8-9-2019

Preliminary characterization of physical and mechanical properties of species used in staircase manufactures

Cristian Grecca Turkot

Recommended Citation

Grecca Turkot, Cristian, "Preliminary characterization of physical and mechanical properties of species used in staircase manufactures" (2019). *Theses and Dissertations*. 3619.
https://scholarsjunction.msstate.edu/td/3619

Preliminary characterization of physical and mechanical properties of species used in staircase manufactures

By

Cristian Grecca Turkot

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Sustainable Bioproducts
in the Department of Sustainable Bioproducts

Mississippi State, Mississippi

August 2019

Preliminary characterization of physical and mechanical properties of species used in staircase manufactures

By

Cristian Grecca Turkot

Approved:

R. Dan Seale
(Major Professor)

Rubin Shmulsky
(Committee Member)

Jason Tyler Street
(Committee Member)

H. Michael Barnes
(Graduate Coordinator)

George M. Hopper
(Dean)
College of Forest Resources

Name: Cristian Grecca Turkot

Date of Degree: August 9, 2019

Institution: Mississippi State University

Major Field: Sustainable Bioproducts

Major Professor: R. Dan Seale

Title of Study: Preliminary characterization of physical and mechanical properties of species used in staircase manufactures

Pages in Study: 35

Candidate for Degree of Master of Science

In Phase I of this study, the purpose was to compare mechanical and physical wood properties from current wood supplies to those from previous studies (Newlin and Wilson 1917, Markwardt and Wilson 1935, wood handbook 2010). The results indicate that minor changes have occurred in the hardwood species values from the previous two studies with a few exceptions. Differences, where they occurred, could be explained by the growth locations of each sample. Differences between pine values occurred for MOE and MOR, an increase in MOE and a decrease in MOR.

The objective of Phase II was to correlate the non-destructive and destructive testing methods. The non-destructive test by longitudinal vibration wave can be used to predict the static modulus of elasticity since it is strongly correlated with the destructive static bending test for all the three methods used (A-Grader, FFT and Smart-Thumper).

DEDICATION

I dedicate this work to my family, to Taís (who supported me during this period) and to my friends from many nations who helped me and gave a lot of knowledge all the time and made this time in US enjoyable.

ACKNOWLEDGEMENTS

I would like to thank my major professor R. Daniel Seale for the support and direction during my thesis studies and thanks to all professors from the Department of Sustainable Bioproducts and Mississippi State University.

The authors wish to acknowledge the support of U.S. Department of Agriculture (USDA), Research, Education, and Economics (REE), Agriculture Research Service (ARS), Administrative and Financial Management (AFM), Financial Management and Accounting Division (FMAD) Grants and Agreements Management Branch (GAMB), under Agreement No. 58-0202-4-001. Any opinions, findings, conclusion, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Wood is one of the oldest structural materials used by man. It is known for its structural properties and its capacity to be renewable and recyclable. The use of wood for construction is widespread due to its versatility. The diversity of species offers a range of physical and mechanical properties that can be chosen for specific applications. Tree growth location, silvicultural treatments, genetics, weather, and soil conditions all influence growth characteristics and properties within and between species.

In order to use a wood species for structural design, its material properties must be known. Staircase manufacturers, engineers and designers need information concerning their material’s stiffness, strength, and hardness to design stair systems that are safe and aesthetically pleasing. Traditionally, the staircase industry has utilized strength properties for individual species from the Wood Handbook. However, when southern pine structural lumber design values were changed in 2012, code officials began to ask if other species might have also experienced strength changes over time. The mechanical properties of early studies, Newlin and Wilson (1917) and Markwardt and Wilson (1935) contained in the Wood Handbook (FPL 2010) are on the order of 80 to 100 years old. This project and study were initiated to compare mechanical properties of the major species utilized by staircase manufacturers with published values in earlier studies.

Reliable and repeatable information concerning the mechanical properties of wood is required for structural design. Important properties needed for design purposes include how much load a piece can support (bending strength), how much the piece deflects under load (stiffness), the tension and compression strength parallel to the wood grain, and the tension and compression strength perpendicular to the wood grain. Other important properties include the shear strength, hardness, impact strength, and resistance to creep. As an example, for a wood flooring company, one of the most important mechanical properties they are concerned about is the hardness of a particular wood species. The modulus of rupture and modulus of elasticity are main factors that engineers consider when designing flexural members. Compression parallel to grain is important for wall studs and compression perpendicular to grain is important for sills and plates.

Several elements influence mechanical properties. These include knots, species, slope of grain, density, fissures, ratio of earlywood/latewood, rot and other damage, processing or loading history, among others. The mechanical properties presented in this paper were obtained from tests of small clear specimens. The term ‘’clear’’ is used to denote a specimen that does not contain any visible strength reducing characteristics and has limited slope of grain. However, even clear specimens are not homogenous. During the growth process in temperate climates, the change of seasons produces annual rings known as earlywood and latewood. Over time, each annual ring grows at different rates, causing the widths of those rings to vary within and between trees and its influence the property of the wood.

The strength of a material is the ability of a material to undergo a load without plastic or catastrophic deformation. The strength varies from species to species and even from tree to tree of the same species (although this variation is much smaller). The strength of wood increases directly with density. Mechanical properties (FPL 2010) commonly used in designs and studied herein include:

- Modulus of rupture (MOR)
- Modulus of elasticity (MOE)
- Compressive strength parallel to grain (C//)
- Compressive stress perpendicular to grain (C⊥)
- Hardness

CHAPTER II

PHASE I: COMPARISON OF HISTORICAL AND CONTEMPORARY DATA

Introduction

Studies to provide the mechanical properties of small clear wood specimens were first carried out in 1910 by the USDA Forest Products Laboratory (FPL). At the time, there was not any general data that could be used as a basis for comparisons among species or provide a reference for industry.

Early authors conducted studies of mechanical properties of American wood species but did not account for moisture content and included specimens with unspecified strength reducing characteristics. Sargent’s study (U. S. Census Bureau 1880) included more than 2,700 tests of 300 species of American wood species, but this study did not take into account specimen moisture content. Because moisture content was not measured, direct comparisons with contemporary studies are problematic. In another study (Fernow 1897), the author tested 30,000 specimens, but instead of using clear samples, samples with varying strength reducing characteristics were tested. As discussed above, each tree or specimen had its own unique properties, but due to the varying strength reducing characteristics, the study is not repeatable.

