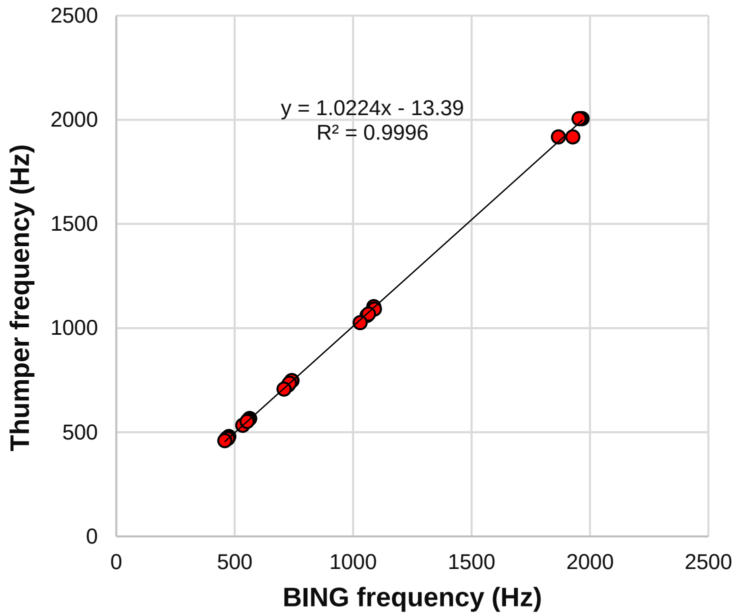

Fig. 16. Regression between the BING© and SMART THUMPER™ frequencies for longer length hardwood samples

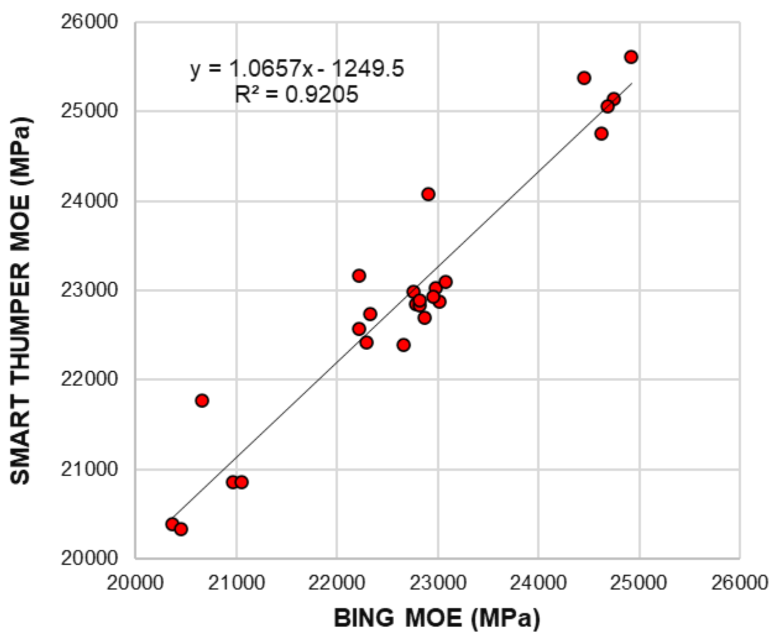

Fig. 17. Regression between the BING© and SMART THUMPER™ MOEs for longer length hardwood samples

The COVs were much smaller for both the BING© and SMART THUMPER™ systems for the longer length hardwood samples, which indicated less variation in the hardwood boards. The COV values for the MOEs at different lengths for each board are given in Table 9. Although the COV of the SMART THUMPER™ MOE was slightly higher, the difference between the BING© and SMART THUMPER™ systems was minimal.

