USE OF NEAR INFRARED SPECTROSCOPY TECHNOLOGY FOR PREDICTING BENDING PROPERTIES OF CLEAR WOOD SPECIMENS

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of Kirk David Kludt find it satisfactory and recommend that it be accepted.

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Chair

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USE OF NEAR INFRARED SPECTROSCOPY TECHNOLOGY FOR PREDICTING BENDING PROPERTIES OF CLEAR WOOD SPECIMENS

Abstract

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The use of near infrared spectroscopy (NIRS) for the prediction of physical and mechanical properties of wood products has shown promise for a wide variety of species. The objective of this study was twofold: (1) to evaluate testing and data analysis methods for using NIRS to predict the modulus of rupture (MOR) and modulus of elasticity (MOE) of clear specimens of common Inland Northwest species and (2) to develop statistically robust prediction models from a large and diverse sampling population to predict MOR and MOE of clear wood specimens.

The first paper (Chapter 2) of this thesis described the evaluation and comparison of probing techniques, sample preparation, and data pretreatment methods for the predicting of bending properties with NIRS. The near infrared spectra were collected using three separate diffuse, reflectance-probing techniques. In addition, spectra were collected from both solid and powdered samples. Prior to statistical analysis, spectra were pretreated with 1st and 2nd derivative as well as being left untreated. Results of this study indicate that each of the probing techniques predicted both MOR and MOE with good correlations with R values ranging from 0.88 to 0.92 for untreated spectra. The derivative pretreatments showed little to no improvement

for prediction values. Solid wood samples gave similar results to powder samples for predicting MOR, and were more accurate than powder samples for predicting MOE. This limited study indicated a good potential for the use of NIRS for the prediction of MOR and MOE, although a larger and more comprehensive sampling population would be needed to develop robust statistical models.

The second paper of this thesis focused on the use of NIRS and multivariate statistical techniques to develop robus statistical prediction models for MOR and MOE for three commercially relevant Inland Northwest species: Douglas-fir, grand-fir, and lodge pole pine. A total of 613 "nearly clear" samples were used in this study to develop robust prediction models for MOR and MOE. Because these samples were prepared from small diameter logs it was difficult to obtain truly clear wood samples. As a result, a smaller subset consisting of 256 of the clearest (defect free) and most straight-grained samples was evaluated to look at the effects that "nearly clear" specimens in the sampling population may have on the prediction models for MOR and MOE. Results indicated that correlations for the subset of clear samples were significantly higher than the total population with R values of MOR and MOE of 0.86 and 0.90 for the clear samples as compared to R values of 0.80 and 0.84 for all the samples. Individual species showed no improvement in predictability and the 1st derivative pretreated spectra produced slightly better results than untreated spectra.

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Chapter 1: Overall Introduction

Near infrared spectroscopy (NIRS) offers a promising technique for non-destructively evaluating the modulus of rupture (MOR) and modulus of elasticity (MOE) of solid sawn lumber. Previous studies have used NIRS to predict MOE and/or MOR of clear wood samples of species such as Norway spruce, Radiata pine and eucalyptus delegatensis (Hoffmeyer & Pederson 1995, Thumm & Meder 2001, and Schimleck, etal. 2001a). Since NIRS is an empirical method, there is a need to expand the sample space to include commercially relevant species grown in the Inland Northwest and used extensively for construction in the U.S.

The NIRS technique is based on the absorption (A) of NIR light (wavelengths from 750 nm to 2500 nm) by the material. When a material is irradiated with infrared light, molecules become excited and vibrate. This vibration and the resulting inharmonic overtones in the molecular bonds give rise to absorption bands. Depending on the chemical make-up of the material, a certain amount of near infrared light is absorbed at each wavelength. The reflectance (R) of light at each wavelength is measured with a spectrometer and the relationship of A = log (1/R) is used to calculate absorption.

This thesis is divided into two studies. The aim of the first study, Chapter 2, is to analyze and compare various probing techniques, sampling preparation, and pretreatment and statistical modeling techniques for use as a predictive tool in determining wood properties. The near infrared spectra were collected using three separate diffuse, reflectance-probing techniques. In addition, spectra were collected from both solid and powder samples. Prior to statistical analysis, spectra were pretreated with 1st and 2nd derivative as well as being left untreated. The goals were to explore the feasibility of using near infrared spectroscopy for predicting bending properties of a limited sample size of Inland Northwest species and to analyze and compare

typical NIRS and multivariate statistical techniques to evaluate which methods may work best for future studies.

The goal of the second study, Chapter 3, is to use NIRS and multivariate statistical techniques to develop statistically robust prediction models for MOR and MOE for three commercially relevant Inland Northwest species: Douglas-fir, grand-fir, and lodge pole pine. Regression models for predicting MOR from static MOE and regression models for predicting MOR from NIR spectra plus MOE were developed and compared to the basic MOR models developed strictly from the NIR spectra. In addition, models were developed and compared for individual species as well as for a mixture of all three species. A subset of the clearest and most straight grained samples was chosen for comparison to the entire sample population due to concerns over the "clearness" of the clear samples obtained from small diameter timber.

Chapter 2: NIR Spectroscopy to Predict Flexural Properties of Clear Wood – Evaluation of Testing and Analysis Methods

ABSTRACT

This paper evaluates and compares the effectiveness of probing techniques, sample preparation, and data pretreatment methods for the predicting of bending properties with near infrared spectroscopy (NIRS). For this study, a total of 61 clear wood samples of lodgepole pine, subalpine fir and Englemann spruce were analyzed. The near infrared spectra were collected using three separate diffuse, reflectance-probing techniques. In addition, spectra were collected from both solid and powder samples. Prior to statistical analysis, 1st and 2nd derivative pretreatment was applied to the spectra as well as being left untreated. Results of this study indicate that each of the probing techniques predicted both modulus of rupture (MOR) and modulus of elasticity (MOE) with good correlations (R values ranging from 0.88 to 0.92 for untreated spectra). The derivative pre-treatments showed little to no improvement for prediction values. Solid wood samples gave similar results to powder samples for predicting MOR, and were more accurate than powder samples for predicting MOE. Although not a specific goal, individual species could be clustered in a principal component analysis, indicating a potential use for NIRS technology to identify species. This limited study indicates a good potential for the use of NIRS for the prediction of MOR and MOE, although a larger and more comprehensive sampling population will be needed to develop robust statistical models.

INTRODUCTION

Near infrared spectroscopy (NIRS) is gaining popularity as a nondestructive evaluation technique for organic materials and has found wide spread use in the food, agriculture,

pharmaceutical, petroleum, polymer, and pulp and paper industries (Burns and Ciurczak, 2001). This method is particularly effective in materials where –CH, -OH, and –NH chemical functional groups influence the properties that will be measured because the NIR region contains absorption bands corresponding to overtones and combinations of vibrations of these chemical groups. For this reason, NIRS techniques have shown promise as a nondestructive evaluator of the properties of wood based materials.

The NIRS technique is based on the absorption (A) of NIR light (wavelengths from 750 nm to 2500 nm) by the material. Irradiating a material with infrared light, excites molecules to vibrate. This vibration and the resulting inharmonic overtones in the molecular bonds give rise to absorption bands. Depending on the chemical make-up of the material, a certain amount of near infrared light is absorbed at each wavelength. The reflectance (R) of light at each wavelength is measured with a spectrometer and the relationship of $A = \log (1/R)$ is used to calculate absorption.

Multivariate statistical methods can be used to characterize and analyze the response of spectra data. The increase of speed and capacity in computing along with advancements in statistical handling of data are both factors in the sucess of NIRS research in the last 15 years. Computer intensive statistical methods such as principal component analysis (PCA) and partial least squares (PLS) can be used to identify trends in the spectral data and to predict desired parameters.

Flexural mechanical properties of wood have been predicted using NIRS for Norway spruce, radiata pine, and eucalyptus delegatensis with promising results (Hoffmeyer & Pederson 1995, Thumm & Meder 2001, and Schimleck, etal. 2001a). Density, compression strength, and biological degradation of Norway spruce (Hoffmeyer & Pederson 1995) have also been predicted

with the use of NIRS. Thygesen (1994) studied NIRS for predicting density and dry matter content of Norway spruce. The effects of moisture content on bending strength predictability have also been explored (Kelley, et al. 2001), with the MOE of dry poplar being predicted from a model developed for wet poplar with reasonable correlations (R=0.75). Since NIRS is an empirical method, there is a need to expand the sample space to include commercially relevant species grown in the Inland Northwest and used extensively for construction in the U.S.