To provide mechanical properties that could be used to compare species, the FPL in collaboration of the University of Wisconsin published Bulletin No. 556 – Mechanical wood grown in the United States on September 15, 1917 (Newlin and Wilson, 1917). The first bulletin included one hundred and twenty-six species. The purpose of Bulletin No. 556 was to: 1) provide reliable information on mechanical proprieties, performed according to standards under controlled conditions; 2) supersede the inaccurate data sets available at that time; 3) disseminate the results in a public manner; and 4) provide true and repeatable values to be considered and potentially used by architects and engineers to safely design wooden structures.

Following Bulletin No. 556 Newlin and Wilson (1917), on September 1935, the FPL released Bulletin No. 479 Markwardt and Wilson (1935) which included the mechanical and physical properties of one hundred sixty-four species collected between 1910 and 1935. Currently, data from the Wood Handbook (2010) relies on the data from Bulletin 556 and is the basis for design specifications of many wood products designed by engineers and architects, including staircases. Due to its importance, the objective of Phase I is to compare the previously published results with results for contemporary specimens distributed across the growing regions normally associated with each species. The tests carried out herein allowed data to be gathered about the physical and mechanical characteristics of each species and included the rings per inch, percentage summerwood, specific gravity, modulus of elasticity (MOE), modulus of rupture (MOR), compression strength parallel to the grain (C//), compression strength perpendicular to the grain (C⊥), and side hardness (tangential and radial face).

Materials and Methods

Raw Material

Mechanical properties are influenced by tree growth characteristics that are determined by the growth location and silvicultural practices. Localized growth characteristics that influence strength dictate that a large sample representative of the entire growth range of a species should be evaluated to yield accurate strength values. The Newlin and Wilson (1917) and Markwardt and Wilson (1935) studies included data about the growth areas where samples were taken.

Figure 1.1 shows the growth areas for samples collected in the Newlin and Wilson (1917) and Markwardt and Wilson (1935) studies.

Figure 2.1 Source of the raw material in green from years 1917 (Newlin and Wilson 1917) and 1935 (Markwardt and Wilson 1935).

In order to compare data in this study to the two previous studies (Newlin and Wilson (1917); Markwardt and Wilson 1935), the Staircase Manufacturers Association (SMA) members randomly picked samples from typical production for testing. Efforts were made to include material from same States that were sampled in the previous studies. In the previous studies, the growing location of each tree was specified as to the state and county. In this study, the staircase manufacturer location is known and most of the samples are traceable to a particular sawmill but not to the county level where grown. Figure 1.2 shows the origin of the samples acquired for this study.

Figure 2.2 Source of the raw material (in green) for the 2019 study.

The common and botanical names of each species are listed in Table 1.1. The Department of Sustainable Bioproducts at Mississippi State University verified each species.

Table 2.1 Wood species used in the study

Common name	Botanical name	Common name	Botanical name
Hard maple (44)	*Acer saccharum*	Red oak (48)	*Quercus rubra* spp.
White oak (44)	*Quercus alba* spp.	Yellow-poplar (38)	*Liriodendron tulipifera*
Southern yellow pine (45)	*Pinus palustris* spp.	(number of boards supplied 219)	

To represent the major area of growth for each species, a large number of samples was needed. Staircase manufacturers sent 219 samples for testing from representative production materials comprised of five species. These species are used in the majority of wood stair systems. The samples were either shipped by courier or picked up at the mill site.

Upon arrival, the sample boards were conditioned for approximately 90 days in room with controlled conditions. The resultant average moisture content of the material after the conditioning period was approximately 12% using a Wagner MMC220 moisture meter. The boards measured approximately 3.1 cm x 11.4 cm in cross section and 91 cm in length. Each board was given an identification label using indelible ink that included letters representing species and a board number within the species. For example, YP101 indicated yellow poplar and 101 indicated the 101st board within that species. The weight, measurements, rings per inch, and latewood percentage on both ends of each board were measured and stored in a database.

The boards tested represented the raw materials used in stair construction and were randomly selected. The number of growth rings and the grain angle varied from one board to the next and the mean of these values can be seen in Table 1.1.

After conditioning at 20 °C to a mean moisture content of 12%, the boards were processed using the cutting pattern shown in Figure 3. A cutting pattern that imitates a previous study (Markwardt and Wilson 1935) was used to produce test specimens from each board. Two bending specimens measuring 1- x 1- x 16-in. (depth x width x length) were produced. Bending A was loaded in the tangential direction and Bending B in the radial direction (Figure 4). Specimens for testing the hardness (1-x2-x8-in.), compression strength perpendicular to the grain, and compression strength parallel to the grain (1-x1-x6-in.) were also cut from each board. Each test specimen was labeled such that it could be traced back to the parent board. Test specimens were returned to the conditioning room.

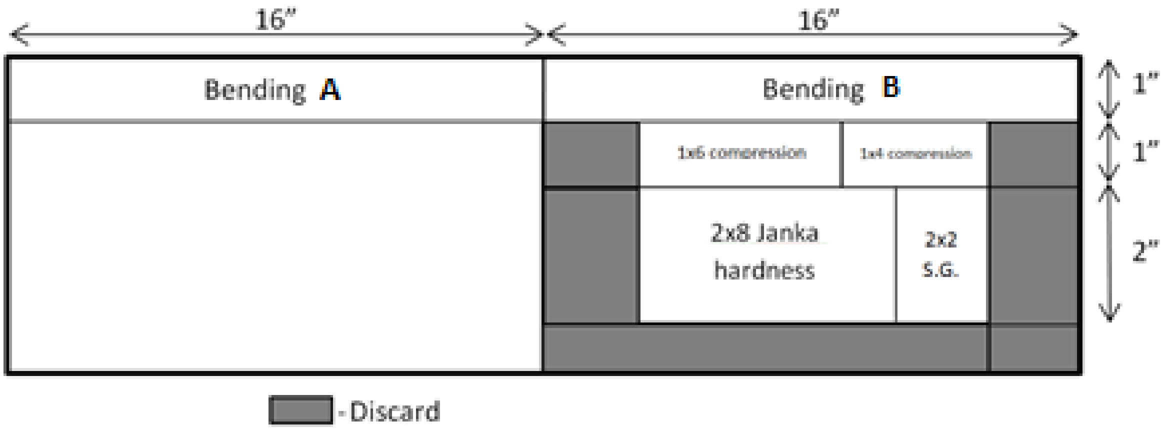

Figure 2.3 Cut-up diagram.

Mechanical Testing

All mechanical tests were performed on Instron universal testing machines. Each machine was controlled by Bluehill 3 Software and the calibrations for each machine and load cell were current. The data from the testing machine was directly written into an SQL database to minimize transcribing errors.