Table 9. COV Values for the BING© and SMART THUMPER™ Systems for Longer Length Hardwood Samples

Sample number	BING© COV (%)	SMART THUMPER™ COV (%)
1	0.70	1.28
2	1.14	1.24
3	0.71	1.21
4	0.25	2.42
5	1.48	2.78

Veneer (Trial 9)

Along with the solid wood and EWPs, a test was conducted on 3 mm southern pine veneer sheets. Figure 18 shows the linear regression between the BING© and SMART THUMPER™ MOEs. A high coefficient of determination ($R^2 = 0.9691$) between BING© and SMART THUMPER™ MOEs was obtained, which indicated the SMART THUMPER™ system was also suitable for measuring the MOE of veneer samples. The bias was also low, as the slope of the regression line with zero intercept is close to one (1.012).

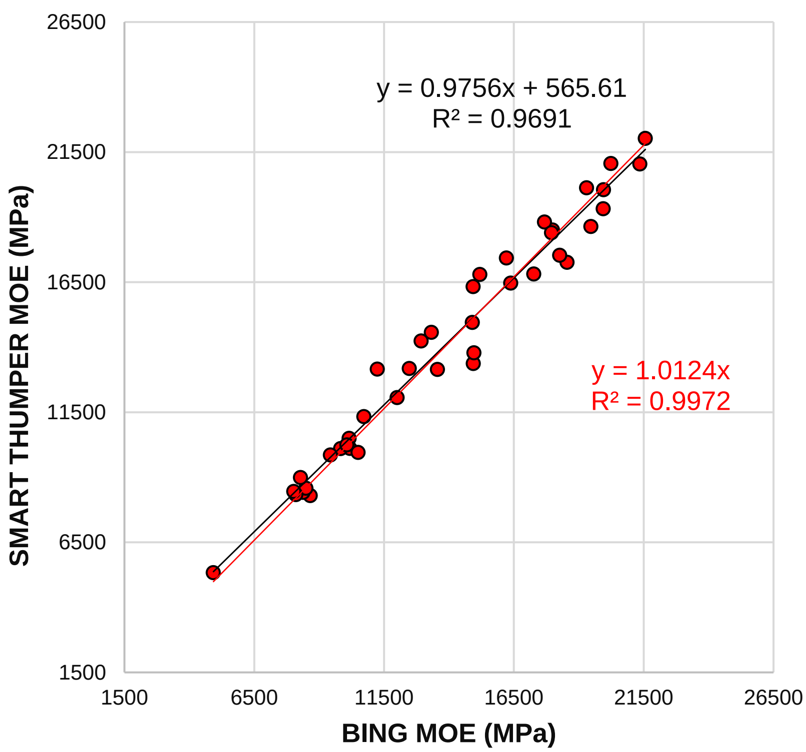

Fig. 18. Regression between the BING© and SMART THUMPER™ MOE for the veneer samples (Note: Red colour represents the regression when the intercept is set to zero, *i.e.*, y = mx line)

The regression between the frequencies obtained from the BING© and SMART THUMPER™ systems showed a good coefficient of determination (R^2 = 0.9342). However, the SMART THUMPER™ values again showed some discretisation, particularly at higher frequencies, *i.e.*, frequencies greater than 2000 Hz.

