

12-15-2012

Rapid Non-Destructive Assessment of Southern Yellow Pine Lumber Properties by Near Infrared Spectroscopy

Ignacio Diaz

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Rapid non-destructive assessment of southern yellow pine lumber properties by near
infrared spectroscopy

By

Ignacio Diaz

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

Mississippi State, Mississippi

December 2012

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2012

Rapid non-destructive assessment of southern yellow pine lumber properties by near
infrared spectroscopy

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Title of Study: Rapid non-destructive assessment of southern yellow pine lumber properties by near infrared spectroscopy

Pages in Study: 68

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Over the last several years questions about the strength of structural lumber have been raised. The purpose of this study was to examine the relationship between physically measured wood properties using Near Infrared spectroscopy. Physical properties were determined from (2 x 4 x 2 in.) cut samples. Destructive mechanical testing was performed on 744; 8 feet long, No.2 grade 2x4's. Diffuse reflectance NIR spectra was collected from the cross-sectional face of each block using FOSS NIR Systems Inc. Model 5000 scanning spectrometer. Calibrations were then created between measured properties and NIR estimates. Density, specific gravity, latewood percentage, MOE and MOR had coefficient of determinations of 0.78, 0.56, 0.02, 0.56, and 0.48 respectively. The low correlation is likely caused by the grade of lumber. Because No.2 lumber has considerable knots, they were the determining factor in strength and stiffness; these results would likely not be similar in a higher grade lumber.

TABLE OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES	v
CHAPTER	
I. INTRODUCTION	1
Forest Resources	1
Forest Products.....	1
Juvenile Wood	2
Silvicultural Practices	3
Conclusions.....	4
Near Infrared Spectroscopy	4
The Objectives Of This Study Are To:	5
References.....	8
II. LITERATURE REVIEW	11
Introduction.....	11
Cellulose	12
Hemicelluloses And Lignin	12
Cell Wall And Microfibril	13
Wood Physical Properties – Introduction / Anisotropic	14
Polar & Hygroscopic.....	14
Moisture Content, Bound & Free Water.....	15
Equilibrium Moisture Content (EMC).....	16
Shrinking And Swelling.....	17
Specific Gravity (SG) & Density	17
Wood Mechanical Properties – Introduction	20
Stress	20
Strain.....	21
Stress Vs. Strain Curve	21
Modulus Of Elasticity & Modulus Of Rupture.....	23
Wood Engineering Material - Introduction.....	24
Softwood Lumber	25
Density & Specific Gravity.....	26
Defects: Knots & Slope Of Grain	26

Grading	27
Wood Science & Behavior – Introduction.....	28
Modulus Of Rupture / Specific Gravity.....	29
Modulus Of Elasticity / Specific Gravity.....	29
Conclusions.....	29
Near Infrared Spectroscopy –Overview.....	31
Spectroscopy	32
Spectra Analysis.....	33
Near Infrared Spectroscopy – Agricultural Industry	34
Morphological Properties - Forest Products	35
Physico-Mechanical Properties - Forest Products	36
References.....	41
III. MATERIALS AND METHODS.....	49
Test Material	49
Specimen Preparation And Testing	50
Near Infrared Spectroscopy	51
Wood Property Calibration.....	52
Prediction Of Wood Properties.....	52
Results.....	53
Wood Property Calibration.....	53
Calibrations	53
Discussions	55
Conclusions.....	59
APPENDIX	
A. SUPPLIMENTARY TABLES AND FIGURES.....	61

LIST OF TABLES

A.1	Summary statistics of variation in southern yellow pine physico-mechanical properties of samples used for the calibration and prediction sets.....	62
A.2	Summary statistics of calibrations and predictions obtained using second derivative treated NIR spectra collected from the cross-sectional face of each strip at 2 nm intervals over the wavelength range 1100-2500 nm.....	63

LIST OF FIGURES

1.1	Forest cover in percentage of total land area FAO 2010.....	6
1.2	Forest cover in percentage of total land area FAO 2010.....	7
2.1	Stress-strain Curve. Mechanics of materials. Pytel A. and Kiusalaas J. 2003.	39
2.2	Southern Yellow Pine Design Values. Southern Pine 2012.....	40
A.1	Calibration Models.....	64
A.2	Relationship between physically measured properties and near infrared (NIR)-predicted measurements	66

CHAPTER I

INTRODUCTION

Forest Resources

The Food and Agriculture Organization (FAO), in cooperation with its member countries, has assessed the world's forests resources at five to ten year intervals since 1946. The Global Forest Resources Assessment 2010 (FRA 2010) is the most comprehensive assessment to date (FAO 2010). It examined the current status and trends for more than ninety variables related to the extent, condition, and uses of all types of forests in 233 countries and areas altogether for four points in time: 1990, 2000, 2005, and 2010. FRA (2010) reported that the world's total forest area was just over four billion hectares, corresponding to thirty-one percent of the total land area. The five most forest-rich countries (China, Canada, Brazil, Russia, and USA) accounted for over half of the total forest area (figure 1.1).

Forest Products

The three main sources of industrial wood supply are (1) old-growth (virgin) forests, (2) secondary growth forests, and (3) plantations. It is estimated that industrial wood plantations currently provide nearly 25 percent of the world's industrial roundwood supply (FAO 2010). In 2010, total US lumber production recorded 29,057 million board feet (bf). Eighty-two percent (23,718 million (bf)) corresponds to softwood lumber with

the remaining eighteen percent (5,339 million bf) corresponding to hardwoods (US census 2010). Fifty-one percent of the softwood lumber (11,934 million bf) corresponds to Southern yellow pine (US census 2010) with plantation grown *Pinus taeda* L. (loblolly pine) being the major fiber source (Wear and Greis 2002). The South (figure 1.2), will continue to be a major timber producer in both national and international markets with the area of plantation forests expected to increase in the Southern United States by 67% between 1995 and 2040 to an area of approximately 22 million acres (Wear and Greis 2002). The area of natural timberland is actually expected to decrease increasing pressure to maximize the volume and quality of wood obtained from the plantation resource of the future (Jones 2006).

Juvenile Wood

The greatest percentage of timber supply is expected to be derived from improved trees grown on managed plantations. This fast-grown resource will tend to be harvested in short-age rotations and will contain higher proportions of juvenile wood compared to wood harvested in earlier decades (Kretschmann et al. 1999). Previous research has helped draw attention to a potential problem associated with fast-grown plantation material: the higher percentage of juvenile wood (Ethington 1970; Kretschmann et al. 1988). In all, there is a strong interest in determining whether the lumber resource has suffered a significant change, particularly a decrease in material properties.

In response to this problem, the global forest products community has addressed this issue by thoroughly studying the effect of juvenile wood on full-size structural lumber properties for various species. Juvenile wood is characterized as having low specific gravity, short tracheids, and large microfibril angles, resulting in lower strength

and stiffness compared to mature wood (Shmulsky and Jones 2011). Complementary research conducted at North Carolina State University and the Forest Products Laboratory on clear wood of loblolly pine demonstrated that the problem of lower properties was the result of juvenile wood not plantation wood (Pearson and Gilmore 1971; Bendtsen and Senft 1986). This research demonstrated that juvenile wood is significantly lower in mechanical properties than is mature wood and generally accounts for the inferior properties of plantation wood compared to that of natural timber (Kretschmann et al. 1999).

Silvicultural Practices

Current silvicultural practices such as planting at wide spacing, stimulates rapid stem diameter growth early in the rotation which results in larger volumes of juvenile wood when compared to slower growing trees (Martin 1984, Clark and Saucier 1989). Planting at wide spacings also stimulates crown growth resulting in larger diameter branches (Baldwin et al. 2000, and Sharma et al. 2002). The diameter of knots is a crucial characteristic that reduces southern pine dimension lumber quality (Schoroeder and Clark 1970; Clark et al 1994). Clark et al. (2008) also investigated the effect of initial spacing, competition control, and fertilization on both the number of knots, knot diameter and average maximum knot size. Lumber cut from trees planted at wide spacing could contain larger knots that result in lower lumber grade and lower stiffness and strength (Clark et al. 2008).

In order for the southern pine industry to maintain its competitive position in the forest products market, it must produce wood from intensively managed plantations with the strength and stiffness required to meet lumber standards. Therefore, the effect of

practices on these intensively managed plantations, and in turn on the ultimate strength of dimension lumber continues to be of serious concern as this type of product is generally accounted for as a lower quality material.

Conclusions

It is expected that forest products markets, especially high quality structural lumber, will continue to demand high quantities of this material (Acuna and Murphy 2006, 2007). In the past, tree dimensions and external quality characteristics such as branch length and curvature were key patterns used to classify logs (Hoadley 1990; Clark et al. 2008). Today, however, there is major emphasis put on physico-mechanical and chemical property assessment (density, extractive content) (So et al. 2004). There exist a number of wood properties that will ultimately affect lumber quality. Aside from defects, microfibril angle (MFA), moisture content (MC), and density can be taken as the key factors that determine the strength of any clear piece of southern pine for structural purposes (FPL Technote 214). This is because density can be used as an indicator property used to make predictions on other properties (such as modulus of elasticity and modulus of rupture), whose evaluation methods are intensive and time-consuming. Therefore an effective evaluation on density in a timely manner, presents an ongoing challenge for industry as lumber manufacturers wish to segregate raw material based on this specific property (Acuna and Murphy 2007).

Near Infrared Spectroscopy

Near infrared spectroscopy (NIR) and its relative low cost (instrumentation and sample preparation) is highly compatible with current industry needs (Jones 2006;

Schimleck 2010; Burns and Ciurczak 1992; Siesler et al. 2004). Correspondingly, through the use of multiple linear regression (MLR), partial least squares (PLS), principal components regression (PCR), factor analysis (FA), among others, one is able to generate prediction models (Burns and Ciurczak 1992; Siesler et al. 2004).

NIR spectroscopy has been intensively used in the Forestry/Forest Products Industry for the quantitative and qualitative determination of: (1) chemical composition (nitrogen, cellulose, lignin), (2) morphological properties (MFA), (3) physical properties (density, SG), and (4) mechanical properties (MOE, MOR). Strong results among the measurement of various wood properties have been obtained as measured by the coefficient of determination R^2 , however, all these studies have been based on clear wood specimens with no trace of strength reducing defects (Schimleck et al. 2003; 2004; 2005; 2007; Kelley et al. 2004; Jones et al. 2005; Sykes et al. 2005; Via et al. 2012).

The Objectives Of This Study Are To:

1. To create wood property calibrations for (density, specific gravity, latewood percentage, MOE and MOR) from, Southern pine No.2 grade lumber obtained from five states: Alabama, Arkansas, Georgia, Mississippi and Texas.
2. To examine the performance of the wood property calibrations when applied to samples not in the calibration data set.

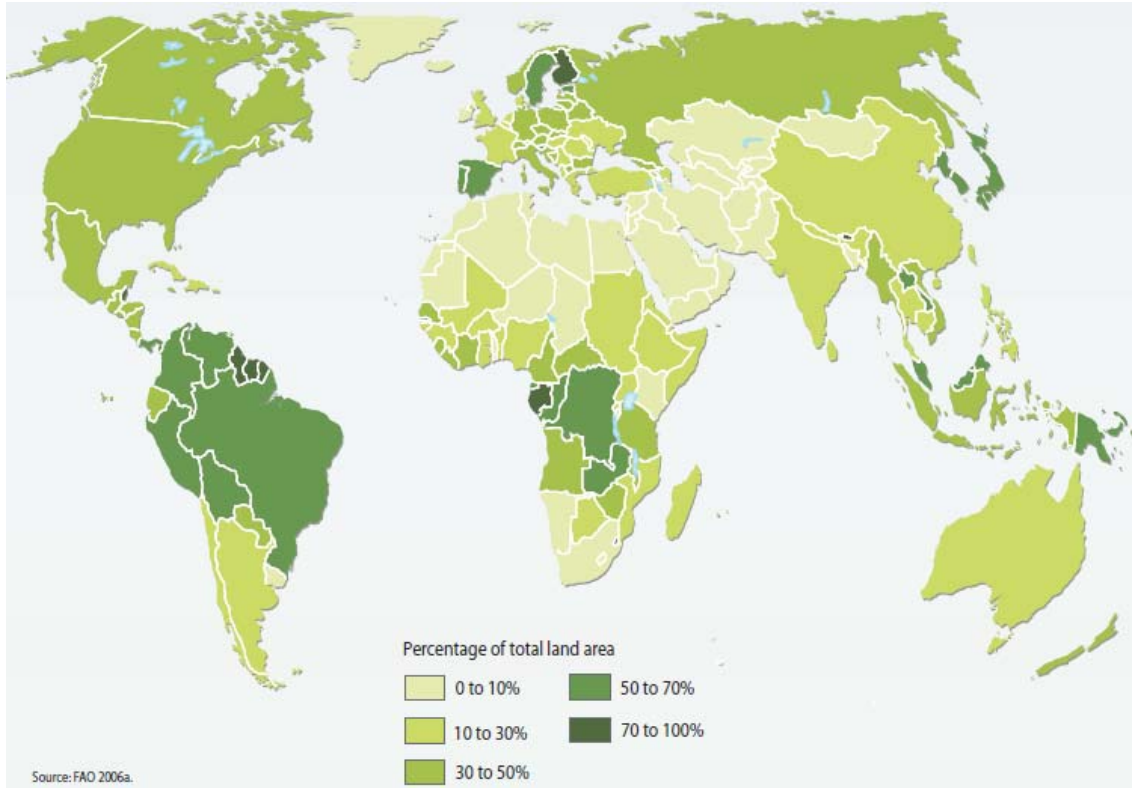


Figure 1.1 Forest cover in percentage of total land area FAO 2010.