Static bending test

Static bending specimens were cut to dimensions of 2.54 x 2.54 x 40.6 centimeters (1x1x16 inches) in accordance with Section 8.1 of ASTM-D 143 Section 8.1 for secondary specimens (ASTM 2014). The load span was 35.6 centimeters (14 inches) and the test was conducted using center point loading with a test speed of 0.127 centimeters per minute (0.05 inches per minute). The machine bearing blocks and load heads conformed to the standard.

A. B.

Figure 2.4 Specimen A was loaded on the radial face and specimen B was loaded with the tangential face nearest to the pith.

Compression parallel to the grain

The test setup for determining a specimen's compression strength parallel to the grain is shown in Figure 5. The test specimen was cut to the measurements specified in ASTM-D 143 (ASTM 2014) for secondary specimens. Secondary specimen sizes were selected because parent boards were 1-inch thick. Each specimen measured 25 by 25 by 100 mm (1x1x4 inches). The load was applied at a rate of 0.00762 cm/cm (0.003 in/in) of the nominal specimen length per minute.

Figure 2.5 Compression parallel to the grain test setup.

Compression perpendicular to the grain

The test setup for determining a specimen’s compression strength perpendicular to the grain is shown in Figure 6. Each specimen measured 25 x 25 x 150 mm (1 x 1 x 6 in.). The load was applied through a square 5.08 x 5.08 cm (2 x 2 in.) metal bearing plate atop the surface of the specimen in contact with its radial surface. The standard specifies a 50 x 50 x 150 mm test specimen, but the parent boards only measured 25 mm thick so a minor modification to the standard was made as appropriate. The rate of loading was 0.00305 cm/min (0.012 in./min) per the ASTM D143 standard.

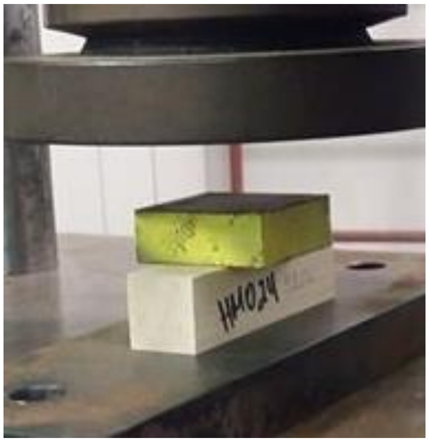

Figure 2.6 Compression perpendicular to the grain test setup.

Janka ball side hardness

Due to the size constraints of each parent board, test samples were cut to 20 x 50 x 150 mm (1 x 2 x 6 in.), a minor modification to ASTM D 143 (ASTM 2014) size requirement of 2- x 2- x 6-in.. Each specimen was penetrated using a steel (Janka) 1.13 cm (0.444 in.) diameter ball at a rate of 0.6 cm per minute (0.25 in./min). To best calculate the average of the hardness, two penetrations were made in the radial surface, two penetrations were made in the tangential surface, and the average force required to embed the ball halfway, per the standard, was determined using both orientations.

Figure 2.7 Janka ball side hardness test setup.

Results and Discussion

The results for the five different species/species groups can be found in Table 1.2. Each section corresponds a unique species with the data from the Bulletin No. 479 (Newlin and Wilson, 1917), Bulletin No. 556 (Markwardt and Wilson 1935), values from the Wood Handbook (2010) and the results found in this study (2019). The data show in the table are the average for each property and species.

Previous works (Newlin and Wilson, 1917, Markwardt and Wilson 1935, Wood Handbook 2010) tested specimens from at least five trees from each location and only the average results from those studies are presented here.

Table 2.2 Test results from 1917, 1935, and 2019.

Year	N	Location	Rings per inch	% Summerwood	Specific Gravity 12%	MOE (1,000 psi)	MOR (psi)	Compression parallel at maximum (psi)	Compression perpendicular (psi)	Hardness side (lbf)
Hard maple, *Acer saccharum*										
1917	15	IN, PA, WI	21	49	0.62	1,820	15,800	8,570	1,620	1,430
1935	17	IN, PA, WI, VT	18	x	0.63	1,830	15,800	5,390	1,810	1,450
Wood Handbook					0.63	1,830	15,800	7,830	1,470	1,450
2019	44	NY, PA, Appalachian, Upper Midwest.	12	31.07	0.63	1,839	18,423	8,919	2,528	1,410
Red oak, *Quercus rubra* spp.										
1917	20	Arkansas, Louisiana, Indiana, Tennessee	11	62	.63	1,870	14,200	7,370	1,210	1,310
1935	4	Louisiana	20	46	.59	1,490	10,900	6,090	1,080	1,060
Wood Handbook					.59	1,490	10,900	6,090	870	1,060
2019	48	West Virginia, Pennsylvania, Appalachian, Upper middle west.	9.67	69.14	.62	1,640	16,428	8,358	2,354	1,226
White oak, *Quercus alba* spp.										
1917	15	Arkansas, Indiana, Louisiana	17	60	.69	1,780	15,200	7,610	1,340	1,370
1935	20	Arkansas, Indiana, Louisiana.	17	60	.68	1,780	15,200	7,440	1,320	1,360
Wood Handbook					.68	1,780	15,200	7,440	1,070	1360
2019	44	Kentucky, West Virginia, Appalachian, Upper Mid-West region.	11.13	68.25	.70	1,200	16,332	8,093	2,728	1,459
Yellow-poplar, *Liriodendron tulipifera*										
1917	5	Tennessee	14	x	.41	1,610	11,800	7,480	740	450
1935	11	Kentucky, Tennessee	14	x	.40	1,500	9,200	5,200	580	450
Wood Handbook					.42	1,580	10,100	5,540	500	540
2019	38	Appalachian.	6.18	25.04	.48	1,540	13,429	6,737	1,335	742
Southern yellow pine, *Pinus palustris* spp.										
1917	5	Florida	9	42	.57	2,130	15,600	11,300	1,600	840
1935	56	Florida, Maryland, NC, SC, Virginia	9	34	.51	1,800	12,800	7,080	980	690
Wood Handbook					.51	1,790	12,800	7,130	790	690
2019	45	Carolinas, Southeast region.	6.8	40.57	.51	1,535	13,738	7,381	1,694	729

The small clear specimens from the trees cited above were taken from four ft. to16 ft. from each log. The several locations on the trunk improves the variability. The results obtained herein were conducted on lumber from several trees located in different parts of the country. While similar in many ways, these differerces in sampling may account for some of the differences in results.