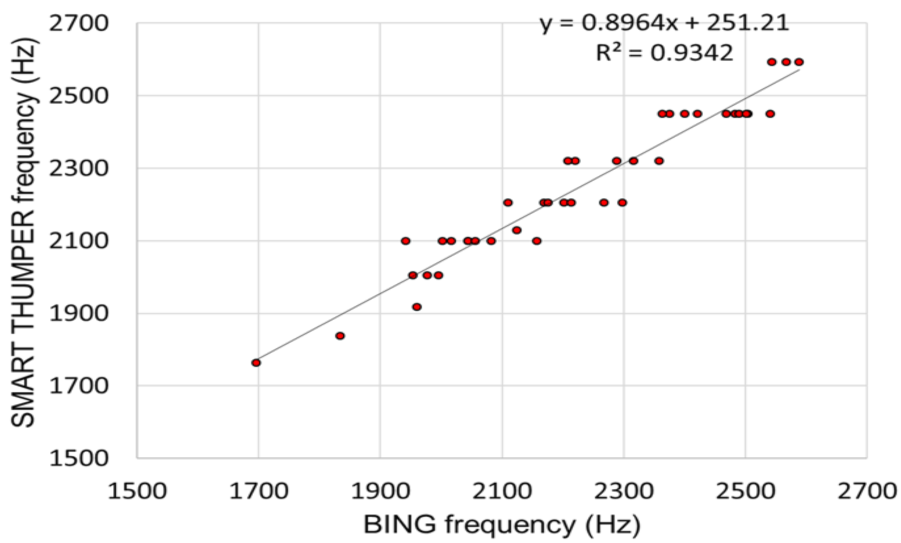

Fig. 19. Regression between the BING© and SMART THUMPER™ frequencies for the veneer samples

Effect of the Cross-Section (Trial 10)

The correlation between the BING© and SMART THUMPER™ MOEs for various cross-sections of southern pine samples showed a low coefficient of determination (R^2 = 0.3943) (Fig. 20).

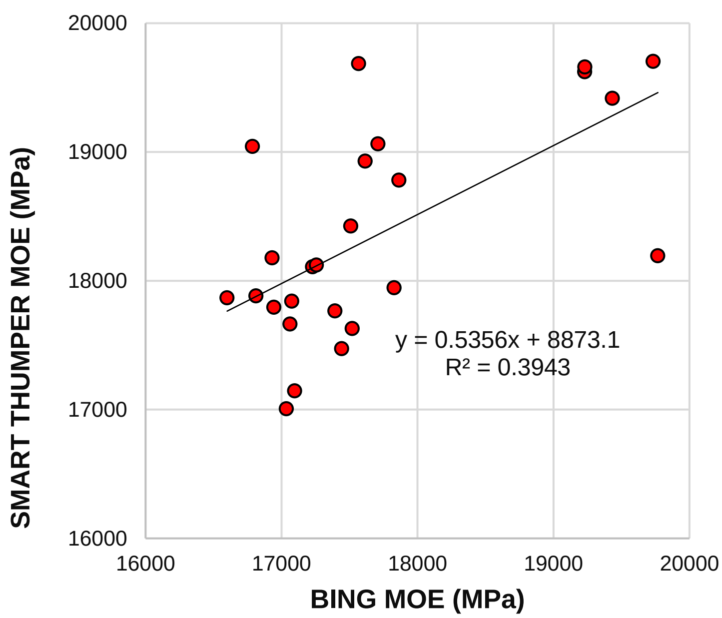

Fig. 20. Regression between the BING© and SMART THUMPER™ MOEs for the different cross section softwood samples

This can be explained by the frequency rounding off, as shown in Fig. 21. The frequency extracted from the SMART THUMPER™ system appears to be rounded off near the 2100 Hz to 2200 Hz range, whereas the BING© system remains precise. This results in less accurate SMART THUMPER™ MOEs at higher frequencies.