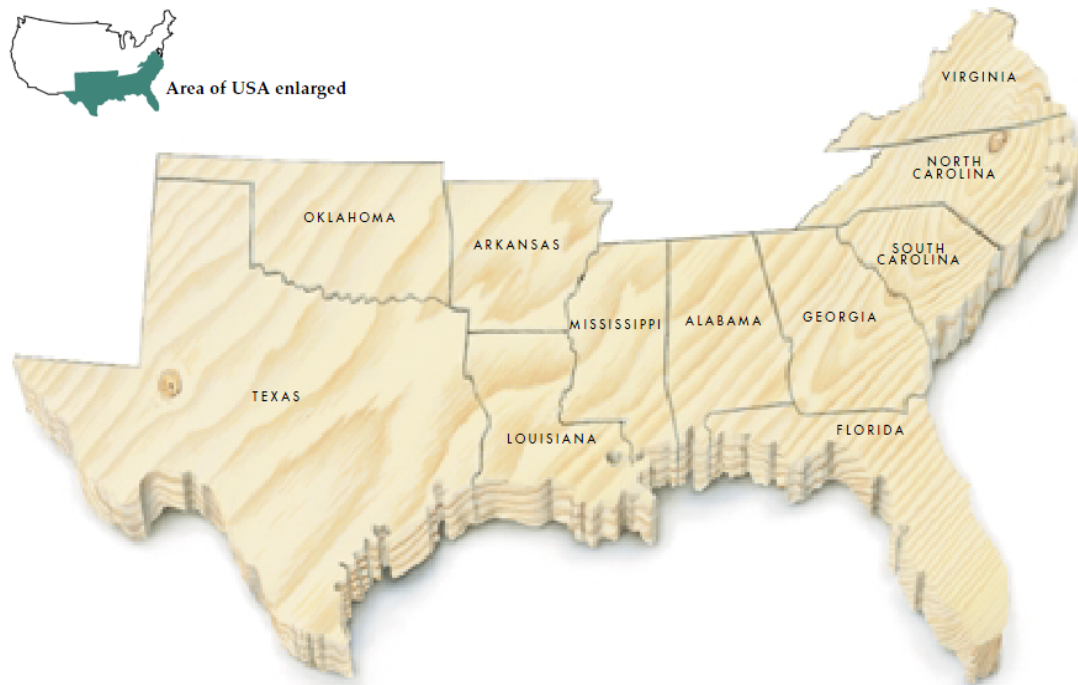


Figure 1.2 Forest cover in percentage of total land area FAO 2010.

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CHAPTER II

LITERATURE REVIEW

Introduction

Wood present in the stem of trees is formed by a unique group of cells that systematically form the xylem tissue. The xylem tissue is formed by a group of cells whose organization varies from species to species, but varies even more between softwoods and hardwoods (Gracia 2004). Additionally, because of its origin as a product of metabolism, wood properties are subject to further variations (Panshin and De Zeeuw 1980; Schultz and Taylor 1989). Despite the fact that wood has great diversity in physical properties, the chemical constituents of all woods are fundamentally the same (Schultz and Taylor 1989). Overall, wood (wood cell wall) is composed of carbon (49.4%), oxygen (44.0%), hydrogen (06.0%), nitrogen (<00.1%), and inorganic ash (~00.5%) (Snow 1917; Pettersen 1984; Shmulsky and Jones 2011). These elements are then combined into organic polymers: cellulose, hemicelluloses and lignin; thus, wood is an organic material.

While cellulose is slightly less than fifty percent of wood's dry weight, the proportion of lignin and hemicelluloses varies widely among species (Shmulsky and Jones 2011). For practical purposes, assume the cell walls are chemically composed of 50% cellulose, 25% hemicelluloses and 25% lignin. More than two thirds of the wood constituents are polysaccharide (Sjöström 1996). As a result, it is important to understand

wood's carbohydrate chemistry. These compounds are mixed in the cell wall in such a complex and highly ordered manner, that this arrangement will ultimately be the one factor determining wood's physical and mechanical properties.

Cellulose

Cellulose is the single most important component in the cell wall both, in terms of volume and on its effect on wood properties (Panshin and De Zeeuw 1980). It has been shown by proton nuclear magnetic resonance spectroscopy that the β -D-glucopyranose adopts the C_1 chair conformation (Kaplan 1998). Upon this configuration, two key features are of critical importance. First, glucose molecules combine (through H-bonding) and second, as the polymerization degree increases, it will continue to do so via hydrogen bonding. This increases the number of bonds (Klemm et al. 1993; Rao et al. 1998; Sjöström 1993). All these events occur by the action of specific enzymatic terminal complexes, called cellulose synthase complexes (CelS) (Habibi and Dufresne 2011). They coordinate the synthesis of glucose chains and the linear association of cellulose to form cellulose microfibrils. The CelS synthesizes 36 glucose chains which can be organized into microfibrils that will be further associated with hemicelluloses and lignin (Sjöström 1996).

Hemicelluloses And Lignin

Like cellulose, hemicelluloses are also polysaccharides. The functions of hemicelluloses include sheathing microfibril bundles, hydrogen bonding with lignin and linking lignin and cellulose (Bower et al. 2002). Lignin is our third wood chemical component. It is a three-dimensional polymer of phenylpropane units (Sjöström 1996)

formed by the dehydration of carbohydrates that generate aromatic structures (Gracia 2004). Lignin occurs between individual cells and within the cell walls of wood. Between cells, it serves as a binding agent to hold cells together. Within cell walls, lignin is very intimately associated with cellulose and hemicelluloses as it gives rigidity to the cell (Shmulsky and Jones 2011). Chemical bonds have been reported between lignin and practically all the hemicelluloses constituents. There are even indications of lignin and cellulose bonds (Sjöström 1996). Lignin is quite insoluble and presents low hygroscopicity. As a result, lignin greatly reduces moisture related dimensional changes occurring in the cell wall. However, the most important property of this polymer is its rigidity and the increased stiffness it imparts to wood's cell wall (Panshin and De Zeeuw 1980).

Cell Wall And Microfibril

The wood cell wall is made up of two layers: (1) Primary wall and (2) Secondary wall. The secondary wall is further sub-divided into three sub-layers: S1, S2, and S3 layers. There is a definite distinction between chemical composition of the primary and secondary cell walls. The most remarkable one is concerning the quantities of cellulose and lignin (Festucci-Buselli 2007). Also of importance, is the microfibril angle (MFA). MFA refers to the angle between the long axis of the fiber and the cellulose microfibrils as they wind around the cell. The steeper the pitch of the helical winding, the smaller the MFA. Thus, the flat spirals of the S1 and S3 layers have a large MFA, while the steeper spiral of the S2 layer has a smaller MFA (Barnett and Bonham 2003). The S2 layer is the central layer in the secondary wall and it has the microfibrils nearly parallel to the cell axis (10-30°). This is the thickest layer, ranging from 30-40 cells in earlywood up to 150

or more in latewood. This layer has the greatest effect on how the cell behaves as its dense organization of microfibrillar lamellae constitutes the bulk of the cell wall (Panshin and De Zeeuw 1980).

In the process of wall formation the microfibrils are enclosed in a continuous system of amorphous lignin. This organization of wall components has been generalized as the reinforced matrix theory to explain many of the physical properties of the cell wall. In this concept, strands of microfibrils, with high tensile strength parallel to their length, are embedded in an amorphous matrix which is plastic in nature. The combination of high elasticity of the cellulose under short-term loads and the plastic flow under long-term loads, which is traceable to the lignin matrix, gives wood its viscoelastic properties (Panshin and De Zeeuw 1980).

Wood Physical Properties – Introduction / Anisotropic

Far from being a homogeneous material, wood is composed of different cellular arrangements throughout its anatomy. Differences in these arrangements result in differences in material properties along its three phases. Accordingly, wood phases can be identified as: (1) longitudinal, (2) radial, and (3) tangential (FPL 2010). As a consequence, wood can be considered an orthotropic material as it has different properties in the three mutually perpendicular axes (Shmulsky and Jones 2011).

Polar & Hygroscopic

Wood can also be considered chemically as being a polar structure, thus having affinity with other polar structures such as water, adhesives and finishes (Vignote, Martínez 2005). Hygroscopy is the ability of a material to attract and hold water from its

environment. This is achieved through either absorption or adsorption (Siau 1995). Absorption results from surface tension and capillary forces, and it results in a bulk accumulation of water in the porous wood. Adsorption, in contrast, involves the attraction of water molecules to hydrogen-bonding sites present in cellulose, hemicelluloses and lignin (Shmulsky and Jones 2011). As the material attracts water molecules, its physical properties change as a response to changes in material weight and volume.

Moisture Content, Bound & Free Water

The total amount of water in a wood element is called the moisture content (MC). It is expressed as a percentage of the oven-dry weight of the wood and it can be calculated as:

$$MC = ((m_{\text{water}}) / (m_{\text{wood}})) \times 100\% \quad (2.1)$$

,where m_{water} is the mass of water in wood and m_{wood} is the mass of the oven-dry wood.

Operationally, the moisture content of a given piece of wood can be calculated as:

$$MC = ((m_{\text{wet}} - m_{\text{dry}}) / (m_{\text{dry}})) \times 100\% \quad (2.2)$$

,where m_{wet} is the mass of the specimen at a given moisture content and m_{dry} is the mass of the oven-dry specimen. The oven-dry weight is used as a basis because it is a repeatable measure of the mass of the material (Shmulsky and Jones 2011).

Water can be taken up by wood in two different ways. It can either be adsorbed by the cell wall (bound water) or it can be absorbed in the cell lumen (free water). The forces of attraction between dry wood and water are so large that it is impossible to prevent the gain of moisture, and in consequence, wood is a hygroscopic material.

(Panshin and De Zeeuw 1980). Molecules of polar liquids diffuse into the spaces in the cell wall structure and between the microfibrils (Vignote and Martínez 2005). Polar liquids bond with dry cell wall material by means of hydrogen bonding (Sjöström 1996). Once all the hydrogen-bonding sites within the cell wall have been occupied by the liquid molecules (hydroxyl groups), the cell wall is considered saturated (Panshin and De Zeeuw 1980). This is called the fiber saturation point (FSP). This condition represents the moisture content at which the cell wall is completely saturated with water (bound water), but no liquid moisture is present in the cell lumen (free water). It is widely accepted to be approximately 30% moisture content (Panshin and De Zeeuw 1980; Siau 1995, Shmulsky and Jones 2011).

As the molecules of liquids enter the cell wall, the microfibrillar framework expands laterally. This condition is associated with the maximum swollen volume of the cell wall and thus causes major changes in the physical properties of wood (Panshin and De Zeeuw 1980). Eventually, maximum moisture content is reached when all spaces in the wall and the lumens are filled. The amount of water held at this point of total saturation will be determined by the void volume of wood (Siau 1995).

Equilibrium Moisture Content (EMC)

Wood exposed to an environment containing moisture will in time, reach a steady moisture content condition called the equilibrium moisture content (EMC) (Siau 1995). EMC of wood exposed to normal outdoor conditions is about 12 to 15% in the Southeastern USA (Panshin and De Zeeuw 1980). This steady-moisture state depends on the relative humidity, temperature of the environment and the drying conditions to which the wood has been previously exposed to. According to Panshin and De Zeeuw (1980),

previous drying conditions may cause the formation of permanent hydroxyl bonds that decrease the capacity of wood to gain moisture.