It was not possible to provide the exact geographical locations of the samples tested from previous studies, but the goal of this study was to obtain as many samples from different localities as possible to provide a study which could be comparable to previous literature (Newlin and Wilson 1917); Markwardt and Wilson 1935). The geographical location of the tree influences the results of this study. The wood from multiple trees has a natural variability even when trees are grown in similar locations, and this can also increase or decrease the strength of wood and its specific properties. The difference in the percentage of summer wood is correlated with the number of rings. The number of rings per inch are a measure of one layer of earlywood and one layer of latewood. Strength is directly related to density and this relationship was shown herein. Density is also correlated to the quantity of summer wood.

For the five species (groups) presented in this study, the number of rings per inch decreased when compared to previous studies. This observation is at least partially explained by the faster growth of the trees and improvement of silvicultural practices involving forests in recent years. Due the fast growth rate and the decrease of number per rings per inch, the percentage of summer wood increased in almost all species; Faster growth rates have little to no effect on diffuse porous hardwoods (maple, yellow poplar); faster growth rate on ring porous hardwoods (oaks) leads to higher strength. With softwoods, faster usually means lower density and strength.

The specific gravity results from each species were similar to results from previous studies (Newlin and Wilson 1917); Markwardt and Wilson 1935) with differences found with yellow poplar and southern yellow pine. The previous studies tested species from a limited number of locations so the previous results (Newlin and Wilson 1917); Markwardt and Wilson 1935) may not have been a thorough represenation of the entire population of the species at that time.

The MOE results from this study were very simlar to results from the previous studies concerning hard maple, yellow poplar and red oak (Newlin and Wilson 1917); Markwardt and Wilson 1935). However, the MOE values of white oak and southern yellow pine were reduced 32.6% and 19.4%, respectively when compared to the results from Markwardt and Wilson (1935). The MOR of all species in this study increased when compared to the results of Markwardt and Wilson (1935).

The results concerning the compression strength perpendicular to the grain increased for all species when comparing this study with Markwardt and Wilson (1935).

Conclusions

The results presented here show that physical and mechanical properties of five specific wood species have occurred within the last 80 years. For the five species presented in this study, the number of rings per inch decreased when compared to previous studies. This can be explained by the faster growth of the trees and improvement of silvicultural practices involving forests during the past 80-100 years. Due the faster growth rates the numbers of rings per inch were reduced as compared to previous work. Compared to previous work, as tested herein, the percentage of summer wood increased in almost all species.

The MOE results from this study were very simlar to results from the previous studies concerning hard maple, yellow poplar and red oak (Newlin and Wilson, 1917); Markwardt and Wilson 1935). However, the MOE of white oak and southern yellow pine decreased 32.6% and 19.4%, respectively when compared to the results from Markwardt and Wilson (1935). For the majority of properties and species, this study appears to suggest that the basic mechanical properties of these species have not changed appreciably in the past 100 years and that the basic properties in wood handbook (2010) are largely unchanged. As such, excepting where changes have occurred as noted herein, those clear wood values can potentially still be used in the calculation of situation specific designs.

CHAPTER III

PHASE II - NON-DESTRUCTIVE TESTS OF FOR FOUR HARDWOODS AND ONE SOFTWOOD SPECIES

Introduction

Wood is a natural material with a diverse variability in its mechanical properties. In order to use a wood species for structural design, numerical simulations, material selection and its quality control, material properties must be known. Reliable and repeatable information concerning the mechanical properties of wood is required to promote the introduction of species into market for specific purposes.

The mechanical properties can be obtained by destructive and non-destructive methods. These properties are necessary to assess the quality of the wood and further compare to other species. Normally the destructive mechanical tests are performed according to ASTM D 143 using small, clear specimens to evaluate strength. Non-destructive tests can be used to determine the stiffness.

Tree growth location, silvicultural treatments, genetics, weather, and soil conditions all influence growth characteristics and properties within and between species. Several elements influence mechanical properties. These include knots, species, slope of grain, density, fissures, ratio of earlywood/latewood, rot and other damage, processing or loading history. Since the wood is a natural material exposed to different conditions and locations, it is impossible to replicate a sample or results exactly as previous studies. The standard demand for “clear” specimens, free of defects. The term “clear’’ is used to denote a specimen that does not contain any visible strength reducing characteristics and has a limited slope of grain.

When performed, destructive tests increases the cost for companies, since after test the samples cannot be used. For these reasons, in the last decades, the study of non-destructive techniques to assess the quality of wood has been increasing. Non-destructive tests produce a reliable and fast result, without changing the wood properties or destroying the test sample.

Among several non-destructive techniques, this paper will focus on acoustic-based methods such longitudinal wave, to predict the modulus of elasticity and modulus of rupture.

The knowledge of longitudinal vibration waves in solid materials is crucial for several non-destructive techniques that characterize materials. The use of longitudinal vibration waves has been a popular basic parameter often used in material such as wood, stones and refractory products to estimate the modulus of elasticity and predict its modulus of rupture. The advantage of using longitudinal vibration waves as a tool to determine the modulus of elasticity is the simplicity of its determination, inexpensive and suitable for several applications. This technique provides an estimation of the material parameters without the rupture of the material, leading to a savings.

The longitudinal vibration frequency can be obtained using the standard ASTM E1876 “impulse excitation of vibration”. It is a method based on measuring the frequency of the test specimen after hitting the sample to obtain the fundamental frequency. The signal is analyzed based on the fast Fourier transform (FFT) that identifies the value of the highest frequency. With the frequency is possible to predict the dynamic Modulus of elasticity (dMOE).

Modulus of elasticity (MOE) is used to predict the stiffness of the material and for the evaluation of the strength parameters such as modulus of rupture (MOR), since they have a positive correlation between stiffness and strength. In general, hardwoods have higher elastic modulus and strength values compared to softwoods.

Objective

The objective of Phase II was to predict and assess the relationship between dynamic MOE measured by non-destructive tests (A-Grader, FFT and Smart-Thumper).and static MOE measured by destructive tests in comparison with Modulus of rupture, compression parallel, compression perpendicular, hardness tangential and hardness radial.

Material and Methods

Material

Mechanical properties are influenced by tree growth characteristics that are determined by the growth location and silvicultural practices. Localized growth characteristics that influence strength dictate that a large sample representative of the entire growth range of a species should be evaluated to yield accurate strength values.

Staircase manufacturers sent 219 samples for testing from representative production materials. Random samples of each species from different locations were shipped or picked up by the Department of Sustainable Bioproducts. In this study, the staircase manufacturer location is known and most of the samples are traceable to a particular sawmill.