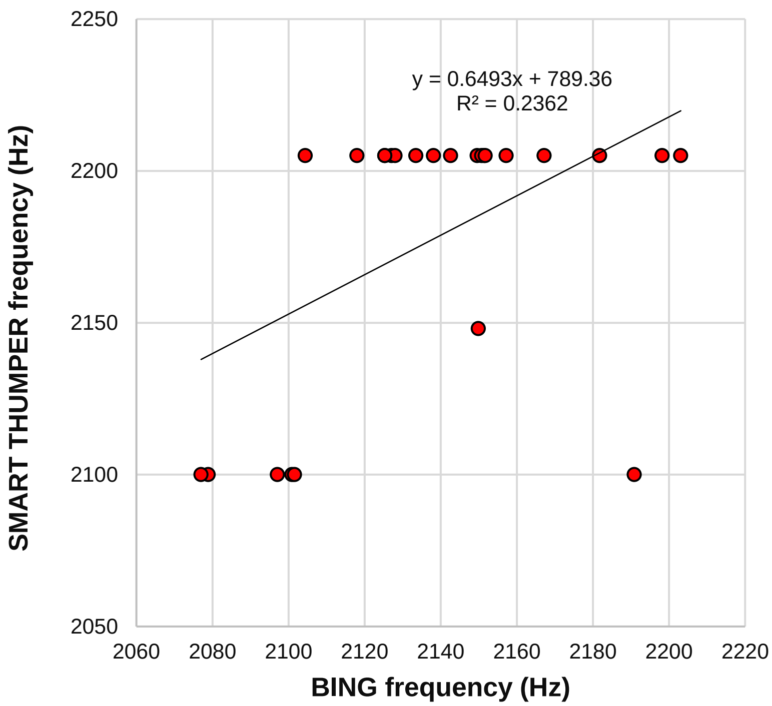

Fig. 21. Regression between the BING© and SMART THUMPER™ frequencies for the different cross section softwood samples

As the MOE range of the samples was quite narrow (approximately 17000 MPa to 20000 MPa), similar frequencies would be expected between samples. However, obvious discretisation bands in the SMART THUMPER™ frequency measurements were evident (Fig. 21). The COV values obtained for various cross-sections of each sample are shown in Table 10.

Table 10. COV Values for the BING© and SMART THUMPER™ Systems for the Various Cross-Section Sizes

Sample number	BING© COV (%)	SMART THUMPER™ COV (%)
1	1.47	0.74
2	2.37	2.96
3	2.63	4.73
4	7.32	0.76
5	4.91	0.68

The effect of the cross-section could not be readily quantified/assessed as the samples selected for assessment yielded frequencies in a range where the SMART THUMPER™ is less reliable.

Table 11 is a simplified summary of this study for potential SMART THUMPER™

users. It provides a graphical indication of the accuracy of the SMART THUMPER™ results for varying combinations of timber product lengths, densities, and expected modulus of elasticities. It is relevant for all product types and cross sections. Green cells indicate a combination of parameters for which the MOE provided by the app can be considered highly accurate. For example, for 10000 MPa, the timber must be greater than 1.2 m in length to produce accurate results using the application. The results for yellow cells should be treated as indicative only, whist red cells are considered unreliable. In addition to providing an indication of the accuracy of the results obtained, the matrix may also prove useful in selecting appropriate sample lengths prior to testing.

Table 11. Reliability Matrix Showing Accuracy of MOE Estimation Using the SMART THUMPER™

Max expeceted MOE (MPa)	Sample Length (m)	Density (kg/m^3)					
		600	700	800	900	1000	1100
6000	0.9						
	1.2						
	1.5						
	1.8						
8000	0.9						
	1.2						
	1.5						
	1.8						
10000	0.9						
	1.2						
	1.5						
	1.8						
12000	0.9						
	1.2						
	1.5						
	1.8						
15000	0.9						
	1.2						
	1.5						
	1.8						
18000	0.9						
	1.2						
	1.5						
	1.8						
22000	0.9						
	1.2						
	1.5						
	1.8						
28000	0.9						
	1.2						
	1.5						
	1.8						
32000	0.9						
	1.2						
	1.5						
	1.8						

Note: Green = Accurate, Yellow = Indicative, Red = Not Reliable. The number in the cells shows the frequency values for that specific dimension, MOE, and density.

CONCLUSIONS

1. The results of this study show that the SMART THUMPER™ application can be used to evaluate the stiffness of both hardwood and softwood boards, as well as rotary veneer strips in a wide variation of densities and dimension, with reasonable accuracy.
2. The biggest limitation of the SMART THUMPER™ app is that it cannot reliably estimate the resonance frequencies at a higher frequency level (4000 Hz and higher) because the iPhone microphone is engineered to pick up human voices at a lower frequency range. Therefore, the app starts to measure inaccurate frequencies and MOE values when the frequency is approximately 4000 Hz and above. The frequencies start to be clustered (single frequency value for many boards) due to a rounding function at relatively higher frequencies (2000 Hz and above).
3. This rounding function could be due to a limitation of the SMART THUMPER™ app or the iPhone itself, and requires further investigation. Although the SMART THUMPER™ app works for various lengths of samples, longer samples with lower resonance frequency (well below 2000 Hz) provided better results and lowered the clustering of frequency.
4. The correlation matrix between the MOEs of various lengths showed that plywood had the lowest correlation coefficient, most likely due to the cross-grain orientation of the alternating layers.
5. The application can be used for veneer and plywood, although the correlation is relatively weaker compared to solid wood.
6. A reliability matrix showing the accuracy of MOE estimation *via* the SMART THUMPER™ system was developed and presented.
7. Overall, the SMART THUMPER™ can be used as a low-cost, portable tool to estimate the indicative stiffness properties of solid timber and veneer with a lower frequency range (less than 4000 Hz). It may have a particular application in developing countries, where access to expensive and complicated hardware and software, as well as a computer, might be limited.