Shrinking And Swelling

Addition bound water will cause the microfibrillar network to expand, this will continue until the fiber saturation condition has been attained. Further addition of water to the wood produces no change in the volume, but the mass of the wood will continue to increase until the maximum moisture content is reached. Conversely, wood does not begin to shrink until moisture content falls below the FSP (Panshin and De Zeeuw 1980).

Specific Gravity (SG) & Density

Specific gravity (Sg) is a ratio of the density of a material to the density of water (a unitless ratio). It is the single most important physical property of wood as it is strongly correlated to most mechanical and physical properties (Shmulsky and Jones 2011). The physico-mechanical properties of wood are mainly determined by three characteristics: (1) the porosity or proportion of void volume, (2) the organization of the cell structure, which includes the microstructure of the cell walls and the variety and proportions of cells types and (3) the moisture content (Panshin and De Zeeuw 1980).

When calculating Sg, it is mandatory to specify the moisture content at which wood volume was determined. This is because the physical changes (volume and mass) that occur with changes in moisture content below the FSP (Vignote and Martínez 2005). More specifically, when calculating specific gravity we use oven-dry weight. This is to account for such MC% conditions above the FSP in which Sg ends up being the same value for wood samples at different MC%. This happens because volume is constant

above the FSP as no further dimensional changes (microfibrillar expansion) occur at the cell wall (Panshin and De Zeeuw 1980; Siau 1996).

Density is a ratio of the mass of a material to its unit volume. The density of wood depends on specific gravity and moisture content (Simpson 1993). When calculating wood density it is also important to record the conditions at which the material was measured. It is a good practice to calculate density by determining the mass and the volume at the same moisture content (Shmulsky and Jones 2011). Therefore, as in specific gravity, when calculating density it is mandatory to specify the moisture content at which wood volume was determined as well as its volume. Density decreases as moisture content decreases, but below the FSP the Sg increases as the moisture content decreases. This occurs because the dry weight remains constant while the volume decreases during drying (Panshin and De Zeeuw 1980; Siau 1996; Vignote and Martínez 2005; Ananias 2006; Shmulsky and Jones 2011).

Based on knowledge of the moisture content, there are two approaches to the determination of specific gravity of small wood samples. The first is the weight-volume method. If the metric system is used, then 1 gram is the weight of 1 cubic centimeter of water, and the formula for specific gravity becomes:

$$G_f = (m_o / V_f) \text{ or } G_o = (m_o / V_o) \quad (2.3)$$

where G_f and G_o are the specific gravities of the wood sample based on green and oven-dry volumes, respectively; m_o is oven-dry weight in grams; V_f is green volume in cubic centimeters; and V_o is oven-dry volume in cubic centimeters.

The relationship between the specific gravity of a piece of wood and its maximum moisture content offers a new method of determining the specific gravity of small

samples (Smith 1954). From the maximum water content of the completely saturated wood, the specific gravity of the wood (based on green volume) is determined directly without first having to obtain the volume of the sample. The following gives the derivation of the formula:

$$M_{\max} = m_m - m_o / m_o \quad (2.4)$$

$$M_{\max} = m_w / m_o \quad (2.5)$$

$$M_{\max} = V_f - V_{so} / m_o \quad (2.6)$$

$$M_{\max} = V_f/m_o - V_{so}/m_o \quad (2.7)$$

where M_{\max} is maximum water content in grams of water per gram of oven-dry wood; m_m is mass of water-saturated wood in grams; m_w is mass of water in the wood in grams; V_{so} is volume, in cubic centimeters of the oven-dry cell walls constituting the wood sample.

From formula (1) this becomes:

$$M_{\max} = 1/G_f - 1/G_{so} \quad (2.8)$$

where G_{so} is the specific gravity of wood substance comprising the cell walls, and from this it follows that:

$$G_f = 1 / (M_{\max} + (1/G_{so})) \quad (2.9)$$

It has been shown that the density of wood substance is relatively constant and varies only slightly among species as a result of variation in chemical composition of the species (Smith 1954; Panshin and De Zeeuw 1980). In general, Sg and density are used interchangeably as they refer to the same concept of determining the amount of wood contained in a given volume. Numerically speaking, the density of the wood substance in the cell wall is about 1520 kg m^{-3} . On the other hand, the specific gravity of wood

substance, as determined by the water-displacement method, varies between 1.50 and 1.56 and has an average value of 1.53 (Smith 1954; Panshin and De Zeeuw 1980; WHB 2010; Shmulsky and Jones 2011).

Wood Mechanical Properties – Introduction

The three fundamental areas of engineering mechanics are statics, dynamics and mechanics of materials. Statics and dynamics are devoted primarily to the study of the external effects upon rigid bodies – that is, bodies for which the change in shape (deformation) can be neglected (Pytel and Kiusalass 2003). In contrast, mechanics of materials deals with the internal effects and deformations that are caused by the applied loads. In the end, both considerations are of critical importance when considering the design of a structural material (any material).

The strength of materials refers to the load-carrying capacity of the material subject to external loads (WHB 2010). This behavior varies in a number of ways depending upon the kinds of force exerted on the member, but also from any differences in the composition and organization of wood (Panshin and De Zeeuw 1980).

Stress

By definition, normal stress acting on an interior surface is directed perpendicular to that surface. Shear stress, on the other hand, is tangent to the surface on which it acts (Pytel and Kiusalass 2003). There are three kinds of primary stresses, compression, tension and shear. First, the force may act in compression (compressive stress), if it contracts a dimension or decreases the volume of the body. Second, the force may act in tension (tensile stress), if it expands a dimension or increases the volume of the body.

Finally, the force may act as shear (shear stress), if the force acting on the body causes one portion of the body to slide past its adjacent section (Pytel and Kiusalass 2003).

Shear stress is of concern in timber beams because of the low shear strength of wood along the grain (Panshin and De Zeeuw 1980). The stresses caused by the bending moment are known as bending stresses (flexure stresses). Bending stresses result from a combination of all three primary stresses (FPL 2010). Since there are a number of different kinds of stresses, the strength of the material must be stated in terms of its compressive, tensile, shear or bending strength (Panshin and De Zeeuw 1980).

Strain

In all materials, the stresses which act on a body produce a change in shape and size (Pytel and Kiusalass 2003). The measure of distortion resulting from an applied load is defined as strain. This value is expressed in terms of the deformation per unit area or volume (Shmulsky and Jones 2011) There are two major types of strain: normal strain, which characterizes dimensional changes, and shear strain, which describes distortion (changes in angles) (FPL 2010). Each different type of stress produces a corresponding strain, so as is the case with stresses, the kind of strain produced, compressive, tensile, shear, or bending, must be stated (Panshin and De Zeeuw 1980).

Stress Vs. Strain Curve

One fundamental component in the study of the mechanics of deformable bodies is the strength properties of materials. These properties relate the stresses to the strains (figure 1.12). Their relationship to each other defines the mechanical properties of a material (Panshin and De Zeeuw 1980). One of the simplest tests for determining

mechanical properties is the tensile test. In this test, a load is applied along the longitudinal axis of a test specimen. The applied load and the resulting elongation of the member are measured. In many cases, the process is repeated with increased load until the desired load levels are reached or the specimen breaks.

Load-deformation data obtained from tensile and compressive tests do not give a direct indication of the material behavior, because this behavior is also dependent upon the specimen's geometry. However, using fundamental engineering relationships, loads and deformations may be converted to stresses and strains. The resulting stress-strain curve or diagram gives a direct indication of the material properties (figure 1.12).

In wood, when the strain is small, the strain induced is proportional to the applied stress. It is also fully recoverable if the time of application of the stress is short and the strain remains small. The point up to which the stress and strain are linearly related is called the proportional limit (Pytel and Kiusalass 2003) (figure 1.12). For any given piece of wood subjected to stress, the load vs. deformation curve reaches a proportional limit, beyond which the total deformation is non-recoverable and some permanent set is imposed on the specimen (Vable 2012). The area under the stress-strain curve represents the amount of energy absorbed by the wood during its deformation (called the work of deformation) and is an indication of the degree of toughness. (Panshin and De Zeeuw 1980).

The largest stress magnitude in the stress-strain curve is called the ultimate stress. (figure 1.12). The stress at the point of rupture is called the rupture stress. The region of the stress-strain curve in which the material returns to the undeformed state (when applied forces are removed), is called the elastic region. The region which the material

deforms permanently is called the plastic region. The point demarcating the elastic region from the plastic is called the yield point (figure 1.12). The stress at yield point is called the yield stress (Vable 2012).

The initial portion of the stress-strain diagram (for most materials used in engineering structures) is a straight line (figure 1.12). For this initial portion, the stress σ is directly proportional to the strain ϵ (figure 1.12), therefore, for a specimen subjected to a uniaxial load, we can write $\sigma = E\epsilon$. This relationship is known as Hooke's Law. Hooke's Law describes only the initial linear portion of the stress-strain curve for a bar subjected to uniaxial extension. The modulus of elasticity for compressive and tensile stresses is known as young's modulus and the modulus of bending elasticity is commonly indicated as E.

Modulus Of Elasticity & Modulus Of Rupture

Modulus of elasticity (MOE) is the measure of elastic deformation when subject to external loads. Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed (Pytel and Kiusalass 2003). The modulus of elasticity of a material is defined as the slope of its stress-strain curve in the elastic deformation region (figure 1.12). The steepness of the slope of the elastic line is a measure of the magnitude of MOE, the steeper the slope, the greater stiffness.

As an anisotropic material, the three moduli of elasticity of lumber, which are denoted by EL, ER, and ET, respectively, are the elastic moduli along the longitudinal, radial, and tangential axes of wood (FPL 2010). The elastic ratios, as well as the elastic constants, vary within and between species and with MC% and Sg. Available data of the

modulus of elasticity determined from bending, EL, rather than from an axial test, may be the only modulus of elasticity data available for a species (WHB 2010).

In bending, the magnitude of the stress required to cause failure is expressed by the modulus of rupture (MOR). Modulus of rupture reflects the maximum load carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted criterion of strength, though it is not necessarily the true stress as the formula by which it is computed is valid only to the elastic limit (WHB 2010).

Wood Engineering Material - Introduction

As stated earlier, wood polymer constituents are mixed in the cell wall in such a highly ordered manner, that this arrangement is a major factor determining wood's properties. There are other factors that will also be of crucial importance (to various degrees) at the time of considering wood as an engineering material. For example, the mechanical properties of wood will be significantly affected by the specimen's moisture content (Panshin and De Zeeuw 1980). Therefore, any mechanical property should always be reported with its corresponding MC (Shmulsky and Jones 2011). Also, S_g should always be reported, as this property is greatly used as an index of clear wood mechanical properties (WHB 2010; Green and Kretschmann 1997). Clear straight-grained wood is used for determining fundamental mechanical properties; however, because of natural growth characteristics of trees, wood products vary in specific gravity, may contain cross grain, or may have knots and localized slope of grain (FPL 2010).

Softwood Lumber

Softwood lumber grades can be classified into three major categories of use: (a) yard lumber, (b) structural lumber, and (c) factory and shop lumber. Yard lumber and structural lumber grades relate principally to lumber expected to function as graded and sized after primary processing (sawing and planing). Factory and shop grades refer to lumber that will undergo a number of further manufacturing steps.

Almost all softwood lumber standard 38 to 89 mm thick (nominal 2 to 4 in. thick, actual 1-1/2 to 3-1/2 in. thick) is produced as dimension lumber. Dimension lumber is stress graded and assigned allowable properties under the National Grading Rule, a part of the American Softwood Lumber Standard. For dimension lumber, a single set of grade names and descriptions is used throughout the United States, although the allowable properties vary among species, but most importantly within regions (Jordan et al. 2009; Anthony et al. 2011).

Timbers (lumber standard 114 mm [nominal 5 in.] or more in least dimension) are also structurally graded under ALSC procedures (FPL 2010). Unlike grade descriptions for dimension lumber, grade descriptions for structural timbers are not standardized across species. Beams and stringers are members standard 114 mm (nominal 5 in.) or more in thickness with a width more than 51 mm (2 in.) greater than the thickness. Beams and stringers are primarily used to resist bending stresses. Posts and timbers are members standard 114 by 114 mm (nominal 5 by 5 in.) and larger, where the width is not more than 51 mm (2 in.) greater than the thickness. Post and timbers are primarily used to resist compressive stresses.