The goal of this study was to evaluate laboratory test methods and data analysis techniques for using near infrared spectroscopy to predict modulus of rupture (MOR) and modulus of elasticity (MOE) of clear specimens of selected Inland Northwest timber species (lodgepole pine, subalpine fir, and Engelmann spruce). Specific objectives were to: (a) compare three NIR probing techniques, (b) compare solid versus powder sample preparation, and (c) compare 1st and 2nd derivative pre-treatment of spectral data versus raw spectral data.

LITERATURE REVIEW

Prediction models have been developed using NIRS techniques for a variety of properties of both solid sawn wood and wood composites. A review of the literature relevant to this study is presented below. The literature has been broken into the two categories, solid sawn wood and wood composites and pulp/paper products.

Solid Sawn Wood

Of particular interest to this study, flexural properties of hardwood and softwood species have been predicted with NIRS technology with success. Hoffmeyer and Pederson (1995) evaluated correlations between NIR spectra and density, moisture content, compression strength in addition to the bending strength for Norway spruce specimens with a range of natural growth

characteristics. Density, moisture content, and compression strength tests were conducted on 20 x 20 x 60 mm specimens. Flexural tests were conducted on 45 x 90 x 1800 mm timbers, where normal growth characteristics such as knots were present. Modulus of rupture was predicted with relatively low accuracy (R = 0.54). Since the NIR method relies heavily on scan areas being representative of the entire sample (homogeneity), it is not surprising that this method did not show very strong prediction for bending specimens with knots, varying slope of grain and other growth characterizations. Reflectance spectra were gathered on solid samples over a wavelength range of 1200 nm to 2400 nm. In sampling the NIR spectra, each sample was measured twice and averaged prior to statistical handling. No signal pretreatments (1^{st} or 2^{nd} derivatives) were conducted on the spectra. Calibration models were developed using the partial least squares (PLS) and principal component regression (PCR) statistical methods, and validated on independent test tests. Linear correlations between predicted values and measured values were used to evaluate the fit of the prediction models. Compressive strength (correlation coefficient = R = 0.96), density (R = 0.87), and moisture content (R = 0.99) were predicted with excellent agreement for four-factor calibrations. The compression strength of biologically degraded samples was also well predicted (R = 0.90).

In contrast to Hoffmey and Pederson (1995), other studies have focused on predicting the MOR and/or MOE for clear wood specimens (Thumm and Meder, 2001; Schimleck et al., 2001a and 2001b; Gindl et al., 2001), and not surprisingly, have found much higher correlations.

Thumm and Meder (2001) studied NIRS for the prediction of modulus of elasticity (MOE) of radiata pine clear wood test pieces using a moving spectral scan (900 mm/min.). All tests were conducted on the radial face of solid, clear specimens and spectra were collected over the region of 400 nm to 2500 nm. The total number of samples used in the calibration model

was 486 and the validation model consisted of 80 samples. Calibration models were developed using the PLS method. The spectra in the NIR region (1100 nm to 2500 nm) were found to predict MOE slightly better than the entire range and significantly better than the visible light region (R = 0.85 versus R = 0.84 and R = 0.77, respectively). Further comparisons were made between the effects of raw, 1st derivative, and 2nd derivative pretreatment of the spectra, where the 1st derivative data gave the best results (R = 0.85 and root mean square error of prediction (RMSEP) = 1298, followed closely by the raw spectra (R = 0.84 and RMSEP = 1322) and the 2nd derivative pretreated spectra (R = 0.84 and RMSEP = 1337). Preliminary results on a small subset of 72 samples showed better prediction of MOE with the moving scan (R = 0.74) versus the static scan (R = 0.62).

Schimleck et al. (2001a) predicted physical and mechanical properties of *eucalyptus delegatensis* samples using NIR spectroscopy and the PLS method. In addition to MOR and MOE, density and microfibril angle (MFA) were also predicted from NIR spectra with R values ranging from 0.86 for MFA to 0.96 for density values. One NIR measurement comprised of 50 averaged scans was recorded for the radial-longitudinal face of each 2 x 7 x 20 mm solid sample. Spectra were collected at 2 nm intervals over the range of 1100 – 2500 nm. Second derivative signal processing was found to give the best predictive results in contrast to Thumm and Meder (2001) who found that 1st derivative pretreatment provided slightly better correlations.

Gindl et al. (2001) used NIR spectroscopy and the PLS method to predict MOE, MOR, and compression strength of European larch. The effects of compression wood on predictability were explored, since mechanical property correlations are often different for compression wood compared to normal wood. NIR absorbance correlated well with the desired mechanical properties in both the normal samples and compression wood samples. This indicates that

additional information about wood characteristics other than density is present in the NIR spectra. For this study, three NIR measurements containing 100 scans were averaged for each sample.

Other aspects of using NIR to predict wood properties have been explored. Tsuchikawa (1996) investigated the effects of surface roughness and fiber orientation of wood on the absorption of NIR. He found that as orientation of fibers to the direction of incident light increased and as surface roughness increased, absorbance of NIR spectra decreased. Schimleck et al. (2001b) explored the use of NIRS to develop a calibration model for density, E_L, and MFA from a wide range of species. Spectra were obtained from the radial/longitudinal face of solid samples. NIR spectra from a total of 59 different species, representing a range of wood quality, were used for the calibration models. These general calibration models predicted modulus of elasticity of independent species with encouraging results ($R = 0.84$ for a four factored model). The ability to predict MOE of one species from a model developed from a wide range of species is an important component for a field NDT instrument where a species may not be known.

Wood Composite and Pulp/Paper Products

In the particleboard industry, NIRS techniques are used for the in-line determination of moisture content. Engstrom et al. (1998) explored the potential for a non-contact probing NIRS system that could monitor the physical parameters of raw materials prior to the core furnish resin blender and to make corrections for product variations. Relevant properties such as internal bond strength, modulus of rupture, moisture content, and thickness swell were predicted with R values ranging from 0.90 for MOR to 0.96 for moisture content.

For pulp and paper applications, Thygesen (1994) determined that dry matter content and density of Norway spruce could be estimated using NIRS with good results (root mean square error of 1% to 8 % of the average content and density). Both reflectance of solid shavings and transmittance NIR techniques were used, and no marked differences in the predictive ability of calibration models were found. In contrast to Thygessen's findings, Schimleck et al. (1999) predicted the density of powdered core samples of eucalyptus with limited success, and concluded that NIRS is not a good NDE tool for determination of density. The 2nd derivative pretreatment of NIR spectra resulted in slightly better results than the raw spectra.

NIRS techniques have been used to predict pulp yield in ground samples of eucalyptus (Michell, et al., 1995) as well as in standing trees (Sefara, et al., 2000) and (Michell, et al., 1998). Both methods showed good prediction results with R values ranging from 0.90 in standing trees to 0.95 for standing trees. Characterization of pulp and its physical properties such as lignin content (Wallbacks, et al., 1989) was explored and showed promising results. Garbutt et al. (1992) used NIRS techniques to predict lignin and cellulose contents of various species of eucalyptus with very high R values (0.97 to 0.99).

MATERIALS AND METHODS

Materials

For this experiment, 61 clear samples of Inland Northwest species were machined from a total of 5 logs. Species of logs were identified in the field by a professional log grader. The breakdown of the species is as follows: 27 lodgepole pine clear wood specimens were cut from two logs, 21 subalpine fir specimens from two logs, and 13 Engelmann spruce specimens from one log. Dimensions of the clear wood specimens were 2.54 x 2.54 x 40.64-cm (1 x 1 x 16-

inch) as specified in the secondary method of ASTM D143. Specimens were conditioned to the desired moisture content in a temperature and humidity controlled chamber. NIR spectra were acquired for both solid sawn specimens and powdered wood specimens. Powder samples were subsequently milled from an approximately 2.5 cm long block cut near the failure surface of the clear sample using a Wiley mill with a #40 mesh screen size.

NIR Equipment

The NIR spectrum of each specimen was measured with an Analytical Spectral Devices (ASD) Field Spec ® Pro FR spectrometer. All measurements were conducted using a non-contact, diffuse reflectance, fiber optic sensor. The probe was oriented perpendicular to the sample surface. The longitudinal surface of the samples was illuminated with a DC lamp at a 30-degree orientation. An InGaAs detector with a range of 1000-2500 nm was used. Reflectance data was gathered over a wavelength range of 1000 to 2500 nm at 1 nm intervals.