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REFERENCES CITED

Arriaga, F., Monton, J., Segues, E., and Íñiguez-Gonzalez, G. (2014). "Determination of the mechanical properties of radiata pine timber by means of longitudinal and transverse vibration methods," *Holzforschung* 68(3), 299-305. DOI: 10.1515/hf-2013-0087

Aro, M. D., Wang, X., McDonald, D. E., and Begel, M. (2016). "Tensile strength of thermally modified laminated strand lumber and laminated veneer lumber," *Wood Material Science & Engineering* 12(4), 228-235. DOI: 10.1080/17480272.2016.1164246

AS/NZS 4063.1:2010 (2010). "Characterization of strucural timber test methods," Standards Australia, Sydney, Australia.

Baillères, H., Hopewell, G. P., and Boughton, G. (2009). *MOE and MOR Assessment Technologies for Improving Graded Recovery of Exotic Pines in Australia* (Project No. PNB040-0708), Forest & Wood Products Australia, Melbourne, Australia.

Baillères, H., Lee, D., Kumar, C., Psaltis, S., Hopewell, G. P., and Brancheriau, L. (2019). *Improving Returns From Southern Pine Plantations Through Innovative Resource Characterisation* (Project No.PNC361-1415), Forest & Wood Products Australia, Melbourne, Australia.

Baillères, H., Hopewell, G., Boughton, G., and Brancheriau, L. (2012). "Strength and stiffness assessment technologies for improving grading effectiveness of radiata pine wood," *BioResources* 7(1), 1264-1282.

Baltrušaitis, A., Laurinavičius, A., Ukvalbergienė, K., Pranckevičienė, V., and Minelga, D. (2009). "Acoustic and elastic properties of modified oak wood," Materials science. Kaunas University of Technology, Academy of Sciences of Lithuania. *Kaunas: Technologija* 15(4), 316-320.

Brashaw, B. K., Bucur, V., Divos, F., Gonçalves, R., Lu, J., Meder, R., Pellerin, R. F., Potter, S., Ross, R. J., Wang, X., *et al.* (2009). "Nondestructive testing and evaluation of Wood: A worldwide research update," *Forest Products Journal* 59(3), 7-14.

Bucur, V. (2003). *Nondestructive Characterization and Imaging of Wood,* Springer Science & Business Media. DOI: 10.1007/978-3-662-08986-6

Cran.R-project (2019). "Package 'psych'," (https://cran.r-project.org/web/packages/psych/psych.pdf), Accessed Date Unknown.

Faircloth, A., Brancheriau, L., Karampour, H., So, S., Bailleres, H., and Kumar, C. (2021). "Experimental modal analysis of appropriate boundary conditions for the evaluation of cross-laminated timber panels for an in-line approach," *Forest Products Journal* 71(2), 161-170.

Falk, R. H., Patton-Mallory, M., and McDonald, K. (1990). "Nondestructive testing of wood products and structures: State-of-the-art and research needs," Madison, WI., USDA Forest Service, Forest Products Laboratory.