Density & Specific Gravity

Variations in cellular porosity and in the thickness of the cell walls cause some species to have more wood substance per unit volume and therefore higher specific gravity. Thus, S_g is an excellent index of the amount of wood contained in a piece of wood; it is a good index of mechanical properties as long as the wood is clear, straight grained, and free from defects (Jordan et al. 2008; FPL 2010).

Defects: Knots & Slope Of Grain

The presence of knots in lumber has a direct relationship to the mechanical behavior of the member. Most mechanical properties are lower in sections containing knots than in clear straight-grained wood because (a) the clear wood is displaced by the knot, (b) the fibers around the knot are distorted (cross grain) (c) the discontinuity of wood fiber leads to stress concentrations, and (d) checking often occurs around the knots during drying (FPL 2010). The influence of knots depends on their size, location, shape, and soundness; attendant local slope of grain; and type of stress to which the wood member is subjected (FPL 2010). Compressive stress is not greatly affected by sound knots. The greatest loss of strength from the presence of knots occurs in members subjected to bending stresses. MOR is critically influenced by grain deviations, while bending is the most sensitive property to cross-grain (Panshin & De Zeeuw 1980; FPL2010).

Any form of deviation from the straight grained condition is considered to be a defect in structural lumber because of the reduction of strength in the member in which it occurs. Since truly straight grained lumber is the exception, the extent of grain deviations is an important consideration when using wood for structural purposes.

Grading

For simplicity and economical purposes, pieces of wood of similar mechanical properties are placed in categories called grades (figure 1.19) There are two kinds of graded material: visually graded and E-rated.

Visual grading is the original method for stress grading. It is based on the premise that mechanical properties of lumber differ from mechanical properties of clear wood because many growth characteristics affect properties and these characteristics can be seen and judged by trained grading personnel (FPL 2010). Design values for visually graded dimension lumber are based on results of the North American In-Grade Program that tested full-size pieces of lumber. Southern Pine is the only visually graded softwood species that has been regularly monitored (SPIB 2010).

Machine-graded lumber is lumber evaluated by a machine using a nondestructive test followed by visual grading to evaluate characteristics that the machine may not properly evaluate. These grades are expressed in terms of the size of maximum edge characteristic permitted, along with a specified long-span modulus of elasticity (for example, 1/6–2.2E) (figure 1.17). Machine-stress-rated (MSR) lumber and machine-evaluated-lumber (MEL) are two types of machine-graded lumber. MSR is lumber that has modulus of elasticity evaluated by mechanical stress equipment. MEL is lumber that has a parameter, often density, also nondestructively evaluated by mechanical grading equipment to predict mechanical properties. The MSR and MEL systems differ in grade names, quality control, and coefficient of variation (COV) for E values (MOE). In all, machine grading greatly reduces the variability associated with assigning stress grades to

lumber. Accordingly, SYP grading and design values can be summarized as follows:
figure 1.19.

Wood Science & Behavior – Introduction

In 1964, the Southern Pine Inspection Bureau (SPIB) began a research program at the U.S Forest Products Laboratory (FPL) to determine the flexural and compressive properties of several structural grades of southern pine dimension lumber (for load-sharing framing systems). The study of southern pine dimension lumber was planned to provide a selection of representative samples in a statistically significant quantity from 10 states in the southern pine region. Six structural grades of material and four different sizes were represented. Grades were No. 1, No. 1 Dense, No. 2, No. 2 Dense, No. 3 Medium Grain, and Special and sizes 2x4, 2x6, 2x8, and 2x10 inches. In all, 1,349 static bending and 495 compression parallel-to-the grain tests were made on full-sized pieces, together with 1,414 tests of small clear specimens. As a result, this research represents one of the most comprehensive compilations of data as yet undertaken as a basis for evaluating the potential of machine structural grading (FPL-64).

In the analysis of the results, the correlation coefficient is one of the most important statistical relationships among properties. A correlation coefficient of 1.0 denotes a perfect linear relationship between the properties in which an increase in one property is associated with a direct increase in another. A correlation coefficient of 0 means there is no relationship at all.

Modulus Of Rupture / Specific Gravity

The relationship between the MOR and Sg (based on OD mass and volume) is given for the small clear specimens and the dimension lumber specimens of grades No. 1, No. 2, and No. 3 (from which the small clear specimens were cut). The correlation coefficient was 0.707 for the small clear specimens and 0.494 for the full-size specimens. The regression lines for the two sets of specimens have about the same slope. The correlation coefficients for the different grades and sizes of dimension lumber ranged from 0.246 to 0.581 for the MOR vs. Sg relationship and was 0.516 for all grades and sizes combined. These relationships reflect the limitations of Sg in evaluating the bending strength of dimension lumber containing strength-reducing characteristics (Doyle and Markwardt 1966).

Modulus Of Elasticity / Specific Gravity

The relationship between the flatwise MOE of dimension lumber and Sg is given for all grades and sizes of lumber. The correlation coefficient for these data was 0.614. The relationship between the MOE of the small clear specimens and Sg does not show as good correlations as those obtained for the dimension lumber specimens. The coefficient of correlation was 0.437. These relationships are all low for reliable correlations (Doyle and Markwardt 1966).

Conclusions

The relationships between lumber properties have been used extensively in deriving allowable properties for lumber. The relationship between modulus of elasticity and modulus of rupture forms the basis for sorting most machine-stress-rated lumber sold

in the United States (Galligan et al. 1979). Because of the difficulty in assessing the strength of wood in tension parallel to the grain, the ratio of ultimate tensile stress to MOR has historically been used to estimate allowable tensile strength for both visually and mechanically graded lumber (Green and Kretschmann 1990). The ultimate compression stress parallel to the grain of MSR lumber is also estimated from MOR. Property relationships have also been used to reduce the cost associated with large lumber-testing programs (Green and Evans 1988). Furthermore, property ratios are used in international standards as a basis for standardized property classification (stress class) systems (Fewell 1989; Green and Kretschmann 1990).

A better understanding of lumber property relationships is therefore essential for improved property assignment in engineering design standards. Until recently, studies of lumber property relationships have tended to be based on a limited number of specimens or specimens collected over a limited geographic range. The availability of large data sets collected over a wide geographic range offers the opportunity to establish a better basis for lumber property relationships used in engineering design standards (Green and Evans 1987; Canadian Wood Council 1988; Jones et al. 2005; Jordan et al. 2008; Anthony et al. 2011).

As stated earlier, it is expected that forest products markets, especially high quality structural lumber, will continue to demand high quantities of this material (Acuna and Murphy 2007; Barbour and Kellog 1990; McKeever 2000 and Craig 2003). In the past, tree dimensions and external quality characteristics such as branch length and curvature were key patterns used to classify logs (Hoadley 1996; Clark et al. 2008). Today, however, there is major emphasis put on physical and chemical property

assessment (density, MFA, extractive content) (Andrews 2002; So et al. 2002 and Young 2002).

There exists a number of wood properties that will ultimately affect lumber quality. Aside from defects, MFA and moisture content, density can be taken as the key factor that determines the strength of any piece of southern pine for structural purposes (FPL Technote 214). This is because density can be used as an indicator property into making predictions on other properties (such as modulus of elasticity and modulus of rupture), whose evaluation methods are intensive and time-consuming. Therefore an effective evaluation on density in a timely manner, presents an ongoing challenge for industry as lumber manufacturers wish to segregate raw material based on this specific property (Acuna and Murphy 2007).

No other wood quality evaluation method will yield a better assessment of material property than destructive mechanical testing; however, this concept is neither economical nor practical (ASTM 198). Mechanical testing is very intensive and time consuming. Visually graded lumber more than adequately meets the needs in most traditional applications, but for those more demanding engineered uses, MSR lumber can be advantageous in competing against steel and concrete (SPIB 2012). This procedure has served the public well over the years.

Near Infrared Spectroscopy –Overview

Near infrared (NIR) spectroscopy and its relative low cost (instrumentation and sample preparation) is highly compatible with current industry needs (Jones 2006; Schimleck 2010; Burns and Ciurczak 1992; Siesler et al. 2004). Near infrared coupled with efficient chemometric evaluation routines and modern technologies such as light-

fiber optic, has launched NIR spectroscopy into a new era for industrial control (Burns and Ciurczak 1992). Correspondingly, there is a well-defined mechanism which strengthens this technology with the very core concepts of mathematics and statistics. In fact, without mathematical treatments, NIR spectra would not reveal its full potential. Throughout the use of multiple linear regression (MLR), partial least squares (PLS), principal components regression (PCR), factor analysis (FA), among others, one is eventually able to generate a type of prediction model (Burns and Ciurczak 1992; Siesler et al. 2004).

Spectroscopy

Infrared spectroscopy is one of the most important analytical techniques available to today's scientists. One of the great advantages of infrared spectroscopy is that virtually any sample in any state may be studied (Stuart 1996). Infrared spectrometers have been commercially available since the 1940's. At that time, the instruments relied on prisms to act as dispersive elements, but by the mid-1950s, diffraction gratings had been introduced into dispersive machines (Hollas 2004). The most significant advances in infrared spectroscopy, however, have come about as a result of the introduction of Fourier-transform spectrometers (Lakowicz 2006). Fourier-transform infrared (FTIR) spectroscopy has dramatically improved the quality of infrared spectra and minimized the time required to obtain data. In addition, with constant improvements to computers, infrared spectroscopy has made further great strides (Stuart 1996).

Infrared spectroscopy is a technique based on the vibrations of the atoms of a molecule. An infrared spectrum is commonly obtained by passing infrared radiation through a sample and determining what fraction of the incident radiation is absorbed at a

particular energy. The energy at which any peak in an absorption spectrum appears corresponds to the frequency of a vibration of a part of a sample molecule (Stuart 1996; Acuna and Murphy 2007).

Spectra Analysis

Once the spectra have been recorded, it must then be mathematically processed so as to extract its contained information. There are three key methods into making efficient use of near infrared spectra. First, principal component analysis (PCA) can be used for grouping the samples. Second, if laboratory analysis of a given property has been established, calibrations can be constructed with the data and spectra using simple regression, multiple regression, or multivariate analysis. Third, once a calibration has been created multivariate techniques can be used on the spectra for prediction purposes (the results of the calibration being presented in a plot of NIR-predicted property vs. measured property (Emea 2003). Spectral pre-processing techniques are often applied to remove extraneous information from the NIR data with the purpose of producing strong, robust models (So et al. 2004). These techniques are often used to remove baseline offsets and slopes from spectra. The choice of pretreatment should be considered on a case-to-case basis, and is often a matter of trial and error. However, care must be taken not to lose relevant information during this process (So et al. 2004).

Three of the more commonly used math treatments for the reduction of noise in spectra are multiplicative scatter correction, first derivative, and second derivative (Næs et al. 2002, Jones 2006, Green 2010). Multivariate analysis gives a more complete analysis of the mathematically treated data and therefore is used more often than the other two methods (Næs et al. 2002). The two forms of multivariate analyses generally used for

analysis are principal component analysis and partial least squares (PLS) regression. PCA is a mathematical procedure for resolving sets of data into orthogonal components, whose linear combinations approximate the original data to any desired degree of accuracy (Naes et al. 2002). In PCA, the information in the data is projected down to a small number of latent variables called principal components. PCA is a data reduction method that uses linear combinations of the known variables to create predicted variables, which is most often used for pattern recognition. The first predicted component captures as much variability as possible, and the rest of the principal components thereafter account for as much of the remaining variability as possible (Brereton 2007; Härdle and Simar 2007; Tobias et al. 1995).

Near Infrared Spectroscopy – Agricultural Industry

The first application of MVA to NIR spectra came to prominence with studies by Karl Norris in the 1960's in which reflectance spectra were collected from wheat, revolutionizing the measurement of moisture in the food industry (Norris and Hart 1965; Burns and Ciurczak 1992; So et al. 2004). Further studies were successfully conducted into other properties such as fat content (Norris 1968), which led to increased acceptance of this technology in the food and agricultural industries. The US Department of Agriculture, the then-employer of Norris, made a decision to provide research facilities for continued work in rapid measurement of agricultural products by using NIR (Burns and Ciurczak 1992).

Morphological Properties - Forest Products

Fiber length also plays an important role in the pulp and paper industry. Long fibers yield paper with greater tensile and tear strength for products such as cardboard and paper bags (Myers 2001). Short fibers are preferred for products such as fine printing paper, where surface smoothness and resistance to ink bleeding are important. Coarseness is the total mass of a sample of fibers divided by the total length of all fibers. Coarser fibers tend to have large lumens; therefore it is difficult to separate the effects of lumen size and wall thickness (Kerekes and Schell 1995). Lower coarseness values result in easier fiber collapse, allowing better bonding of fibers and the formation of dense paper with a smooth surface. Wood with higher coarseness values yields pulp and paper products with higher bulk, which is beneficial for products requiring higher absorbance and (or) greater stiffness to bending (all from Sykes et al. 2005).