NIR spectra also were collected using the Nicolet Nexus 670 FT-IR spectrometer. A KBr window (beam splitter) and a Thermo Nicolet MCT-A detector were used for these tests in the near infrared region. Although the MCT-A detector has the capability to detect a wide range of the light spectra (850 – 16500 nm), its optimal range is more suited for the mid-IR region of (2000 – 16500 nm). A Tungsten-Halogen white light was used for the light source. Two probes were used in this preliminary study: the Nicolet Smart Near-IR UpDrift port and the Nicolet Smart Near IR Fiberport. The UpDrift port is a top-loading, diffuse reflectance port. The Fiberport, with its diffuse reflectance probe and attached fiber optic cables, allows for testing on remote samples or samples too large or heavy to fit into the UpDrift port. Reflectance data was gathered over a wavelength range of 1000 to 2500 nm at 1 nm intervals.

Figure 2-1. Nicolet 670 FT-IR Spectrometer with fiber port probe installation.

Methods

Flexural tests

Flexural tests were performed according to ASTM D143 for determining modulus of rupture (MOR) and modulus of elasticity (MOE). MOR values ranged from 52.1 to 120.1 MPa, and MOE values ranged from 3.603 to 12.700 GPa. Moisture contents of the specimens ranged from 6.8 to 8.6% and were measured at the time of flexural testing per ASTM D4442, Method A.

NIR Spectral Acquisition

Near infrared spectra were collected for all 61 specimens on both solid and powdered samples. Prior to testing, the solid samples were sanded or planed smooth and care was taken to avoid contamination of the wood surface. For powdered samples, no special sample preparation was used after the powders were created in the Wiley mill.

Measurements on the solid samples were performed using the ASD non-contact probe, the Nicolet UpDrift and the Fiberport systems. Each specimen was measured two times on the

compression face and two times on the tension face, where each measurement represents the average of 40 scans. Measurements were taken on areas of early wood (as much as possible), avoiding any checks, discolorations, or rough surfaces. The four total measurements for each specimen were then averaged prior to statistical analysis. A background correction with a reference ceramic was conducted at 30-minute intervals for the ASD instrument and at 10-minute intervals for the Nicolet instrument, in accordance with manufacturer recommendations.

For the powder samples, measurements were performed using the ASD non-contact probe and Nicolet UpDrift and Fiberport probes. The powdered wood of each specimen was placed in an open steel container and subsequently packed and smoothed to a relatively consistent density for the ASD measurements. Each specimen was measured once, rotated approximately 90 degrees and measured again. For the Nicolet measurements, the wood powder was placed in a glass container and packed to achieve a relatively consistent density. The glass container with powder was then placed on the UpDrift port and measured once, rotated 90 degrees and measured again. The two measurements for each specimen were averaged prior to statistical analysis. As with the solid samples, background corrections were done at 30-minute and 10-minute intervals for the ASD and Nicolet instruments, respectively.

Moisture Content Testing

After the flexural testing was completed on the samples conditioned to approximately 8 percent, the specimens were re-conditioned to three different moisture contents (6, 12, and 20 percent). The NIR spectra of each of the 61 samples were measured with the Nicolet UpDrift probe at each moisture content. The actual moisture content was subsequently determined in accordance with ASTM D4442, Method A.

Pretreatment of Spectral Data

Prior to statistical analysis, the spectral data from each of the tests were handled in three ways: untreated (raw), 1st derivative, and 2nd derivative. For the 1st and 2nd derivatives, the data were differentiated using the Savitsky-Golay (S-G) method. The S-G method computes derivatives of any order, based on a polynomial approximation of the curve. For both derivations, five data points were taken into account on the left and right side of each cell, and a second-degree polynomial was chosen to fit the data points.

Statistical Analysis

With all of the strength data collected and the spectral data collected and treated, a statistical analysis was performed using the software Unscrambler® 7.6, CAMO. The NIR variables data were mean centered, and a principal component analysis (PCA) was performed to look for trends and groupings in the data and to identify potential outliers.

A multivariate method, partial least squares (PLS), was used to calibrate the spectra against the reference MOR and MOE values to develop a regression model. PLS is an effective method for regression modeling when candidate predictor variables are significantly correlated (as with spectral data). PLS uses the latent structure of spectral data to find the "hidden" relationships between blocks (Antii, 1999). Variation in the predictor block is described by the X-scores, **T**, while the variation in the response block is described by the Y-scores, **U**. A weight vector, **w**, is calculated for each wavelength and represents the contribution of each X-variable to the Y-variable. The matrix of the weight vectors, **w,** is notated, **W.** A corresponding matrix of weights for the Y-block is designated **C**. A separate matrix of X-loading, **P**, is calculated for each wavelength. The residual variance (error) matrices, **E** and **F,** are calculated for the X-scores and the Y-scores, respectively.

The decomposition of **X** and **Y** can be described by equations 1, 2 and 3 (Esbensen, 2000).

Equation 2-1 $X = TP^T + E$

Equation 2-2 $Y = UC^T + F$

The set of regression coefficients are calculated by:

Equation 2-3 $B = W(P^TW)^{-1}C^T$

Further details on PLS regression modeling using the NIPALS Algorithm are given by Esbensen (2000).

For this study, a calibration or model set consisting of 40 specimens was randomly selected from the 61 total specimens. The remaining 21 specimens were used as the validation or prediction set. The same calibration and validation sets were used for all of the tests for comparison purposes. For the PLS models, the X-matrix consisted of the absorption values at each wavelength (1500 values for 1000-2500 nm). The Y-matrix consisted of the MOR and MOE values. Both the X- and Y-matrices were mean centered variance normalized prior to performing the analysis. The Y-matrix was scaled by multiplying MOR and MOE by the inverse of their standard of deviations to account for the large differences in magnitude. The X-matrix, however, was not scaled by the inverse of the standard of deviation because of concerns that noise would be over-emphasized. This amplification of noise factors can decrease the interpretability of the load and regression coefficient plots (Esbenson, 2000). See Appendix C for a summary of the procedures used to generate the PLS models.

The statistical parameters correlation coefficient (R) and root mean square errors of prediction (RMSEP) were used to describe the effectiveness and robustness of each calibration

and prediction models. In addition, the number of orthogonal factors used to form the calibration model is included for comparison. The choice of the number of factors is an important piece of information. Ideally, the number of factors will include only the variation in the data that correlates to the desired parameter. The optimal number of factors will minimize the RMSEP. Too many factors in the calibration will include outside noise, which can lead to "over prediction" of the desired property. Too few factors will leave out pertinent variation in the spectra and will not predict the desired property with as much accuracy.

Comparisons of prediction accuracies of MOR and MOE were made between the three different sampling techniques (ASD non-contact, Nicolet UpDrift, and Nicolet Fiber optic probe), between the solid versus powder samples, and also between the three signal treatments (raw, 1^{st} derivative, and 2^{nd} derivative).

RESULTS AND DISCUSSION

The bending properties of the 61 clear samples were determined using an Instron universal test machine per ASTM D143 standards. A summary of these mechanical properties including the modulus of rupture (MOR), the static modulus of elasticity (MOE), and the density are shown in Table 2-1.

Table 2-1 Summary of statistical properties for the 61 samples

Property	Average	COV (%)	Minimum	Maximum
MOR (MPa)	77.5	23.7	52.1	120.1
MOE (MPa)	8265	24.0	3603	12700
Density (g/cm^3)	0.41	18.3	0.32	0.56

Near infrared spectra were collected from the 61 samples after mechanical testing was completed. As discussed in the methods section, spectra were collected from each sample with three different spectrometers and/or probes. The averaged, untreated spectra of the three moisture contents are shown in Figure 2-2. The primary overtone for water, which is located at the 1920-1940 nm ranges, can be seen quite clearly by the large peaks in all three moisture contents. There is also a noticeable shift up in the amplitude of absorption in the water region as the moisture content is increased. In addition, there appears to be a slight upward shift in the entire spectra as the moisture content increases. Because of this noticeable shift in spectra between varying moisture content, all subsequent statistical and regression analysis was conducted on samples held at constant 8% moisture to eliminate variation in the data. The effects of moisture content on prediction of strength with NIR technology is a topic that may need to be addressed in future analysis.

Figure 2-2 Averaged raw NIR spectra of the 61 samples at three different moisture contents.