The five species selected for this study; hard maple (*Acer saccharum*), red oak (*Quercus rubra* spp.), white oak (*Quercus alba* spp.), yellow-poplar (*Liriodendron tulipifera*) and southern yellow pine (*Pinus palustris* spp.), are a representation of random samples from typical SMA members production for testing. Figure 1 shows the origin of the samples acquired in this study.

The boards have the same quality and specification that is used during typical production, since it is a high-quality material, the boards are free of defects.

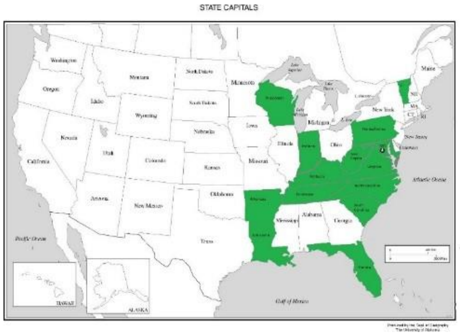

Figure 3.1 Source of the raw material in green.

The dimensions are approximately 3.1cm x 11.4cm in cross section and 91 cm in length. Each air-dried clear board was placed in a conditioned space for 90 days, resulting in a homogeneous pack of samples with approximately 12% moisture content as measured by Wagner MMC220 moisture machine. The tests performed for this study had the same environment where the boards were conditioned (12% equilibrium moisture content).

Each board was given an identification label using indelible ink that included letters representing species and a board number within the species. For example, YP101 indicated yellow poplar and 101 indicated the 101st board within that species. A database record was created to hold the label, weight measured by general calibrated scale, dimension and results from destructive and non-destructive tests.

The Department of Sustainable Bioproducts identified the common name and the botanical name for each species as shown in Table 1.

Table 3.1 Botanical names, location of the mills and number of samples.

Common and botanical name	**Locality**	Number of boards
Hard maple, *Acer saccharum*	NY, PA, Appalachian region, Upper mid-west.	44
Red oak, *Quercus rubra* spp.	WV, VA, PA, Appalachian region, Upper Midwest region	48
White oak, *Quercus alba* spp.	KY, WV, Appalachian region, Upper Midwest region.	44
Yellow-poplar, *Liriodendron tulipifera*	Appalachian region	38
Southern yellow pine, *Pinus palustris* spp.	Carolinas, Southeast region	45

Non-destructive Testing

To measure the frequency of the boards, a hammer was used to induce a measurable mechanical vibration in the board. The test board was supported at each end by two pieces of foam to reduce the contact between sample and support. The signal detection used a direct contact transducer (acoustic microphone) connected to a computer. Three NDT tools were used to collect dMOE data. Two computer software tools that use external microphones (Fakopp 2005 and Falcon A-grader) and an iPhone with a new App (Smart Thumper) were used to read the longitudinal vibration wave. The acoustic velocities obtained by these methods were according standard ASTM E1876-07. Fig 2. Set up to record the resonance frequency in longitudinal vibration. (Chauhan and Sethy, 2016).

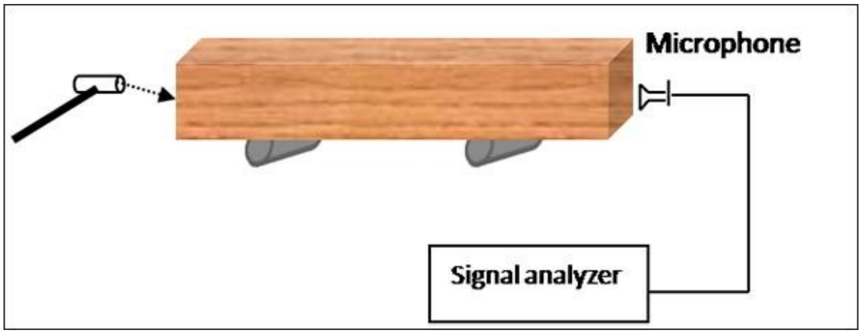

Figure 3.2 Test set-up for non-destructive test.

The dynamic modulus of elasticity was obtained from the software A-grader, smart-Thumper and Falcon from its longitudinal vibration was recorded. The FFT tool provides a frequency but not a direct dMOE reading. The frequency was converted to a dMOE value using the following equation, (Chauhan and Sethy 2016),

$$\mathrm{dMOE} = 4 * \rho * f^2 * L^2 * 10^{-9} \tag{3.1}$$

Where:
MOE = modulus of elasticity (Mpsi),
ρ = density ($kg.m^{-3}$),
L = length of the piece (m),
f = first harmonic longitudinal vibration frequency (Hz).

After performing the non-destructive tests, the parent boards were moved to a cut-up area. The parent boards were then cut into small test samples using the cutting pattern illustrated in Figure 3. The cutting pattern yielded small clear specimens consistent with ASTM 143. The result was two bending samples named A and B to be loaded in the radial orientation (Bending A) and tangential orientation (Bending B) respectively (Figure 3). Specimens for hardness, compression strength perpendicular to the grain, and compression strength parallel to the grain.

The specimens were labeled using a system that could traced to its respective parent board and subsequently returned to conditioning room.

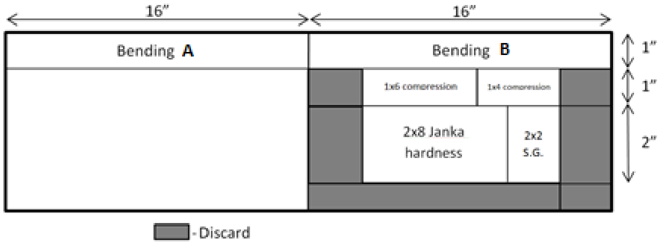

Figure 3.3 Cutting pattern for producing test specimens from each parent board.

Mechanical Tests

The mechanical tests occurred at the Department of Sustainable Bioproducts, Mississippi State University. The machines used were manufactured by Tinious Olsen and Instron. Both machines were controlled by Bluehill 3 Software and the calibrations for each machine were current. The data were moved directly into a SQL database from Bluehill 3 to minimize transcribing errors.

Static bending test

The static bending was conducted on the radial face of samples produced according to Figure 3 and labeled as A and tangential face of samples labeled as B. The testing in both directions can yield a reliable average number. The highest values can be found on tangential surface and lowest on radial surface, its important test both directions to adequately describe the material. The samples were cut 2.54 x 2.54 x 40.64 centimeters (1x1x16 inches) in accordance with Section 8.1 of ASTM-D 143 for secondary specimens. The test specifies the three-point bending test using a center point loading with a test speed of .127 centimeters per minute (.05 inches per minute) and load span of 36 centimeters (14 inches).