Schimleck et al. (2004) also worked on predicting tracheid length of *Pinus taeda* from radial wood strip samples. Relationships were good, with coefficients of determination of 0.88 for arithmetic tracheid length and 0.96 for length-weighted tracheid length.

Extensive work carried by Jones et al. (2005) has also targeted the assessment of morphological characteristics of *Pinus taeda*. Tracheid coarseness, specific surface, wall thickness, perimeter, and radial and tangential diameter from 119 radial strips of loblolly pine tree, grown on 14 sites in three physiographic regions of Georgia were measured. As opposed to most of the research previously done, these measurements were carried by SilviScan. In general, strong correlations were obtained for properties

related to density, the strongest being coarseness 0.80, specific surface 0.78 and wall thickness 0.84.

Physico-Mechanical Properties - Forest Products

The relation between NIR estimates and the physical properties of *Pinus taeda* has been studied intensively (Schimleck et al. 2004; 2005; 2006; 2007; Jones et al. 2004; 2005). Schimleck et al. (2003) investigated the physical properties of wood cut from *Pinus taeda* radial samples in response to NIR spectra collected from both, green wood samples at moisture content between 100% and 154% and dried wood at 7%. Twenty *Pinus taeda* wood samples were obtained from a poorly drained forest site in Williamsburg County, South Carolina. That research was carried to determine density, microfibril angle and stiffness. Relationships between measured properties and NIR estimates for wood at a green condition were good. Coefficients of determination R^2 ranged from 0.79 for MFA to 0.85 for density. The prediction R^2 (R_p^2) was calculated as the proportion of variation in the independent prediction set that was explained by the calibration (Jones 2005; 2006). Likewise, dry wood calibrations demonstrated a strong predictive overall relationship with R_p^2 ranging from 0.87 for density to 0.95 for stiffness. Results based from this study suggest that NIR spectroscopy does in fact have the potential to predict density, microfibril angle, and stiffness based on green *Pinus taeda* wood samples. This in turn suggests that NIR spectroscopy could potentially be used to test wood from standing trees, at such high moisture contents. However, previous work carried by Thygesen (1994) on calibrations obtained from *Picea abies* density at high moisture contents provided calibrations statistics that were inferior to those obtained using dry samples (Schimleck et al. 2003). A problem with NIR analysis of samples with

high moisture content is the presence of strong absorption bands (Blosser 1989), whose broad peaks may obscure the spectral information. Therefore, it could be possible that this noise could limit the accuracy of the prediction model.

Further research carried by Schimleck et al. (2005), looked at the estimation of specific gravity (SG), modulus of elasticity (MOE), and modulus of rupture (MOR) of loblolly pine (*Pinus taeda*) clear wood samples, but now from a diverse range of sites across the southern United States. NIR spectra were obtained from the radial and cross sectional (original, rough, and sanded) surfaces of blocks cut from the ends of 280 clear wood samples (140 matching juvenile and mature wood). Calibrations based only on juvenile or mature wood samples had weak calibration statistics and failed to perform well when applied to a separate test set. Calibrations developed using both juvenile and mature wood NIR spectra provided good relationships for all properties with coefficients of determination R^2 ranging from 0.82 (MOE, radial face) to 0.90 (SG, radial face). This study demonstrates that it is possible to obtain multi-site calibrations for SG, MOE, and MOR estimation.

Other research carried by Kelley et al. (2004) has not only proven the accuracy of using NIR as faithful tool for mechanical property assessment, but also that the mechanical properties could be predicted using a reduced spectral range (650 nm-1150 nm), which could allow in field measurements with cheaper, lighter, handheld NIR spectrometers. Additional work by Kelley et al. (2004) took a step ahead into conducting research on a higher sampling population. The NIR spectra and mechanical properties of almost 1000 small clear wood samples from six softwood species were measured. Partial Least Squares (PLS) modeling confirmed that the NIR spectra of these softwoods could

be used to predict the mechanical properties of the clear-wood samples. The coefficients of correlation for most of these models were greater 0.80 As a response to such good results, all six softwood species were combined into one data set and a PLS model was constructed to effectively predict the strength properties of any of the individual softwood. Perhaps the biggest flaw of the NIR technology is its (past) limitation as an indoor lab tool. As also reported by Via et al (2003), in manufacturing, the online monitoring of mechanical properties of wood with near infrared spectroscopy (NIR) is an attractive alternative to more conventional methods.

In this same manufacturing scenario, work done by Rial et al. (2003) validates the use of NIR spectroscopy to characterize medium-density fiberboard (MDF) samples. NIR spectra, in combination with projection to latent structures (PLS) modeling, effectively predicted the mechanical strength of MDF samples with a wide range of physical properties. The stiffness, strength, and internal bond properties of the MDF samples could be predicted from the NIR spectra measured from MDF surface. Results obtained highlight the potential value of NIR spectroscopy for process monitoring and quality control applications, thus confirming this technology as an efficient tool for both solid wood and composite panel property assessment.

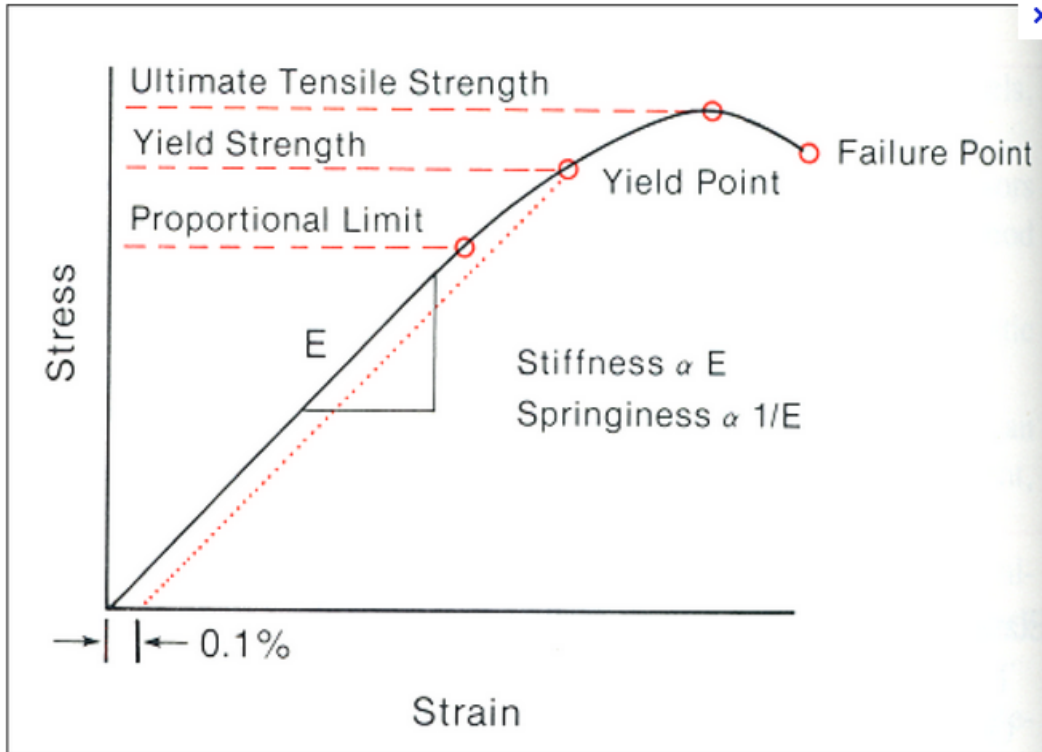


Figure 2.1 Stress-strain Curve. Mechanics of materials. Pytel A. and Kiusalaas J. 2003.

SOUTHERN PINE REFERENCE DESIGN VALUES

and AF&PA National Design Specification®
Values in pounds per square inch (psi)

Table 1 Dimension Lumber – 2” to 4” thick, 2” and wider

Based on Normal Load Duration and Dry Service (MC ≤ 19%)¹ — See Tables A-1 thru A-4 for Adjustment Factors

Size	Grade	Bending F _b		Tension Parallel to Grain F _t	Shear Parallel to Grain F _v	Compression Perpendicular to Grain F _{c⊥}	Compression Parallel to Grain F _c	Modulus of Elasticity ⁵ E E _{min}		
		Single Member Uses	Repetitive Member Uses ²							
2” to 4” thick, 10” wide Includes: 2x10 3x10 4x10 ³	Dense Select Structural.	2150	2470	1200	175	660	2000	1,900,000	690,000	
	Select Structural.	2050	2360	1100	175	565	1850	1,800,000	660,000	
	NonDense Select Struc.	1850	2130	950	175	480	1750	1,700,000	620,000	
	No.1 Dense.	1450	1670	775	175	660	1750	1,800,000	660,000	
	No.1.	1300	1500	725	175	565	1600	1,700,000	620,000	
	No.1 NonDense.	1200	1380	650	175	480	1500	1,600,000	580,000	
	No.2 Dense.	1200	1380	625	175	660	1650	1,700,000	620,000	
	No.2.	1050	1210	575	175	565	1500	1,600,000	580,000	
	No.2 NonDense.	950	1090	550	175	480	1400	1,400,000	510,000	
	No.3 and Stud.	600	690	325	175	565	850	1,400,000	510,000	
	2” to 4” thick, 12” wide⁴ Includes: 2x12 3x12 4x12 ³	Dense Select Structural.	2050	2360	1100	175	660	1950	1,900,000	690,000
		Select Structural.	1900	2190	1050	175	565	1800	1,800,000	660,000
NonDense Select Struc.		1750	2010	900	175	480	1700	1,700,000	620,000	
No.1 Dense.		1350	1550	725	175	660	1700	1,800,000	660,000	
No.1.		1250	1440	675	175	565	1600	1,700,000	620,000	
No.1 NonDense.		1150	1320	600	175	480	1500	1,600,000	580,000	
No.2 Dense.		1150	1320	575	175	660	1600	1,700,000	620,000	
No.2.		975	1120	550	175	565	1450	1,600,000	580,000	
No.2 NonDense.		900	1040	525	175	480	1350	1,400,000	510,000	
No.3 and Stud.		575	660	325	175	565	825	1,400,000	510,000	

Figure 2.2 Southern Yellow Pine Design Values. Southern Pine 2012

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CHAPTER III

MATERIALS AND METHODS

Test Material

The ASTM D1990 standards require a representative population from at least three subregions and a total sampling set of at least 360 pieces when establishing design values (ASTM International 2007). To mimic this approach to account for more variation, 6 packages of No. 2 2×4 material measuring approximately 38 mm \times 89 mm \times 2438 mm of Southern pine lumber were obtained from commercial mills throughout the southeastern US. Number 2 lumber was selected for testing because it accounts for the largest percentage of Southern pine production by grade (Southern Forest Products Association 2005). Each package contained approximately 208 pieces of lumber stamped as kiln dried and heat treated. SP lumber was acquired from SPIB and TPI graded mills in Alabama, Arkansas, Georgia, Mississippi, and Texas. From each pack, the top, bottom, and outside layers were discarded in the event of any shipping damage. From the remaining lumber in each package, 124 pieces were sequentially selected for structural testing. Sequential sampling, where pieces are selected for testing in series, can indicate how well lumber will perform in a structure because they are used in the sequence as found in a package of lumber (ASTM D2915; ASTM International 2010). In the original in-grade testing, the grade of each piece was confirmed by a grading supervisor prior to testing (on-grade) (Jones 1989); for this study, each piece was not regraded because there

was an interest in determining the characteristics of lumber commonly available in commerce (as-graded). A total of 750 pieces of lumber from the 6 packages were selected for testing.