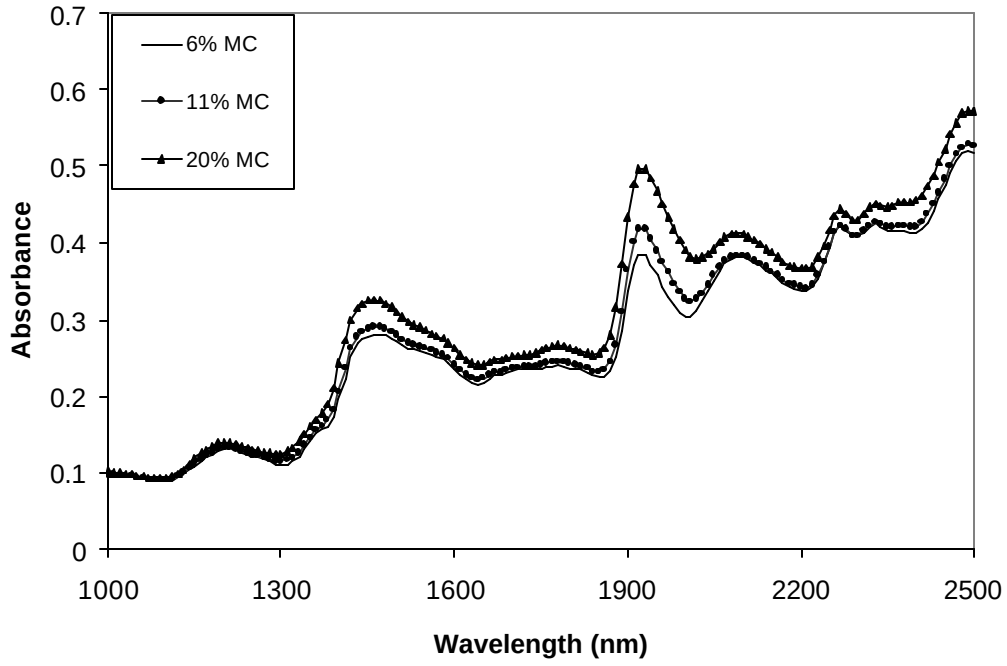
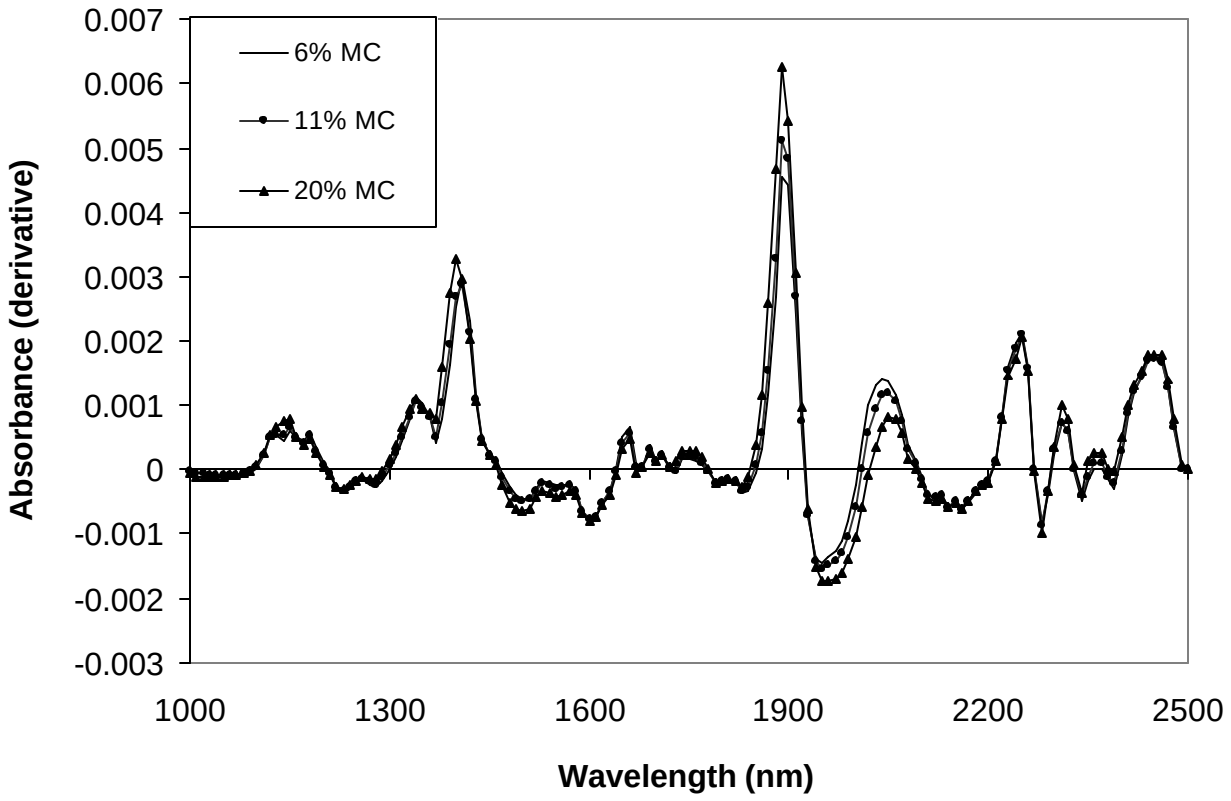


Figure 2-3 shows the exact same averaged spectra as those in Figure 2-2, except that these have been pretreated with the 1st derivative. As described earlier, the 1st derivative is a smoothing technique commonly used with NIRS to improve predictive accuracy. This technique measure the rate of change of each spectral component with respect to the 5 points in front and back of it, and can be an effective tool to smooth out baseline shifts in a spectrometer. Figure 2-3 provides a graphical representation of how the derivative treatment affects the raw spectral data. It can be seen that the amplitude of the change in absorbance (particularly in the 1920 to 1940 nm range) tends to increase as the moisture content increases.

Figure 2-3 Comparison of averaged 1st Derivative pretreated NIR spectra of the samples at three different moisture contents.



A visual inspection of both the raw and 1st derivative spectra reveals little about the underlying properties that exist in the broad peaks and valleys of the NIR absorbance bands. A

multivariate statistical analysis (MVA) was used to quantify and develop the hidden relationships between these large amounts of correlated spectral data. A principal component analysis (PCA) was conducted on each of the sets of NIR spectra to look at possible species clustering. Although species identification was not a specific objective of this study, the PCA analysis was conducted as a comparison for the quality of the spectra collected from the three spectrometers and for the three spectral pretreatment methods employed in this study. The 2nd derivative pretreated spectra gave poor results for clustering as well as for the prediction models and will not be shown in any plots or graphs. All of the score plots shown (Figure 2-4 through Figure 2-9) are a PC1 versus PC2 comparison.

Although it is difficult to quantify, the tightest clustering of species appears to occur for the ASD non-contact probe spectra that have been pretreated with the 1st derivative (see Figure 2-5). There is a clear separation of the lodgepole pine from the other species along PC1, while the subalpine fir and Englemann spruce are separated vertically along PC2. In general, it appears that for identifying species, the ASD non-contact probe data was slightly better than the Nicolet UpDrift and FiberPort probe and that the the 1st derivative pretreatment yielded better defined clusters than the raw data.

Figure 2-4 Score plot PC1 versus PC2 using the ASD non-contact probe showing the clustering of three species (LP = lodgepole pine, AF = subalpine fir, and ES = Engelmann spruce). Raw spectra.