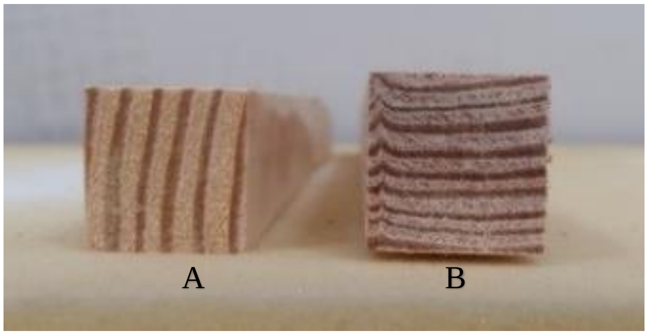

Figure 3.4 Specimen A specimen B

Specimen A was loaded on the radial face and specimen B was loaded with the tangential face nearest to the pith.

Compression parallel to the grain

Figure 5 shows the set up for compression parallel, the specimen measured 25 by 25 by 100mm (1x1x4 inches) specified by ASTM-D 143 (ASTM 2014) for secondary specimens. Since each board had one-inch thick, secondary sizes were necessary for small specimens.

The rate of loading applied to compression parallel tests was of 0.00762 cm /cm (0.003 in./in.) of the nominal specimen length per minute and followed the testing standard.

Figure 3.5 Compression parallel.

Compression parallel to the grain test setup.

Compression perpendicular to the grain

The load is applied through a metal bearing plate measuring 50mm (2 inches) in width across the surface of the specimen in contact with its radial surface. The speed of the test, its 0.00305 cm per minute (0.012 in.). According to standard ASTM 143 (ASTM 2014), the compressed sample should measure 50 by 50 by 150mm, since the boards were only 25mm thick, the actual size of the specimen was 25 by 25 by 150mm (1x1x6 inches). The test setup for determining a specimen's compression strength perpendicular to the grain is shown in Figure 6.

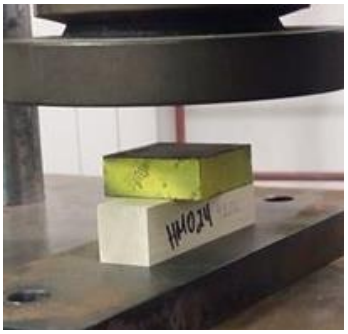

Figure 3.6 Compression perpendicular.

Compression perpendicular to the grain test setup.

Hardness test

To best calculate reliable hardness properties, the average of two hardness tests performed on the radial surface and tangential surface by a steel (Janka) 1.13 cm (0.444 in.) diameter ball at a rate of 0.6 cm per minute (0.25 in. / min) was calculated. The average force required to embed the ball halfway, per the standard, was determined using both orientations.

According to standard ASTM 143 (ASTM 2014) the size specimens specified is 50 by 50 by 150 mm (2x2x6 inches), due to the size of the boards (1-inch-thick), a modification was made to size specimen. The samples were cut to 25 by 50 by 150 mm (1x2x6 inches).

Figure 3.7 Hardness test setup.

Results and Discussion

The data were analyzed using SPSS statistical software. Mean, maximum, medium, standard deviation, coefficient of variation (CV), correlation (r), and coefficient of determination (R^2) were also calculated.

The statistical analysis consisted in comparing the MOE values measured by non-destructive tests such as FFT, A-Grader, Smart Thumper from the boards and compare with the MOE bending values from the small clear specimens A and B from destructive tests to correlate and compare with a modulus of rupture. Further tests such as compression parallel to grain, compression perpendicular to grain, hardness radial, hardness tangential were also measured by destructive tests.

A total of 219 boards of lumber from five different species were evaluated by stress method in order to determine the dynamic modulus of elasticity. The minimum, maximum, mean, standard deviation and coefficient of variation values of dynamic modulus of elasticity, obtained from measurements by longitudinal vibration tests are shown in Table 2.

Table 3.2 Mechanical property values for the five species tested.

Property	Minimum	Maximum	Mean	Std Dev	CV (%)
Hard maple					
MOE Falcon (Mpsi)	1.46	3.00	2.04	0.30	14.7
MOE Smart Thumper (Mpsi)	1.13	1.83	1.56	0.19	12.17
MOE (Mpsi) FFT	1.87	2.71	2.34	0.27	11.53
MOR A (Kpsi)	8.49	22.23	18.33	2.66	14.55
MOE A (Mpsi)	1.43	2.19	1.83	0.22	12.02
MOR B (Kpsi)	11.12	22.75	18.50	2.01	10.87
MOE B (Mpsi)	1.07	2.16	1.84	0.23	12.5
Compression Parallel (Klbf)	7.35	10.19	8.96	0.74	8.31
Compression Perpendicular (Klbf)	1.94	3.004	2.52	0.28	11.28
Hardness Radial (Klbf)	0.96	1.61	1.31	0.17	13.14
Hardness Tangential (Klbf)	1.23	1.81	1.50	0.16	10.66
Red oak					
MOE Falcon (Mpsi)	1	2.31	2.03	0.29	14.3
MOE Smart Thumper (Mpsi)	0.97	1.92	1.45	0.24	16.6
MOE (Mpsi) FFT	1.25	2.74	2.15	0.36	16.7
MOR A (Kpsi)	9.33	21.49	16.34	2.34	14.3
MOE A (Mpsi)	0.82	2.08	1.61	0.26	16.1
MOR B (Kpsi)	9.46	21.64	16.51	2.54	15.4
MOE B (Mpsi)	0.86	2.21	1.66	0.29	17.5
Compression Parallel (Klbf)	6.30	9.69	8.26	0.82	9.87
Compression Perpendicular (Klbf)	1.47	3.03	2.40	0.34	14.3
Hardness Radial (Klbf)	0.89	1.54	1.19	0.17	14.1
Hardness Tangential (Klbf)	0.93	1.65	1.27	0.19	15

Table 3.2 (continued)