Specimen Preparation And Testing

For each specimen, the dimensions, weight, specific gravity, and moisture content (MC) as determined by calibrated moisture meter were recorded. Generally, the pieces were tested in the condition as received but individual pieces that, were excessively wet, were air dried at ambient temperature in the laboratory until they reached a maximum MC of 23% as specified by ASTM D1990 (ASTM International 2007). The edgewise destructive bending test setup was done according to ASTM D198 (ASTM International 2009) via third-point loading (load heads positioned one third of the span distance from the reactions) on an Instron Bluehill Software controlled Tinius Olsen universal testing machine. The span to depth ratio was 21 to 1 (1867 to 89 mm). The pieces were not placed in the test setup to maximize strength but loaded randomly to better simulate actual use. Deflection was measured using a Tinius Olsen deflectometer to determine the MOE; MOR was calculated from the maximum load. The MOE of each sample was adjusted according to ASTM D1990 (ASTM International 2007), ASTM D2915 (ASTM International 2010), and Evans et al. (2001) where pieces were adjusted to standard loading conditions, then adjusted to 15% MC, and finally adjusted to third-point uniform loading (MOE₁₅). The MOR of each sample was adjusted to 15% MC according to ASTM D1990 (ASTM International 2007) (MOR₁₅). To calculate F_b, the dimensions of each piece were adjusted to 15% MC and then MOR₁₅ was adjusted to a characteristic

length of 3.66 m and divided by a 2.1 safety factor according to ASTM D1990 (ASTM International 2007) and Evans et al. (2001).

The specific gravity (SG_x) was calculated from the weight, dimensions, and MC of each piece. Each SG_x was then adjusted to SG₁₅ using the specific gravity and volumetric shrinkage values of loblolly pine as obtained from the Wood Handbook using a fiber saturation point of 28.7% and a scale factor to account for higher/ lower shrinkage at higher/lower specific gravity of each piece compared with the tabular values (Glass and Zelinka 2010; Kretschmann 2010a).

Near Infrared Spectroscopy

After mechanical testing was completed, a block (38.1 mm radially, 88.9 mm tangentially, and approx. 50.8 mm longitudinally) was cut out from each end of every piece of lumber. Diffuse reflectance NIR spectra was collected from the cross-sectional face of each strip using FOSS NIR Systems Inc. Model 5000 scanning spectrometer. All measurements were made in a controlled environment of 40% relative humidity and a temperature of 20 °C. The spectra were collected at two nm intervals over the wavelength range 1100-2500 nm. The instrument reference was a ceramic standard. Two scans were conducted for each section; these scans were averaged to give a single spectrum per section. Further analysis was made to determine the density, specific gravity, latewood percentage, modulus of elasticity, and modulus of rupture, as a response of NIR testing. Seven hundred and forty four spectra were recorded where 537 spectra represent the calibration set and 181 spectra represent the prediction set. These NIR tests were carried at The Warnell School of Forestry and Natural Resources at The University of Georgia.

Wood Property Calibration

Wood property calibrations were developed using the Unscrambler (version 8.0) software package (Camo AS, Norway). Second derivative math treatment was used to create the calibrations using Partial Least Square (PLS) regression. The second derivative was obtained from the untreated spectra using the Savtizky-Golay approach, with left and right gaps of eight nm. PLS regression was used for the calibrations with four cross-validation segments and a maximum of 10 factors. The Unscrambler software recommended the final number of factors to use for each calibration.

The Standard Error of Calibration (SEC) (determined from the residuals of the final calibration), the Standard Error of Cross Validation (SECV) (determined from the residuals of each cross validation phase), the coefficient of determination (R^2), and the ratio of performance to deviation (RPD_c) (Williams and Sobering 1993), calculated as the ratio of the standard deviation of the reference data to the SECV were used to assess calibration performance. Determination of RPD_c allows comparison of calibrations developed for different wood properties that have differing data ranges and units, the higher the RPD_c the more accurate the data is described by the calibration.

Prediction Of Wood Properties

To examine the performance of the calibrations, they were used to predict the wood properties (density, specific gravity, latewood percentage, MOE and MOR) of the test set samples. The Standard Error of Prediction (SEP) (determined from the residuals of the predictions) was calculated and gives a measure of how well a calibration predicts parameters of interest for set of samples not included in the calibration set. The predictive

ability of the calibrations was assessed by calculating the RPD_p (which is similar to the RPD_c) but uses the standard deviation of the prediction set reference data and the SEP.

Results

Wood Property Calibration

Table 3.2 summarizes the calibration results for the second derivative math treatment. In general, based on RPD_c , RPD_p , and R^2 values we can quickly notice that these calibrations are not strong, but rather weak. These results suggest a rather low correlation between the actual physical measurements and the NIR spectroscopic estimates.

Calibrations

For density, the best calibration was yielded using 9 factors, resulting in an R^2 of 0.62, a SEC of 2.66 and an RPD of 1.28. Similarly SG utilized 9 factors and had a slightly lower R^2 of 0.56; the RPD was also lower at 1.16. Latewood percentage, which is often the driver for higher density and SG used 1 factor and had an R^2 of 0.03 and an RPD of 0.17.

There are two reports on the use of NIR on ground wood (Hoffmeyer and Pedersen 1995; Thumm and Meder 2001) to predict strength properties (Kelley 2004). It is well-known that the strength properties of wood are related to its density, microfibril angle and slope of grain. While it is clear that the NIR spectra contain information on the chemical composition of wood, it is much less obvious that these same spectra contain information on the strength properties of solid wood (Kelley 2004).

The results of these predictions using the full spectral range are shown in table 3.1. The correlations between the measured strength properties and the strength properties predicted with NIR are not good. R^2 values for these models are shown in Table 3.1. R^2 values for the model were 0.56 for MOE and 0.48 for MOR. More importantly, the quality of the test set was also revealed to be low, with R values of 0.75 and 0.69 for MOE and MOR, respectively. The SEC values for the strength properties set were 2.3 GPa for MOE and 14.6 MPa for MOR. This summation of results leads to the conclusion that the strength properties, both the MOE and MOR, of an unknown loblolly pine sample, cannot be accurately predicted from its NIR spectrum.

When comparing these results to previous results from related Southern Pine research carried by Schimleck et al. 2004, 2005, 2007 and Jones et al. 2004, 2010, we can observe RPD_c calibration values in the order of 2.60, 2.32, 2.56 and RPD_p prediction values in order of 2.31, 2.06, 2.25 for Specific Gravity, Modulus of Elasticity and Modulus of Rupture, respectively (Schimleck et al. 2005). Likewise, analyzing previous research by means of other statistical indicators, strong correlations have been obtained by Jones et al. 2004, the strongest R^2 values being 0.83 (density), 0.90 (MFA), and 0.93 (stiffness).

When considering the coefficient of determination R^2 for each of the properties being assessed in our research, we notice that the highest value corresponds to density with an R^2 value of 0.62, followed by SG and MOE both at 0.56. Isolately, latewood percentage calibration obtained a low R^2 value of 0.01.

Also, in general, we can observe a relatively high number of factors included on these calibrations - seven to ten. Previous research has obtained well documented

calibrations at lower number of factors – six to eight factors range (Jones et al. 2004). Again, Latewood percentage calibration was developed with just one factor.

Previous research has also been documented with several math treatments applied to the original NIR spectra. First and second derivative and Multiplicative Scatter Correction (MSC) are well known math treatments that all reduce noise that occurs within spectral data (Næs et al. 2002). However, due to the nature of this research, we mainly focused on results obtained from the original spectra processed with second derivative math treatment. Statistics represented by RPD_c , RPD_p , and the coefficient of determination R^2 quickly revealed the low predicting capacity of these calibrations; therefore, there was no need for any further analysis. This low capacity can be traced back to the lumber grade chosen for this research.

The true test of a calibration is to use it to predict values for a set of samples unrelated from those used to develop the calibration. But again, due to preliminary weak statistics, any further prediction or correction work to be done on the original data set proved to be unnecessary. Correction work refers to the improvement of the wood property calibrations by means of adding a single sample from each of the new sites which has demonstrated to be sufficient enough to decrease the error associated with the predictions to acceptable levels (Gutherie and Walsh 2002 and Jones et al. 2004).

Discussions

In determining the reasons behind this low correlation between the NIR spectroscopic reading and the actual physico-mechanical data, we come up with the following ideas:

As density increases, NIR radiation absorbance (wavelength range 1100-2500 nm) will be affected, perhaps retrieving less information. As a consequence, strength and stiffness prediction will be affected, which in addition to the strength reducing facts associated with the lumber grade, plus the inherent variability of this population traced back to the nature of Southern Pine, we can come to the conclusion to attribute the bulk of the total prediction capacity-loss, to a combination of these three major factors: (1) variation at higher density, (2) lumber grade, (3) Southern Pine variability.

While density and SG had reasonable calibrations the driver for higher density, latewood percentage, had a high amount of error leading to a low R^2 and a low RPD. This could be because of the variability in the data set itself or because of the method used to measure latewood percentage.

I. - When considering the calibration statistics for the fundamental property of Density (figure 3.1); one can notice that a higher degree of variation occurs at higher density values. One explanation for this phenomenon may be explained by the fact that as wood density increases, its mass increases for any given volume. In consequence, as wood density increases, NIR radiation (wavelength range 1100-2500 nm) will experience more matter to propagate into the internal woody tissue and thus, it may be possible that the NIR spectroscopic measurement be based on a superficial reading rather than on a deeper, more integral internal reading. This issue can be further expressed by the fact that when comparing both the line of equality vs. the regression line for all figures, we can clearly see how the calibration underestimated the predicting capacity of density and thus; underestimations and variations on the spread of data can be graphically seen for all derived properties (MOE and MOR figure 3.1.). This reasoning is valid as the NIR

spectroscopic measurements were made on the clear ends of boards, free of strength reducing defects.

II.- Number 2 grade softwood lumber has a considerable number of randomly distributed knots. The presence of knots in lumber has a direct relationship to the mechanical behavior of the specimen. Bending strength is a measure of the resistance to failing. Stiffness is a measure of the ability to bend freely and regain normal shape. Most mechanical properties are lower in sections containing knots than in clear straight-grained wood, mainly because of the stress concentrations caused by the discontinuities of wood fiber around the knot. The influence of knots depends on their size, location, shape, and also to the type of stress to which the wood member is subjected (Panshin & De Zeeuw 1980 and Shmulsky and Jones 2011). The greatest loss of strength from the presence of knots occurs in members subjected to bending stresses. The presence of knots at, or near, any edge of a bending member will produce local cross grain at the edge and reduce the mechanical properties of wood (Panshin and De Zeeuw 1980). The low correlation is likely caused by the grade of lumber selected for analysis. Because No.2 lumber has considerable knots, they were the determining factor in strength and stiffness; these results would likely not be similar in a higher grade lumber.

III.- Wood produced by trees of the same species is often mistakenly assumed to be identical in all structural and physical characteristics. In fact, different pieces of wood even from the same tree are never identical and are similar only within limits. All dimensional and physical characteristics of wood are variable. Understanding the extent of variability of wood is important because the uses for each kind of wood are related to its properties. Furthermore, the suitability of wood for a particular purpose is determined

by the variability of one or more of these characteristics which affect its structure and hence its physical properties (Panshin & De Zeeuw 1980).

The commercial timbers in the USA run to about 80, but many more than 80 tree species contribute to the production of these. Six oaks for example, produce the bulk of the white oak lumber for trade (Panshin and De Zeeuw 1980). The same holds true for red oak. White ash lumber in the east may be almost any ash but black ash. This is because wood of a number of botanically closely related species cannot be distinguished with any certainty after a tree is cut and a log converted into lumber, hence the product is commercialized under a single designation. This is just our case with Southern yellow pine. Southern pine does not refer to any one species of tree but rather a group of species which are classified as yellow pine, as opposed to white pine, and are native to the Southern United States. Southern pine is composed of Loblolly, Longleaf, Shortleaf, and Slash pines.

In determining the physico-mechanical properties of Southern yellow pine from the Southeastern United states we will run into two major variability problems: (1) There is an inherent variability factor traced back to the physical origin of the lumber, for example Georgia Pine vs. Texas Pine and (2) in a rather fine tuning mode, we can further accentuate this issue by comparing perhaps a Shortleaf Georgia Pine vs. a Longleaf Texas Pine. With this in mind, it could be possible that such variation (or at least some percentage of it) and in turn, the low predicting capacity of the wood properties calibrations, may be traced back to these variability issues.

Conclusions

The purpose of this study was to examine the use of NIR spectroscopy, Diffuse reflectance NIR spectra, to estimate the wood properties (density, specific gravity, latewood percentage, modulus of elasticity, and modulus of rupture), of 744 samples of number 2 grade softwood lumber with origin at five different regions: Alabama, Arkansas, Georgia, Mississippi, and Texas. Based on RPD_c , RPD_p , and R^2 values obtained from statistical processing PLS we can determine that these results suggest a rather low correlation between the actual physical measurements and the NIR spectroscopic estimates.