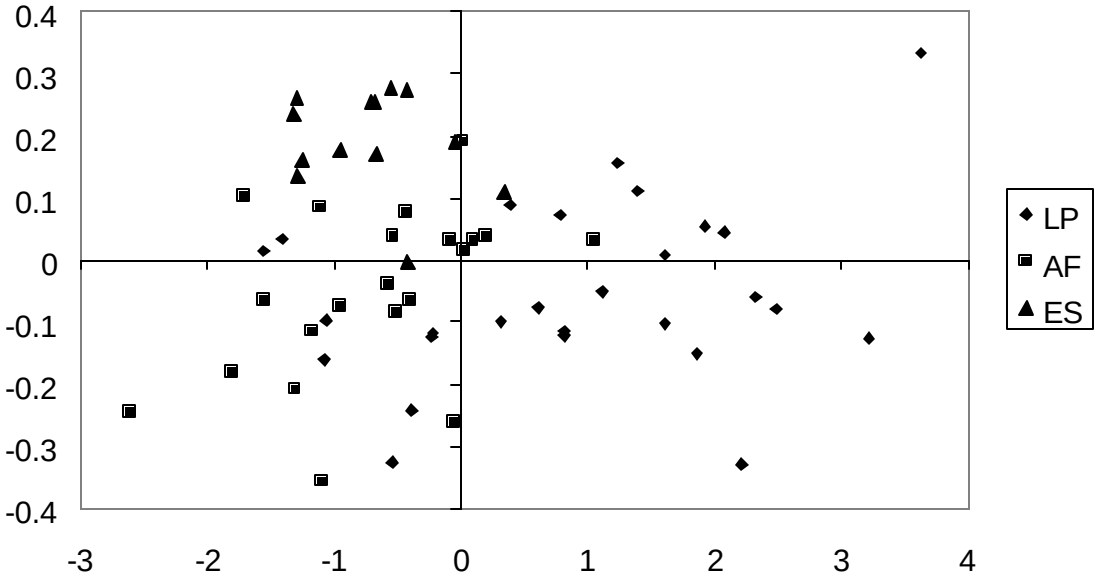


Figure 2-5 Score plot PC1 versus PC2 using the ASD non-contact probe showing the clustering of three species (LP = Lodgepole pine, AF = subalpine fir, and ES = Engelmann spruce). 1st Derivative spectra.

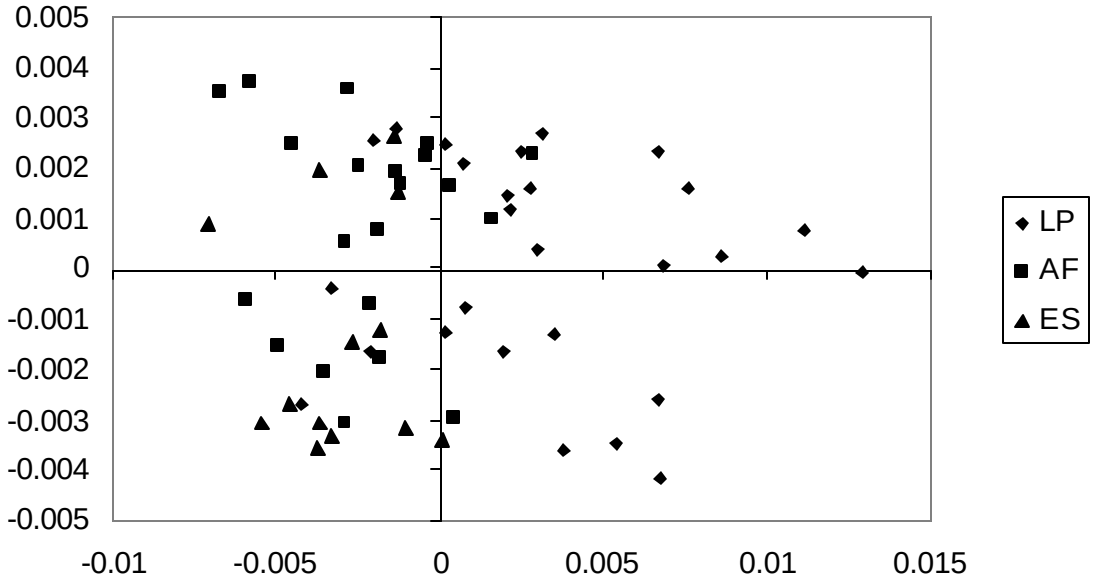


Figure 2-6 Score plot PC1 versus PC2 using the Nicolet UpDrift probe showing the clustering of three species (LP = lodgepole pine, AF = subalpine fir, and ES = Engelmann spruce). Raw spectra.

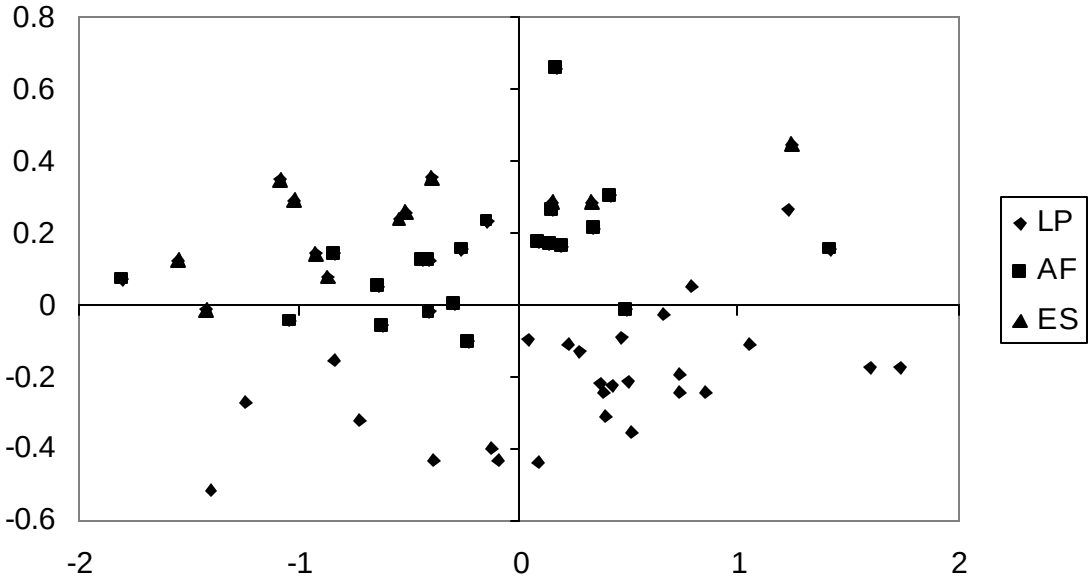


Figure 2-7 Score plot PC1 versus PC2 using the Nicolet UpDrift probe showing the clustering of three species (LP = Lodgepole pine, AF = subalpine fir, and ES = Englemann spruce). 1st Derivative pretreatment.

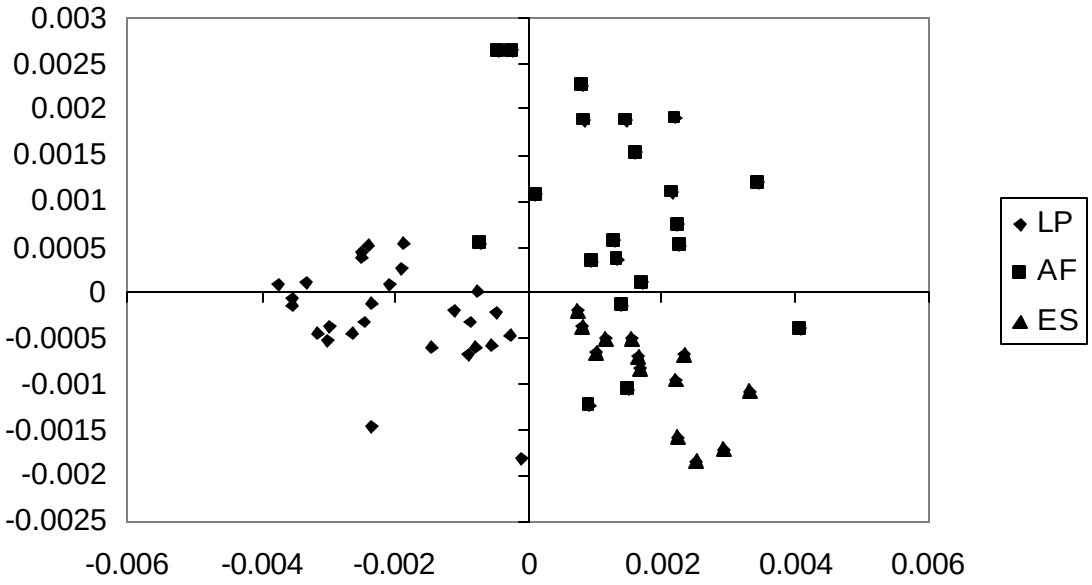


Figure 2-8 Score plot PC1 versus PC2 using the Nicolet Fiberport probe showing the clustering of three species (LP = lodgepole pine, AF = subalpine fir, and ES = Engelmann spruce). Raw Spectra.