Property	Minimum	Maximum	Mean	Std Dev	CV (%)
White oak					
MOE Falcon (Mpsi)	1.01	2.32	1.9	0.32	16.84
MOE Smart Thumper (Mpsi)	0.76	2.06	1.34	0.31	23.13
MOE (Mpsi) FFT	1.12	3.05	1.99	0.43	21.61
MOR A (Kpsi)	7.69	22.19	16.33	3.14	19.2
MOE A (Mpsi)	8.65	22.23	16.86	3.25	19.25
MOR B (Kpsi)	0.93	2.15	1.52	0.29	19.08
MOE B (Mpsi)	0.93	2.12	1.52	0.32	21.05
Compression Parallel (Klbf)	5.98	10.99	8.04	1.08	13.39
Compression Perpendicular (Klbf)	1.76	4.30	2.73	0.55	20.01
Hardness Radial (Klbf)	0.86	2.18	1.40	0.30	21.46
Hardness Tangential (Klbf)	1.03	2.34	1.52	0.36	23.94
Yellow Poplar					
MOE Falcon (Mpsi)	1.41	2.3	2.02	0.25	12.38
MOE Smart Thumper (Mpsi)	0.87	1.73	1.36	0.23	16.91
MOE (Mpsi) FFT	1.33	2.53	2.04	0.33	16.18
MOR A (Kpsi)	9.47	17.81	13.14	2.05	15.63
MOE A (Mpsi)	0.86	1.91	1.52	0.22	14.47
MOR B (Kpsi)	8.35	19.94	13.72	2.20	16.05
MOE B (Mpsi)	1.03	1.93	1.57	0.22	14.01
Compression Parallel (Klbf)	5.13	8.65	6.70	0.95	14.2
Compression Perpendicular (Klbf)	0.89	2.17	1.34	0.32	24.24
Hardness Radial (Klbf)	0.43	1.00	0.72	0.17	23.24
Hardness Tangential (Klbf)	0.58	1.24	0.82	0.19	23.28
Southern yellow pine					
MOE Falcon (Mpsi)	0.8	2.48	1.95	0.36	18.46
MOE Smart Thumper (Mpsi)	0.51	2.03	1.26	0.31	24.6
MOE (Mpsi) FFT	0.76	3.1	1.97	0.47	23.86
MOR A (Kpsi)	9.46	19.64	13.96	2.17	15.54
MOE A (Mpsi)	0.56	2.22	1.53	0.34	22.22
MOR B (Kpsi)	9.27	18.51	13.52	1.78	13.13
MOE B (Mpsi)	0.56	2.22	1.53	0.32	20.92
Compression Parallel (Klbf)	4.33	10.85	7.38	1.24	16.86
Compression Perpendicular (Klbf)	0.88	3.01	1.69	0.48	28.17
Hardness Radial (Klbf)	0.43	1.15	0.70	0.16	22.48
Hardness Tangential (Klbf)	0.48	1.24	0.76	0.18	23.74

The samples of five species with were tested by non-destructive methods based on wave propagation and the possibility of wood stiffness and strength prediction were analyzed.

The results show that the dynamic modulus of elasticity values obtained by the longitudinal wave method is closely correlated with the static modulus of elasticity. A lower coefficient of correlation was observed when the longitudinal wave was used to compare with

MOR. The values of the dynamic modulus of elasticity were always higher than the values obtained by the static bending. The lower static MOE values were expected because static measurement includes shear deflection. The modulus of elasticity order from low value to high value for different methods were Smart Thumper < MOE < Falcon < FFT. All methods used were found to be suitable to assess the stiffness of wood. These methods were found to be less suitable in comparison with static MOE.

Correlation between the longitudinal dynamic modulus of elasticity and static modulus of elasticity

All samples and mechanical properties of the observed species were correlated between the three non-destructive measurements (Falcon, Smart-Thumper and FFT) and the static modulus of elasticity, modulus of rupture, compression parallel/perpendicular, hardness and specific gravity. The correlation between tests are presented in tables 3, 4, 5, 6, and 7. A strong correlation with an R square of 0.91 was found between the dMOE determined by longitudinal vibration and the MOE determined by bending test. The relationship between static and dMOE is given in tables 3, 4, 5, 6, and 7.

Table 3.3 Correlations for hard maple

Property	MOE Falcon (Mpsi)		MOE Smart Thumper (Mpsi)		MOE FFT (Mpsi)	
	r	r^2	r	r^2	r	r^2
MOR A	-0.132	0.018	0.822	0.675	0.878	0.771
MOE A	-0.027	0.001	0.458	0.210	0.514	0.264
MOR B	-0.021	0.000	0.597	0.357	0.668	0.447
MOE B	-0.052	0.003	0.758	0.575	0.849	0.721
Compression Parallel	-0.145	0.021	0.712	0.506	0.722	0.521
Compression Perpendicular	0.051	0.003	0.149	0.022	0.128	0.016
Hardness Radial	-0.149	0.022	0.260	0.067	0.272	0.074
Hardness Tangential	-0.101	0.010	0.244	0.059	0.245	0.060
Specific Gravity 12%	-0.143	0.020	0.277	0.077	0.300	0.090

Table 3.4 Correlations Red Oak (*Quercus spp*)

Property	MOE Falcon (Mpsi)		MOE Smart Thumper (Mpsi)		MOE FFT (Mpsi)	
	r	r^2	r	r^2	r	r^2
MOR A	0.599	0.359	0.706	0.498	0.766	0.586
MOE A	0.581	0.338	0.751	0.564	0.805	0.648
MOR B	0.621	0.386	0.790	0.624	0.818	0.670
MOE B	0.614	0.377	0.830	0.690	0.866	0.750
Compression Parallel	0.523	0.274	0.679	0.461	0.725	0.525
Compression Perpendicular	-0.10	0.01	0.023	0.000529	0.062	0.003844
Hardness Radial	0.149	0.022	0.427	0.182	0.445	0.198
Hardness Tangential	0.119	0.014	0.388	0.151	0.409	0.167
Specific Gravity 12%	0.406	0.165	0.604	0.364	0.637	0.406

Table 3.5 Correlations White Oak (*Quercus spp*)

Property	MOE Falcon (Mpsi)		MOE Smart Thumper (Mpsi)		MOE FFT (Mpsi)	
	r	r^2	r	r^2	r	r^2
MOR A	0.421	0.177	0.477	0.227	0.577	0.332
MOE A	0.555	0.308	0.823	0.677	0.895	0.802
MOR B	0.440	0.194	0.619	0.383	0.686	0.470
MOE B	0.553	0.306	0.853	0.728	0.914	0.835
Compression Parallel	0.543	0.295	0.780	0.609	0.822	0.676
Compression Perpendicular	0.042	0.002	0.016	0.000	0.102	0.010
Hardness Radial	0.288	0.083	0.322	0.104	0.327	0.107
Hardness Tangential	0.195	0.038	0.320	0.102	0.362	0.131
Specific Gravity 12%	0.261	0.068	0.386	0.149	0.435	0.189

Table 3.6 Correlations Yellow Poplar (*Liriodendron tulipifera*)