NIR spectroscopy has been intensively used in the Forestry/Forest Products Industry for the quantitative and qualitative determination of: (1) Chemical Composition (Nitrogen, Cellulose, Lignin), (2) Morphological Properties (MFA), (3) Physical Properties (Density, Sg), and (4) Mechanical Properties (MOE, MOR). Strong results among the measurement of various wood properties have been obtained as measured by the coefficient of determination R^2 , however, all these studies have been based on clear wood specimens with no trace of strength reducing defects (Schimleck et al. 2003; 2004; 2005; 2007; Kelley et al. 2004; Jones et al. 2005; Sykes et al. 2005; Via et al. 2012).

Today it is not a matter of proving whether NIR works or not. We already know it works. The focus of our research, the true objective of our work, has expanded into unleashing NIR's true potential. Unlike previous studies, today we have embraced our research into a higher-ordered sampling population. It has been shown how the use of large diverse sets of data, for example in agricultural applications, have indicated that calibrations based on highly variable populations can give strong statistics and are in fact

more robust (Berzaghi et al. 2002). This has proven that the development of calibrations using a large population size will give the best representation of the population of interest (Jones et al. 2005), in this study *P. taeda* grown in Southeastern USA: (Alabama, Arkansas, Georgia, Mississippi, and Texas). However, when considering the lumber grade chosen for this research, any population size seems to have no effect on such a type of calibration. The presence of knots will eventually reduce the mechanical properties of any piece of wood (Panshin and De Zeeuw 1980). The low correlation is likely caused by the grade of lumber selected for analysis. Because No.2 lumber has considerable knots, they were the determining factor in strength and stiffness; these results would likely not be similar in a higher grade lumber.

APPENDIX A
SUPPLIMENTARY TABLES AND FIGURES

Table A.1 Summary statistics of variation in southern yellow pine physico-mechanical properties of samples used for the calibration and prediction sets

SECOND DERIVATIVE	CALIBRATION (537 spectra)				PREDICTION (181 samples)			
	Maximum	Minimum	Mean	STDV	Maximum	Minimum	Mean	STDV
Density (pcf)	42	23	32	3.4	42	24	32	3.5
Sg	0.64	0.35	0.48	0.04	0.58	0.37	0.48	0.04
Latewood (%)	44	35	39	1.68	43	35	39	1.53
MOE (psi)	2,617,000	519,100	1,578,923	369,117	2,628,000	581,900	1,540,914	377,438
MOR (psi)	13,480	1,455	7,114	2,050	12,410	2,488	7,008	2,113

SECOND DERIVATIVE	CALIBRATION (537 spectra)				PREDICTION (181 samples)			
	Maximum	Minimum	Mean	STDV	Maximum	Minimum	Mean	STDV
Density (kg/m ³)	678	365	517	54.5	678	385	513	56.7
Sg	0.64	0.35	0.48	0.04	0.58	0.37	0.48	0.04
Latewood (%)	44	35	39	1.68	43	35	39	1.53
MOE (GPa)	18.0	3.6	10.9	2.5	18.1	4.0	10.6	2.6
MOR (MPa)	92.9	10.0	49.1	14.1	85.6	17.2	48.3	14.2

US Customary and SI units

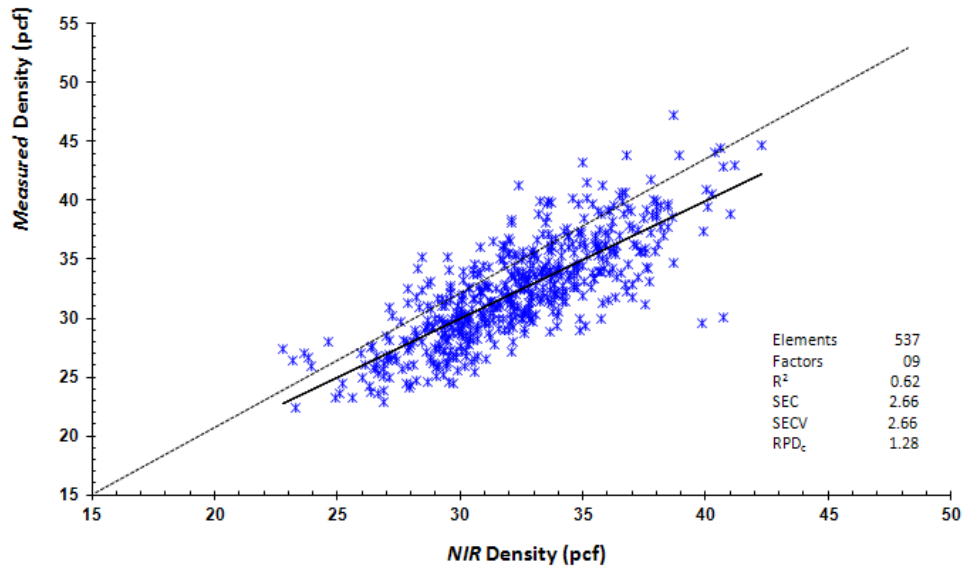
Table A.2 Summary statistics of calibrations and predictions obtained using second derivative treated NIR spectra collected from the cross-sectional face of each strip at 2 nm intervals over the wavelength range 1100-2500 nm.

SECOND DERIVATIVE	CALIBRATION							PREDICTION					
	Factors (#)	Elements (n)	R	R ²	SEC	SECV	RPD _c	Factors (#)	Elements (n)	R	R _p ²	SEP	RPD _p
Density (pcf)	9	537	0.79	0.62	2.66	2.66	1.28	9	181	0.83	0.69	2.70	1.31
Sg	9	537	0.75	0.56	0.04	0.04	1.16	9	181	0.73	0.53	0.04	1.16
Latewood (%)	1	537	0.16	0.03	10.2	10.2	0.17	1	181	0.08	0.01	9.7	0.16
MOE (psi)	7	537	0.75	0.56	327,777	328,082	1.13	7	181	0.75	0.56	312,998	1.21
MOR (psi)	10	537	0.69	0.48	2,124	2,126	0.96	10	181	0.70	0.49	2,053	1.03

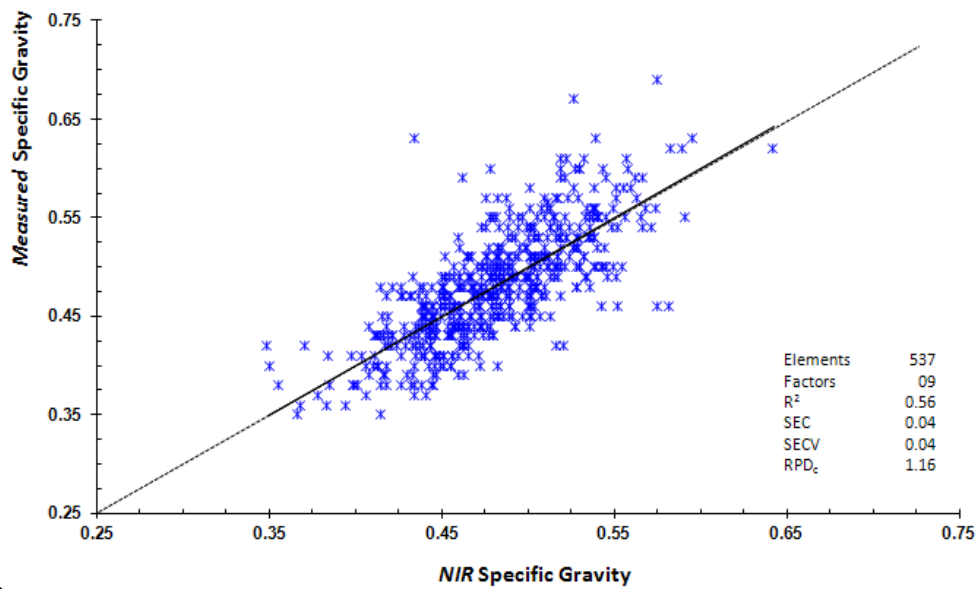
SECOND DERIVATIVE	CALIBRATION							PREDICTION					
	Factors (#)	Elements (n)	R	R ²	SEC	SECV	RPD _c	Factors (#)	Elements (n)	R	R _p ²	SEP	RPD _p
Density (kgs/m ³)	9	537	0.79	0.62	42.63	42.61	1.28	9	181	0.83	0.69	43.20	1.31
Sg	9	537	0.75	0.56	0.04	0.04	1.16	9	181	0.73	0.53	0.04	1.16
Latewood (%)	1	537	0.16	0.03	10.2	10.2	0.17	1	181	0.08	0.01	9.7	0.16
MOE (GPa)	7	537	0.75	0.56	2.3	2.3	1.13	7	181	0.75	0.56	2.2	1.21
MOR (MPa)	10	537	0.69	0.48	14.6	14.7	0.96	10	181	0.70	0.49	14.2	1.03

Customary and SI units.

Calibration statistics include the coefficient of determination (R², R_p²), the standard error of calibration (SEC), the standard error of cross validation (SECV), the standard error of prediction (SEP), and the ratio of performance to standard deviation (RPD_c, RPD_p).



a



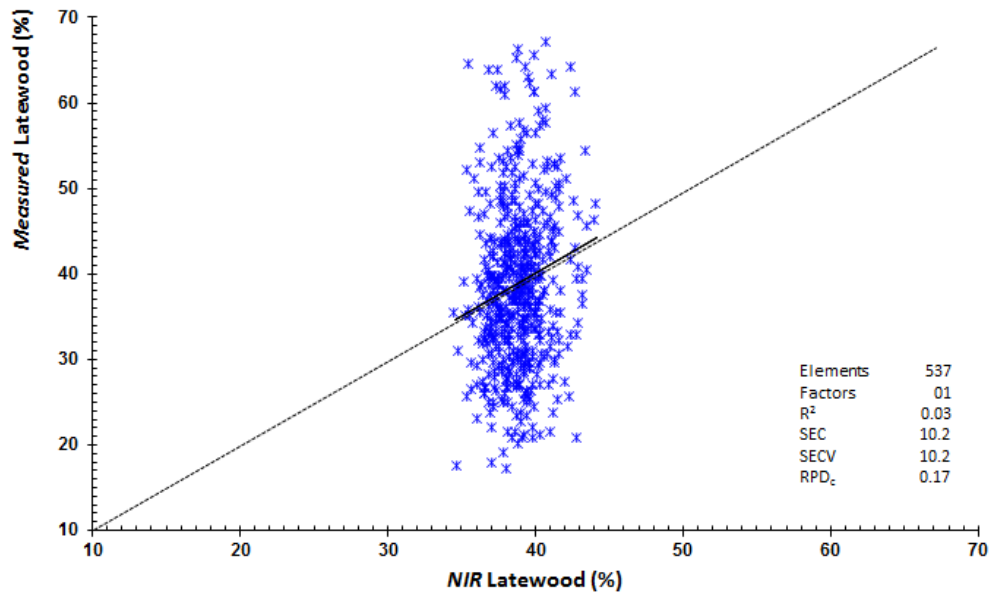
b

Figure A.1 Calibration Models

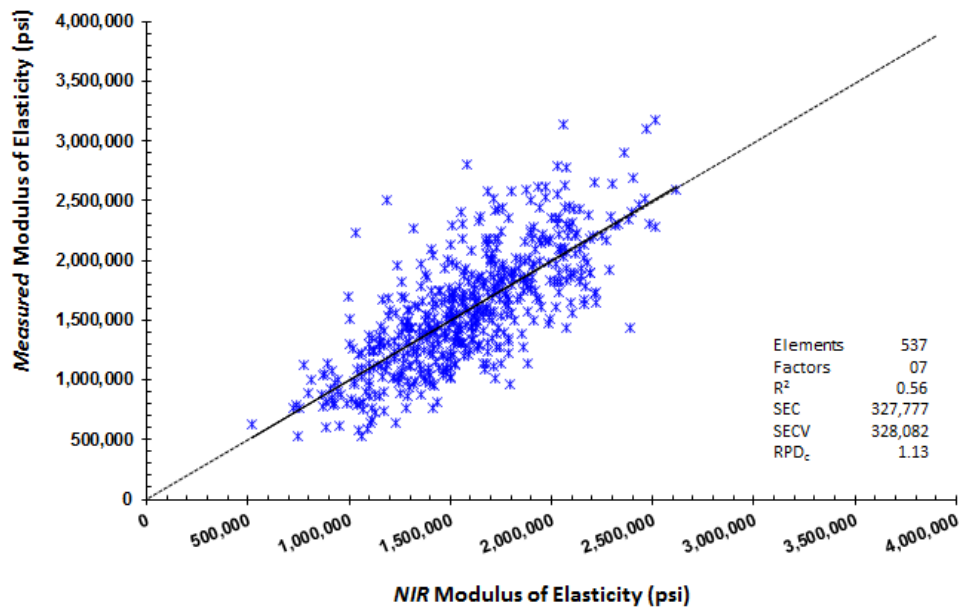
US Customary Units.