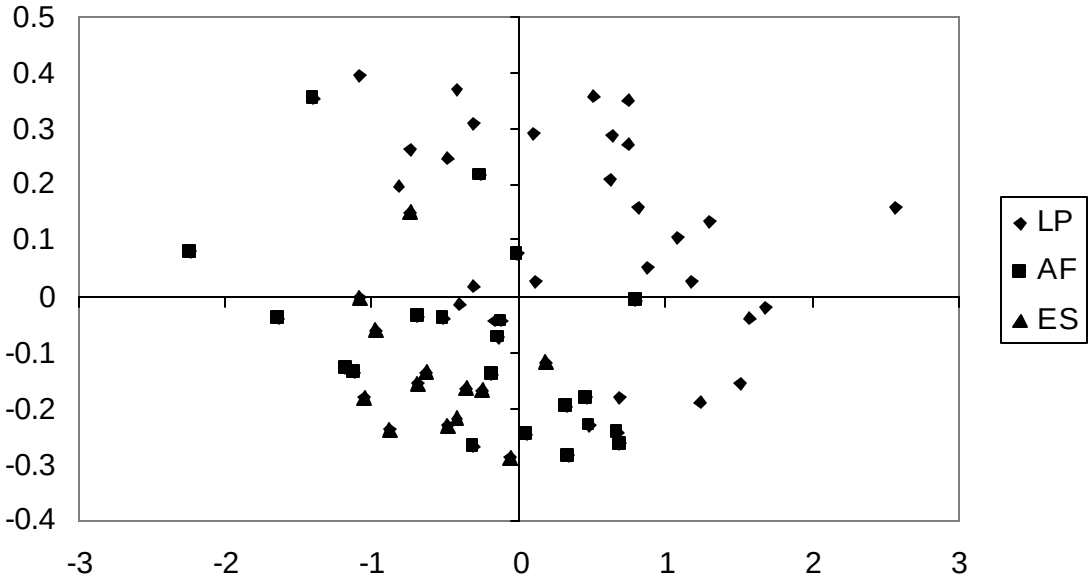
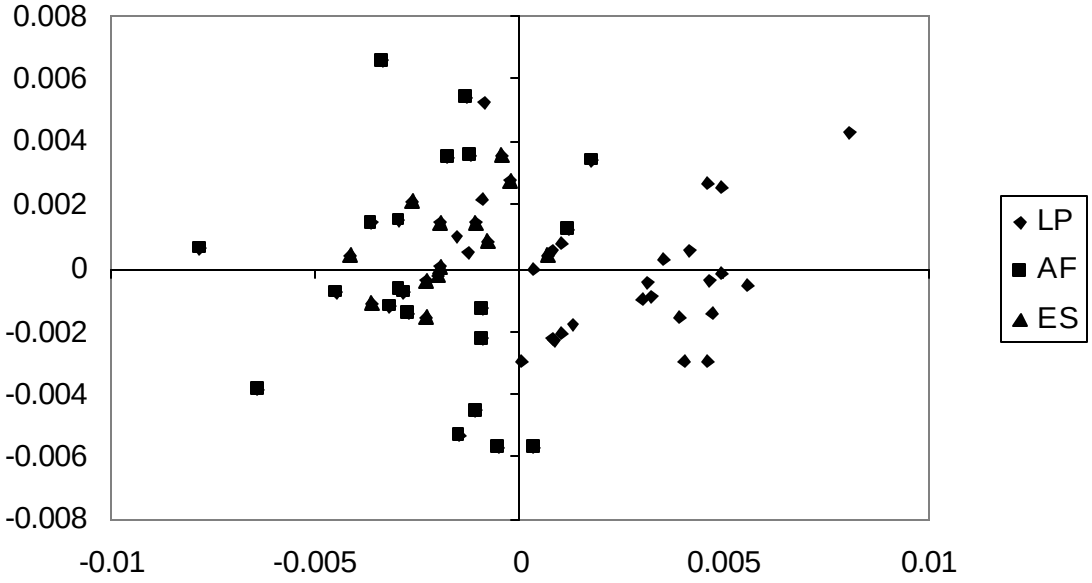


Figure 2-9 Score plot PC1 versus PC2 using the Nicolet Fiberport probe showing the clustering of three species (LP = lodgepole pine, AF = subalpine fir, and ES = Engelmann spruce). 1st Derivative pretreatment of spectra.



The same NIR spectra from the PCA cluster analysis were used to construct PLS models for predicting MOR and MOE. Through the PLS process, predictive models are formed as a function of the regression coefficients and the absorbance at each wavelength. Regression coefficients can be used to identify chemical features that have the most influence on the desired physical property (ie. MOR or MOE). A comparison of the regression coefficients plots for the PLS models that were used for predicting MOR of the raw spectra can be seen in Figure 2-10 (ASD probe), Figure 2-11 (Nicolet UpDrift probe) and Figure 2-12 (Nicolet FiberPort probe). All three models seem to be driven positively by chemical features in the 1400 nm region and negatively in the 1300 and 2250 nm regions; however, each model is quite different in the amplitude and overall make-up of the regression coefficients. The Nicolet probe data appear to be "noisier" than the ASD non-contact probe, particularly in the lower regions of the NIR spectral region (1000 to 1300 nm). This could be attributed to several factors, including the fact that the MCT-A detector used in the Nicolet spectrometer is ideally suited for the mid-IR spectral region and does not have as high of resolution as the ASD system. The ASD non-contact system also bombards the entire sample with an external light source that provides a much higher signal to noise ratio than with the Nicolet contact probes, which are limited by a relatively low intensity, internal light source.

Figure 2-10 Regression coefficients for the ASD probe model for predicting MOR. Spectra untreated.

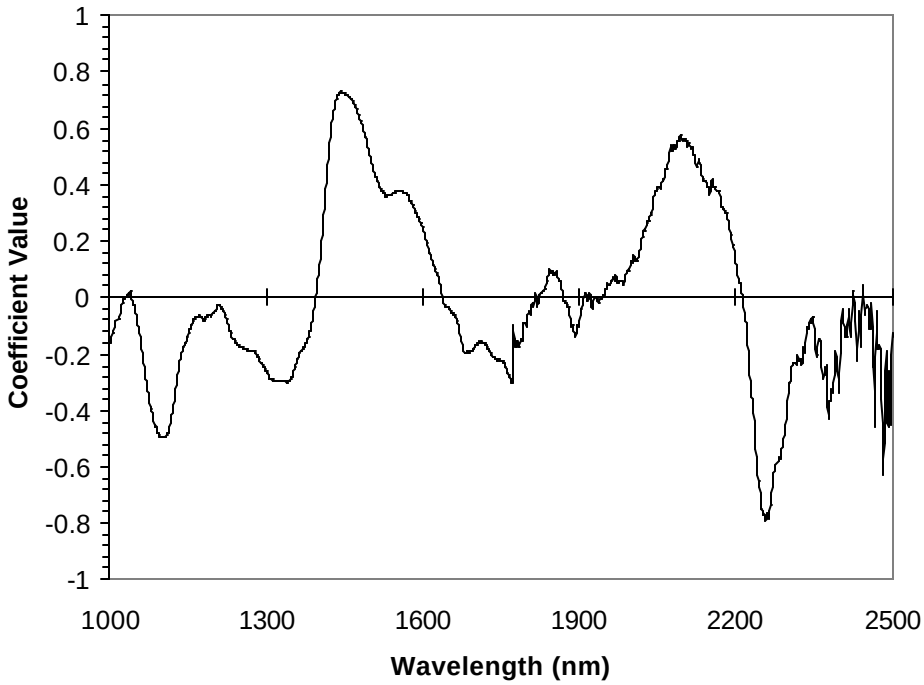


Figure 2-11 Regression coefficients for the Nicolet Updrift probe for predicting MOR. Spectra untreated.