Property	MOE Falcon (Mpsi)		MOE Smart Thumper (Mpsi)		MOE FFT (Mpsi)	
	r	r^2	r	r^2	r	r^2
MOR A	0.379	0.144	0.612	0.374	0.620	0.384
MOE A	0.660	0.436	0.882	0.777	0.897	0.804
MOR B	0.336	0.113	0.543	0.295	0.546	0.298
MOE B	0.645	0.416	0.856	0.733	0.877	0.768
Compression Parallel	0.434	0.188	0.701	0.492	0.707	0.499
Compression Perpendicular	-0.020	0.000	0.189	0.036	0.202	0.041
Hardness Radial	0.203	0.041	0.416	0.173	0.412	0.170
Hardness Tangential	0.124	0.015	.261	0.068	.266	0.070
Specific Gravity 12%	0.223	0.050	0.456	0.208	0.456	0.208

Table 3.7 Correlations Southern Yellow Pine (*Pinus spp*)

Property	MOE Falcon (Mpsi)		MOE Smart Thumper (Mpsi)		MOE FFT (Mpsi)	
	r	r^2	r	r^2	r	r^2
MOR A	0.142	0.020	0.566	0.321	0.370	0.137
MOE A	0.388	0.151	0.859	0.738	0.614	0.377
MOR B	0.238	0.057	0.521	0.272	0.539	0.291
MOE B	0.495	0.245	0.887	0.786	0.796	0.633
Compression Parallel	0.434	0.188	0.697	0.485	0.647	0.418
Compression Perpendicular	0.067	0.005	-0.265	0.070	-0.175	0.031
Hardness Radial	-0.210	0.044	-0.387	0.149	-0.203	0.041
Hardness Tangential	-0.300	0.090	-0.210	0.044	-0.209	0,044
Specific Gravity 12%	-0.018	0.000	0.128	0.016	0.187	0.035

As expected, the dMOE by longitudinal vibration is higher than static MOE using Falcon and FTT in the five species. Maybe the different dMOE by vibration methods is the differences in the frequencies. The differences in dMOE can be explained by short lengths of the boards. Since latewood is denser than earlywood, it provides the fastest way for longitudinal wave. Dynamic MOE may be influenced by the properties of which species.

Correlation between the longitudinal dynamic modulus of elasticity and modulus of rupture MOR

Generally, the MOE is considered the most important strength predictor parameter. The relationship between dynamic modulus of elasticity and the MOR correlation were performed. Coefficients of correlation are shown in tables 3, 4, 5, 6, and 7.. Correlations between MOR and dMOE coefficients ranged from 0.02 to 0.77 depending on species but this correlation were not as strong as dMOE-MOE correlation as expected. The Falcon showed the weakest correlation to MOR.

Correlation between the longitudinal dynamic modulus of elasticity and specific gravity

Specific gravity is an important wood property to determine the mechanical properties of wood. In dense wood, there are more material distributed internal stresses, so the mechanical properties of wood increase as well. The correlation coefficients obtained from the individual species were quite low, from 0.00 (Southern Yellow Pine) to 0.40 (Red Oak) between specific gravity and dMOE. As seen in Table 2, the specific gravity has a poor correlation when in comparison with the static or even the dynamic modulus of elasticity.

A weak correlation was found between the specific gravity and the dMOE (r = 0.00~0.40), which means that the specificity gravity is a poor predictor of this property. In most species, the MOR was more closely correlated with the dynamic modulus of elasticity than with wood density

CHAPTER IV

SUMMARY AND CONCLUSIONS

This study demonstrates the importance of the non-destructive techniques to obtain the modulus of elasticity in the laboratory and its correlation with the destructive technique by static bending test. The results have been achieved under simplified assumptions. Wood presents anisotropic characteristics, meaning that its properties are dependent on the orientation from which the measurements are being taken.

The ability to use a portable acoustical stress-wave system can allow a rapid estimation of flexure modulus of elasticity without the need for destructive sampling. The measurement method of the dynamic Young's modulus by impulse excitation by vibration is simple to use. The simplicity of the procedure and the reliability of the measures, as well as the low cost of the equipment (laptop and microphone or smart phone) suggest that it could have widespread applicability of this procedure as a control tool. In addition, the method allows classifying timber with greater simplicity, according to their strength capacity and not only to their mechanical resistance.

Based on the results obtained in this study and on the ensuing discussion, the following conclusions were reached:

- This paper demonstrated that a longitudinal wave can be used to rapidly estimate dMOE.
- A portable acoustic stress-wave software can be used to rapidly estimate dMOE.

- The values of correlations obtained from the species under study confirmed the accuracy of the longitudinal vibration techniques, indicating that the software's are valid tools for the nondestructive prediction of the modulus of elasticity of structural timber pieces.

- The dynamic modulus of elasticity obtained by the longitudinal vibration method was higher than that obtained by static bending test.

- Simple regression can be developed to predict MOE from dMOE for a given species of interest.

- The study showed that the integrity of the surface will also significantly affect the measurements and may be the main reason to explain the different values of dynamic elastic modulus obtained by longitudinal vibration in short length specimens. Due to the rough surface, there is a damping in the impact into the surface.

LITERATURE CITED

American Society for Testing and Materials. (2014). D 143. Standard test methods for small clear specimens of timber. ASTM International, West Conshohocken, PA pp. 31.

American Society of Testing and Material (2009) ASTM E 1876: Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration. West Conshohocken, PA. pp. 14.

Chauhan S, Sethy A (2016) Differences in dynamic modulus of elasticity determined by three vibration methods and their relationship with static modulus of elasticity. Madeira Ciencia y tecnologia. pp. 373-382.

Fernow BE (1897). Summary of mechanical tests on thirty-two species of American woods. Circular No 15. USDA, Division of Research Forest Service. Washington, DC. pp. 12.

Forest Products Laboratory (2010). Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI, pp. 508.

Newlin JA; Wilson TRC (1917). Mechanical properties of woods grown in the United States. USDA Forest Service, Forest Products Laboratory, Technical Bulletin No. 556, Washington, DC. pp. 551-575.

Markwardt LJ; Wilson TRC (1935). Strength and related properties of woods grown in the United States. USDA Forest Service, Forest Products Laboratory, Technical Bulletin No. 479, Washington, DC. pp. 99.

Rosell, J.; Pérez, F.; Rodríguez Cantalapiedra, I (2009). Simple method of dynamic young's modulus determination in lime and cement mortars. A: International Conference on Construction & Building Research. "1st International Conference on Construction & Building Research". Madrid: Escuela Universitaria de Arquitectura Técnica. Universidad Politécnica de Madrid, 2009, pp. 1-10.

Sargent CS (1884). Report on the forests of North America (exclusive of Mexico), Part II the woods of the United States. Department of the Interior, Census Office. Government Printing Office, Washington, DC. pp. 247-481.