Relationship between physically measured properties vs. second derivative treated, NIR-estimated spectroscopic measurements for a. density, b. specific gravity and c. latewood. d. modulus of elasticity and e. modulus of rupture.

The regression line has been plotted as a thick, dark line. The thin dotted line indicates a one-one relationship.

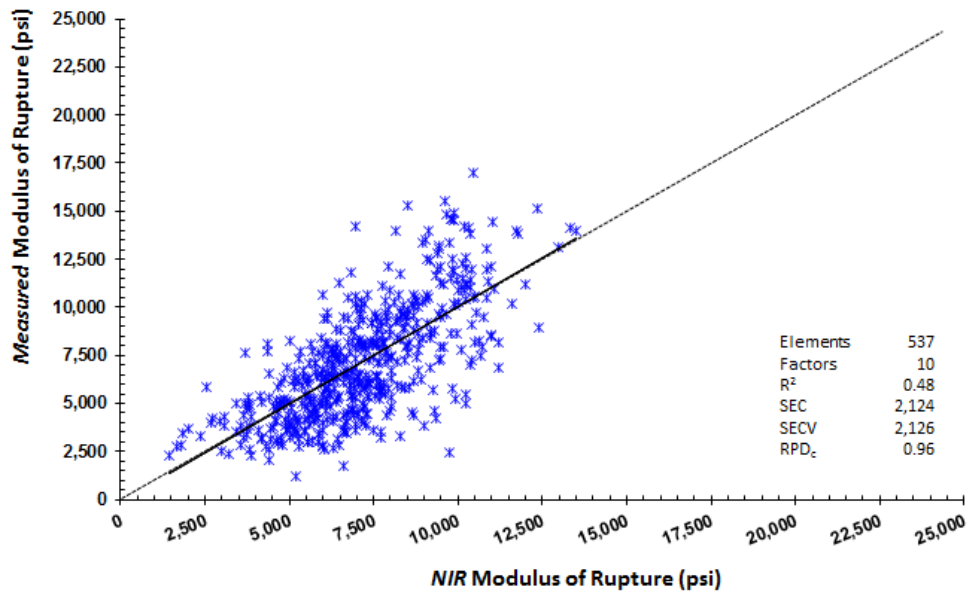


c



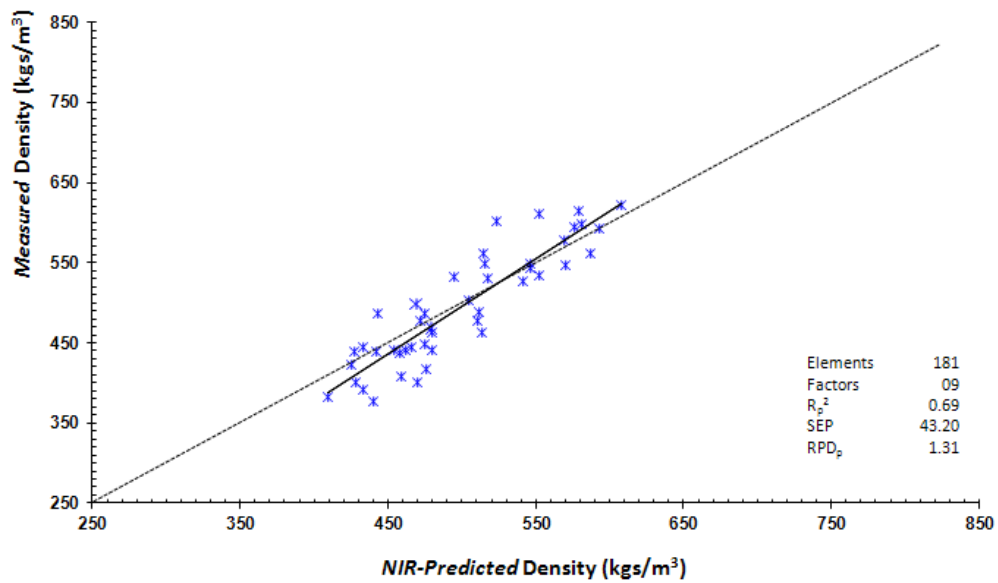
d

Figure A.1 (continued)



e

Figure A.1 (continued)

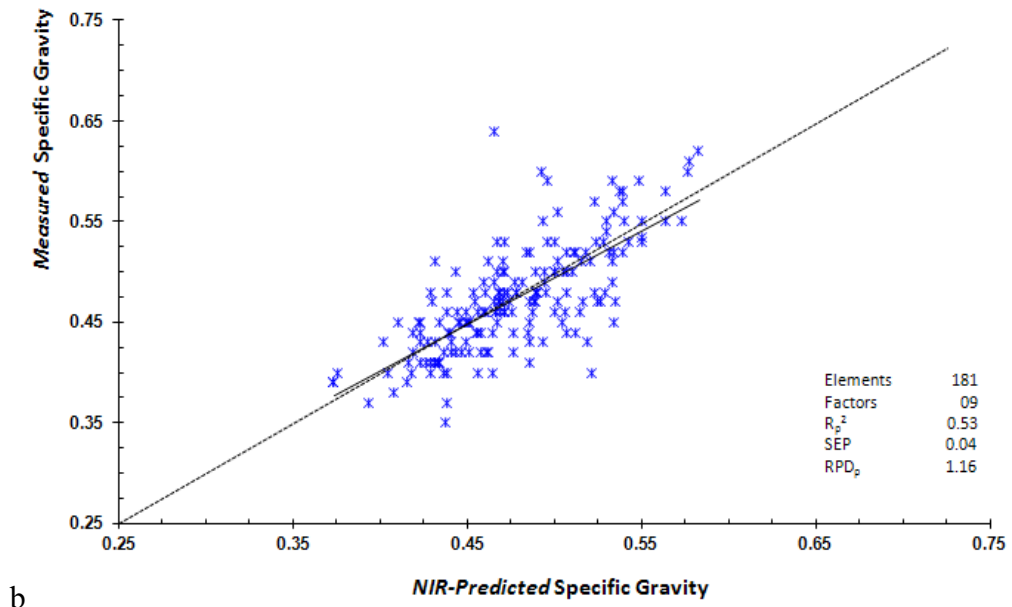


a

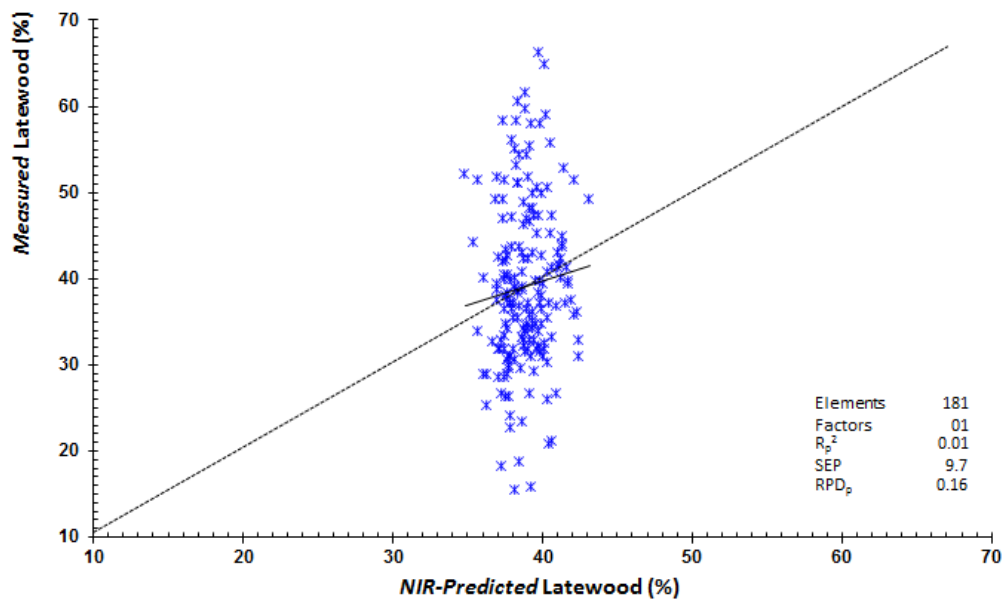
Figure A.2 Relationship between physically measured properties and near infrared (NIR)-predicted measurements

US Customary Units.

a. density, b. specific gravity and c. latewood. d. modulus of elasticity and e. modulus of rupture.

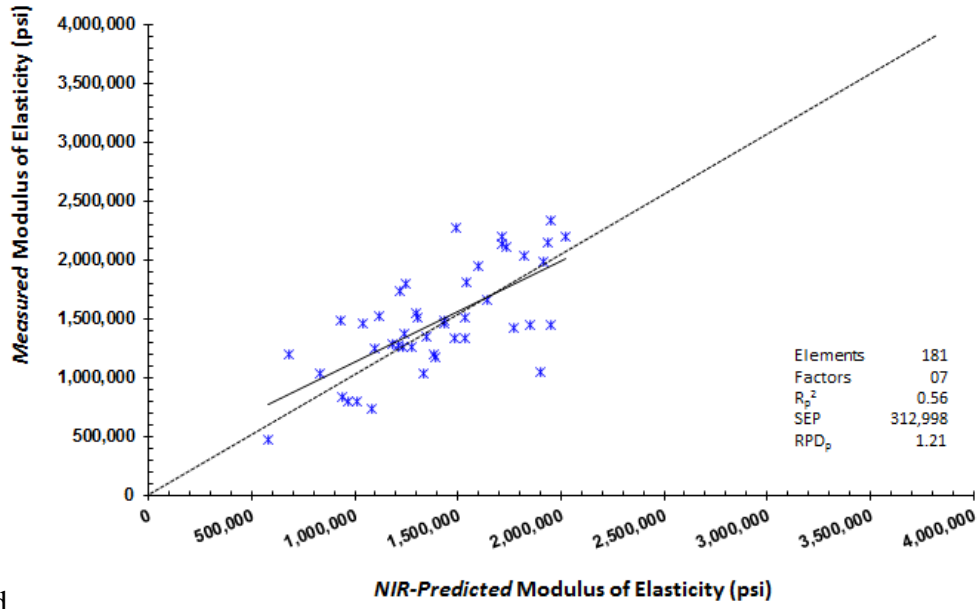


b

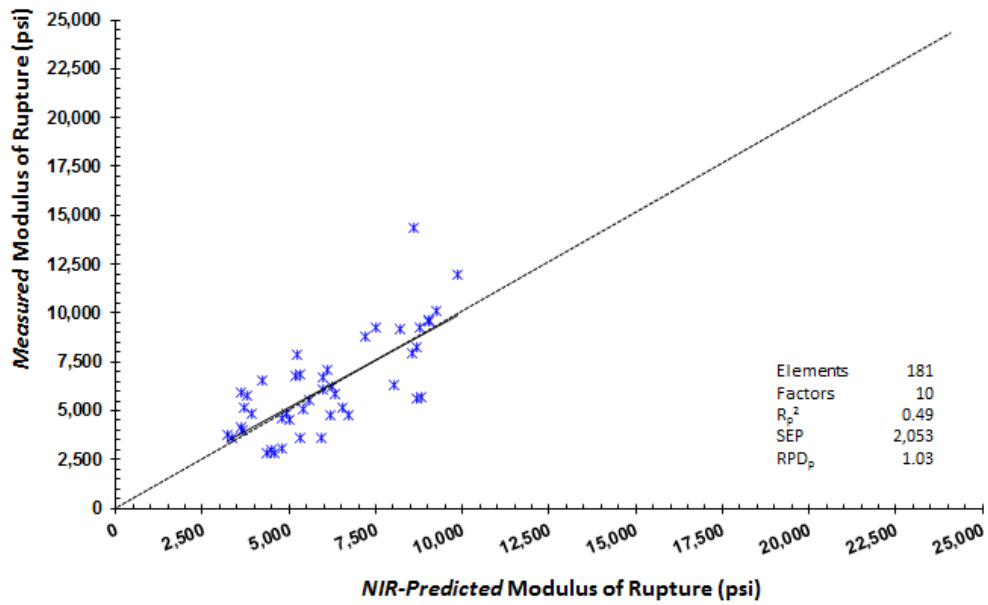


c

Figure A.2 (continued)



d



e

Figure A.2 (continued)