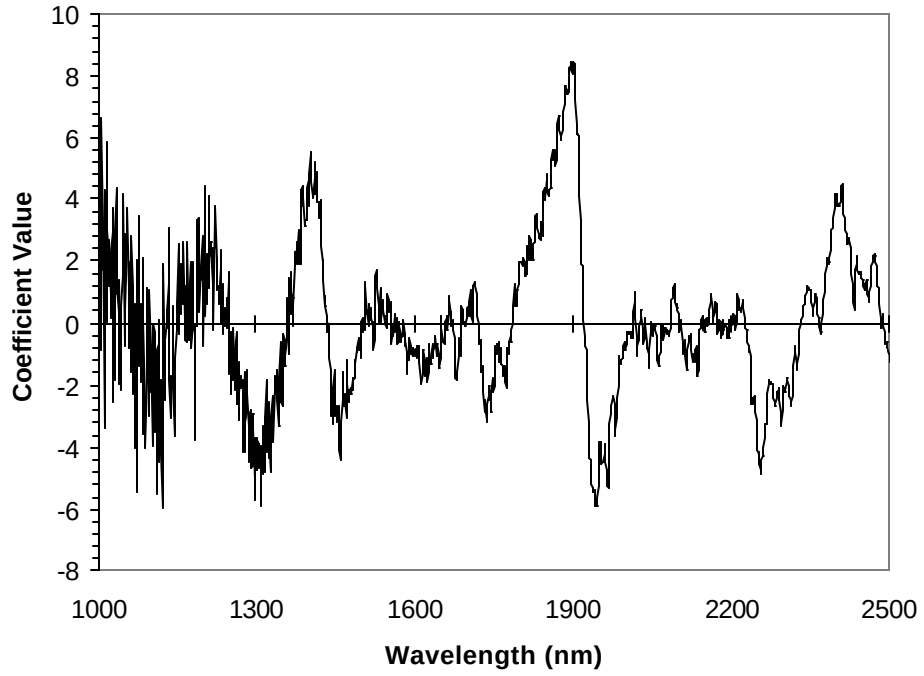
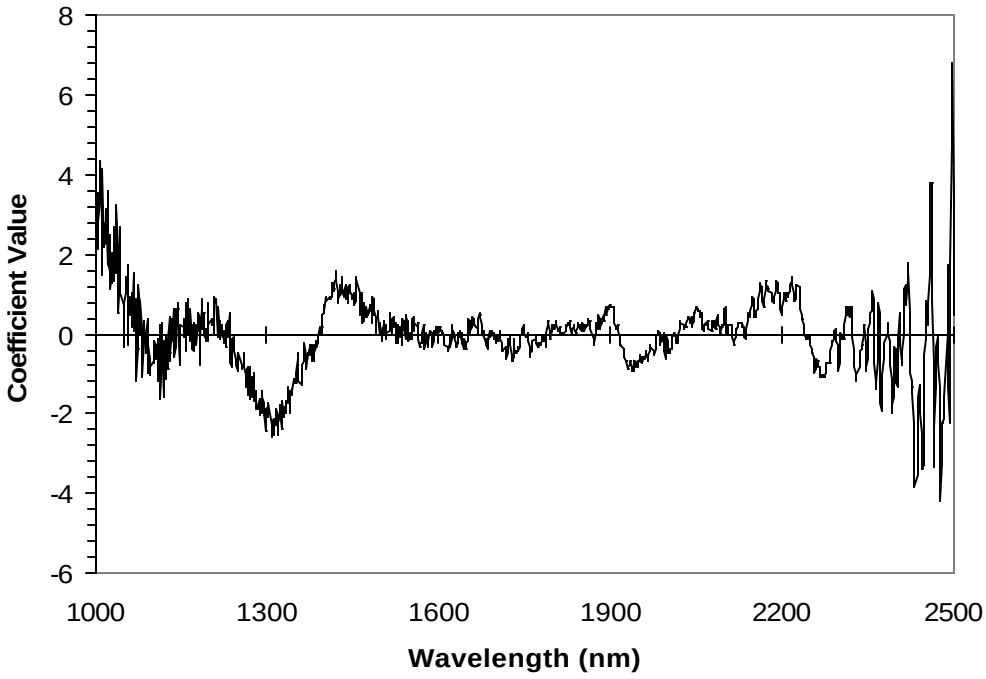
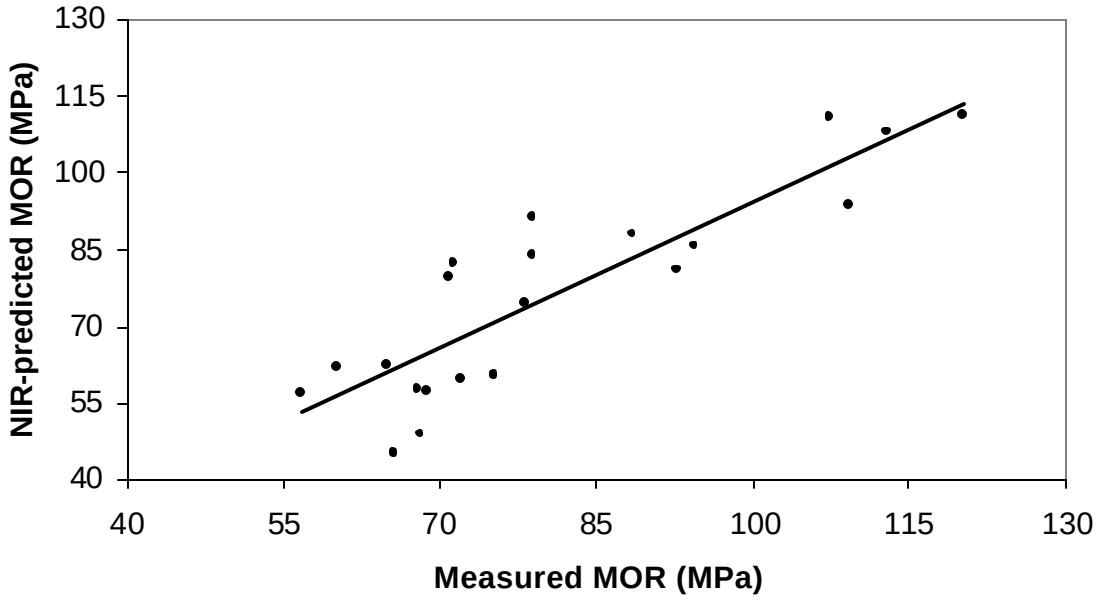


Figure 2-12 Regression coefficients for the Nicolet Fiberport probe for predicting MOR. Spectra untreated.



A graphical representation of the predicted versus actual MOR values from the raw spectra collected with the Nicolet Updrift port is shown in Figure 2-13. This particular result is shown for clarification, and similar results were produced for each probe.

Figure 2-13 Results of the PLS-2 predicted model for MOR (raw spectra, Nicolet Updrift)



The final data for the partial least squares (PLS) analysis are shown in Table 2-2 through Table 2-7. Results from the solid sample tests are shown in Table 2-2 through Table 2-4, while the results for the powder sample tests are shown in Table 2-5 through Table 2-7. The RMSEP values are shown in MPa.

Table 2-2. PLS results for untreated test set data of solid wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	4	0.896	9.03	4	0.923	894
Nicolet Updrift	8	0.876	10.63	8	0.907	1180
Nicolet Fiber Port	5	0.895	8.89	5	0.897	862

Table 2-3. PLS results for 1st derivative test set data of solid wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	5	0.897	8.76	5	0.916	851
Nicolet Updrift	5	0.876	10.38	5	0.912	1065
Nicolet Fiber Port	5	0.756	13.70	5	0.744	1443

Table 2-4. PLS results for 2nd derivative test set data of solid wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	6	0.782	12.09	6	0.865	1036
Nicolet Updrift	4	0.765	13.21	4	0.736	1537
Nicolet Fiber Port	8	0.387	17.28	8	0.375	2005

Table 2-5. PLS results for untreated test set data of powdered wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	5	0.712	14.10	5	0.726	1409
Nicolet Updrift	5	0.886	11.11	5	0.850	1163
Nicolet FiberPort	2	0.800	11.13	3	.789	1254

Table 2-6. PLS results for 1st derivative test set data of powdered wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	4	0.712	13.70	4	0.749	1350
Nicolet Updrift	4	0.841	11.07	4	0.875	1072
Nicolet FiberPort	5	0.544	16.25	7	0.501	1731

Table 2-7. PLS results for 2nd derivative test set data of powdered wood samples

	Modulus of Rupture (MOR)			Modulus of Elasticity (MOE)		
	# Factors	**R value**	**RMSEP**	**# Factors**	**R value**	**RMSEP**
ASD Non-Contact	3	0.171	21.42	3	0.298	2164
Nicolet Updrift	3	0.828	11.51	3	0.784	1363
Nicolet FiberPort	8	0.442	18.91	8	0.361	2110

The results for predicting MOR from specific regions of the spectra are shown in Table 2-8. There is not a large amount of difference between the individual spectral regions or between the instruments themselves.

Table 2-8. Results for predicting MOR from varying ranges of the spectra (raw spectra) for solid samples.