Fortuna, B., Plos, M., Šuligoj, T., and Turk, G. (2018). "Strength grading of structural timber," Common Foundations 2018-uniSTem: 6th Congress of Young Researchers in the Field of Civil Engineering and Related Sciences, Sveučilište u Splitu, Fakultet građevinarstva, arhitekture i geodezije. DOI: 10.31534/CO/ZT.2018.09

Halabe, U. B., Bidigalu, G. M., GangaRao, H. V., and Ross, R. J. (1997). "Nondestructive evaluation of green wood using stress wave and transverse vibration techniques," *Materials Evaluation* 55(9), 1013-1018.

Hearmon, R. F. S. (1946). "The fundamental frequency of vibration of rectangular wood and plywood plates," *Proceedings of the Physical Society* 58(1), 78. DOI: 10.1088/0959-5309/58/1/307

Hearmon, R. F. S. (1958). "The influence of shear and rotatory inertia on the free flexural vibration of wooden beams," *British Journal of Applied Physics* 9(10), 381. DOI: 10.1088/0508-3443/9/10/301

James, W. L. (1961). "Internal friction and speed of sound in Douglar-fir." *Forest Prod J* XI(9), 383-390.

Llana, D. F., Íñiguez-González, G., Díez, M. R., and Arriaga, F. (2020). "Nondestructive testing used on timber in Spain: A literature review," *Maderas. Ciencia y Tecnología* 22(2), 133-156. DOI: 10.4067/S0718-221X2020005000201

Kumar, C., Psaltis, S., Bailleres, H., Turner, I., Brancheriau, L., Hopewell, G., Carr, E. J., Farrell, T., and Lee, D. J. (2021). "Accurate estimation of log MOE from non-destructive standing tree measurements," *Annals of Forest Science* 78(1). DOI: 10.1007/s13595-021-01041-8

Nistal França, F. J., Seale, R., Shmulsky, R., and Filgueira Amorim França, T. S. (2019). "Assessing southern pine 2x4 and 2x6 lumber quality: Longitudinal and transverse vibration," *Wood and Fiber Science* 51, 2-15. DOI: 10.22382/wfs-2019-002

Paradis, S., Brancheriau, L., and Baillères, H. (2017). "Bing software," (https://ur-biowooeb.cirad.fr/en/expertises-products/products/bing-software), Accessed Date 12 Jan 2021. DOI: 10.3390/s130303394

Paradis, N., Auty, D., Carter, P., and Achim, A. (2013). "Using a standing-tree acoustic tool to identify forest stands for the production of mechanically-graded lumber," *Sensors* 13(3), 3394-3408.

Ross, R. J., Brashaw, B. K., and Pellerin, R. F. (1998). "Nondestructive evaluation of wood," *Forest Products Journal* 48(1), 14-19.

Schimleck, L. R., Evans, R., Ilic, J., and Matheson, A. C. (2002). "Estimation of wood stiffness of increment cores by near-infrared spectroscopy," *Canadian Journal of Forest Research* 32(1), 129-135. DOI: 10.1139/x01-176

Simpson, W. T., and Wang, X. (2001). "Relationship between longitudinal stress wave transit time and moisture content of lumber during kiln-drying," *Forest Products Journal* 51, 51-54.

Steiger, R. (1996). "Mechanische Eigenschaften von Schweizer Fichten-Bauholz bei Biege-, Zug-, Druck-und kombinierter M/N Beanspruchung: Sortierung von Rund- und Schnittholz mittels Ultraschall," ETH Zurich.

Timberbiz (2019). "Smart Thumper app to test wood strength," (https://www.timberbiz.com.au/smart-thumper-app-to-test-wood-strength/), Accessed Date 12 Jan 2021.

Yang, B., Seale, R.. Shmulsky, R., Dahlen, J., and Wang, X. (2015). "Comparison of nondestructive testing methods for evaluating no. 2 southern pine lumber: Part A, modulus of elasticity," *Wood and Fiber Science: Journal of the Society of Wood Science and Technology* 47, 375-384.

Yang, X., Ishimaru, Y., Iida, I., and Urakami, H. (2002). "Application of modal analysis by transfer function to nondestructive testing of wood I. Determination of localized defects in wood by the shape of the flexural vibration wave," *Journal of Wood Science* 48, 283-288. DOI: 10.1007/BF00831348

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