Instrument	Parameter	Spectral Range (nm)			
		1000-2500	1000-1500	1501-2000	2001-2500
ASD non-contact probe	R	0.90	0.91	0.94	0.94
	RMSEP (MPa)	9.03	8.00	7.73	6.17
	No. of factors	4	6	2	5
Nicolet Updrift probe	R	0.88	0.85	0.84	0.72
	RMSEP (MPa)	10.63	11.03	12.76	13.38
	No. of factors	8	8	8	4
Nicolet Fiberport probe	R	0.90	0.94	0.92	0.87
	RMSEP (MPa)	8.89	8.00	7.24	10.38
	No. of factors	5	6	7	3

Overall, the ASD non-contact probe provided the highest correlations with the fewest number of factors. The Nicolet Fiberport probe provided slightly better MOR prediction models than the UpDrift for raw spectral data taken on solid samples. A comparison of the regression coefficients indicates that the Nicolet data is considerably noisier than the ASD non-contact probe, particularly in the lower wavelengths (see Appendix D for regression coefficients at each spectral range). The Nicolet detection system is optimized for the mid-IR region (greater than 2000 nm), while the ASD probe, with its InGaAs detector, is more optimized for the entire NIR region (1000-2500 nm). In addition, the ASD system has a much higher signal-to-noise ratio with the external light source than the internal light source of the Nicolet probing systems.

Pretreatment of spectra

The results of this study indicate that the 1st and 2nd derivative pre-treatment methods do not significantly improve the prediction of material properties. Raw spectral data were the best choice for the Nicolet FiberPort probe. The first derivative pre-treatment provide results very similar to the raw data for both the ASD non-contact probe and the Nicolet UpDrift probe. This is consistent with the findings from Thumm and Meder, 2001, who found the first derivative results slightly better, but very similar to the untreated data. In all cases, the second derivative pre-treatment resulted in poorer results than the raw data. This is somewhat unexpected, since the second derivative pretreatment method has shown good results in some previous studies (Schimleck, et al (2001[b]), Schimleck, et al (2001[b]), and Thumm & Meder (2001).

NIR Probe / Hardware

The three systems provided nearly equivalent results on the solid wood samples. There was no definitive difference between the predictive results of each system. At a glance, the ASD non-contact probe appeared to provide the highest correlations for the raw, first derivative and second derivative spectra for both MOR and MOE. However, for the raw spectra, the difference in correlations and RMSEP between the three systems is negligible.

For powdered samples, the Nicolet UpDrift (R = 0.89) with a 5-factored model provided better results than the ASD non-contact probe (R= 0.71) with a 5-factored model and the Nicolet Fiberport (0.80) with a 2-factored model for raw spectra. Because the NIR acquisition methods of the non-contact and contact probes were considerably different, it's difficult to draw conclusions about the effectiveness of one system over another.

Solid Versus Powder Sampling

The solid samples (R = 0.88) and powder samples (R = 0.89) gave very similar results for the prediction of MOR for the Nicolet UpDrift probe. However, for prediction of MOE, the solid samples provided the better results than the powder samples (R = 0.91 and R = 0.85). The powder samples gave relatively similar results for the Nicolet Fiberport probe and poor results for both MOR and MOE in the ASD non-contact tests. One explanation may be the light scattering effect from the powder surface has a more adverse affect on the non-contact probe (located 1" from the surface) than a contact probe (located a fraction of an inch from the powder surface).

SUMMARY AND CONCLUSIONS

This study provided evidence that NIRS techniques coupled with multivariate statistics can lead to accurate predictions of MOR and MOE for clear specimens of Inland Northwest species. It is interesting that the physical properties of a combination of three Inland Northwest species could be predicted with relatively high correlation values. As shown by Schimleck, et al (2001b), it may be possible to predict properties of unknown species, which would be useful for field measurements where the species of members may not be known with certainty. In this preliminary study, we did not have a large enough sample size of individual species to compare predictive abilities of NIRS for each species. A larger and more diverse sample size is needed to draw meaningful inferences about predicting properties of individual species from models developed from many species.

Three measurement systems studied proved to be nearly equivalent for the solid wood specimens, and the Nicolet contact updrift measurement technique is favored for inspecting powdered samples. Solid and powder samples provided similar results for the prediction of

MOR, but MOE predictions were more accurately predicted from the solid samples. Solid wood specimens can be prepared more rapidly with less processing equipment requirements and are well suited for field measurements. Powdered specimens would be preferred when physical averaging is desired (e.g. to minimize local effects of natural growth characteristics such as early wood and late wood). The 1st derivative preprocessing of the spectral data did not significantly improve the predictions of MOE and MOR, and the prediction accuracy for the 2nd derivative pre-treatment decreased in comparison with raw and 1st derivative.

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Chapter 3: Predicting Flexural Properties of Douglas-Fir, Grand Fir and Lodgepole Pine Clear Wood Specimens Using Near Infrared Spectroscopy

ABSTRACT

This paper focused on the use of NIRS and multivariate statistical techniques to develop statistically robust prediction models for MOR and MOE for three commercially relevant Inland Northwest species: Douglas-fir, grand-fir, and lodge pole pine. A total of 613 "nearly clear" samples were used in this study to develop robust prediction models for MOR and MOE. Because these samples were prepared from small diameter timber it was difficult to obtain truly clear samples. As a result, a smaller subset consisting of 256 of the clearest and most straight-grained samples was evaluated to look at the effects that "near clear" specimens in the sampling population may have on the prediction models for MOR and MOE. Results indicated that correlations for the subset of clear samples were significantly higher than the total population with R values of MOR and MOE of 0.86 and 0.90 for the clear samples as compared to R values of 0.80 and 0.84 for all the samples. Individual species showed no improvement in predictability and the 1st derivative pretreated spectra produced slightly better results than untreated spectra.

INTRODUCTION

Near infrared spectroscopy (NIRS) offers a promising technique for nondestructively evaluating the modulus of rupture (MOR) and modulus of elasticity (MOE) of solid sawn lumber. Previous studies have used NIRS to predict MOE and/or MOR of clear wood samples of species such as Norway spruce, Radiata pine, European Larch, and eucalyptus delegatensis (Hoffmeyer and Pederson, 1995; Thumm and Meder, 2001; Gindl etal., 2001; Schimleck etal., 2001a and 2001b). Research is needed to expand the sample space and develop the NIRS

technique to predict MOE and MOR of the three commercially relevant Inland Northwest species (Douglas-fir, grand fir, and lodgepole pine).

Although near infrared spectroscopy is a relatively new technique in the forest product industry, it has been used successfully in other industries (agriculture, pharmaceutical, chemical, etc.) for years (Burns and Ciurczak, 2001). The technique is based on measuring the amount of near infrared light (750 nm to 2500 nm wavelength) absorbed by a material, and then correlating it to a desired property (ie. MOR, MOE, moisture content). Predictive models are developed using statistical regression techniques such as the partial least squares method (PLS). The amount of NIR light that a material absorbs is related to the functional chemical bond groups in the material. The idea of correlating the reflected NIR spectra of wood to flexural properties such as MOR or MOE is intriguing. However, the bending strength of structural timbers is dependent on other factors such as slope of grain, knot size and location, and other natural growth characteristics, which can influence an NIR scan. Fortunately, these growth characteristics can be accounted for with strength ratios found in ASTM D245 (2002), so the key is to develop an accurate method to predict the clear wood strength properties.

The primary objective of this study was to use NIRS and multivariate statistical techniques to develop predictive models of MOR and MOE for three commercially relevant Inland Northwest species: Douglas-fir, grand fir, and lodgepole pine. Samples were collected from three separate regions of the Inland Northwest. A secondary objective was to develop regression models for predicting MOR from NIR spectra plus MOE and compare them to the models developed strictly from NIR spectra. Models were developed and compared for individual species as well as for a mixture of all three species.

BACKGROUND

There have been a number of studies that deal directly with the use of near infrared spectroscopy for predicting mechanical properties of solid wood. This review will focus only on articles that directly involve NIRS techniques for predicting MOR and MOE.

Schimleck et al. (2001a) estimated several physical properties of *eucalyptus delegatensis* samples using NIR spectroscopy and the PLS regression method. The longitudinal modulus of elasticity, E_L, and MOR of clear specimens were both predicted. MOR and E_L data were collected on 20 x 20 x 300 mm clear samples. One NIR spectra, consisting of 50 averaged scans, was accomplished on the radial-longitudinal face of a 2 x 7 x 20 mm solid sample. Spectra were collected at 2 nm intervals over the range of 1100 – 2500 nm, and second derivative signal processing was conducted. MOR was predicted with $R^2 = 0.80$ from a 3 factored model and E_L being predicted with $R^2 = 0.88$ from a 4 factored model.

Thumm and Meder (2001) conducted a study on the use of near infrared spectroscopy for the prediction of modulus of elasticity (MOE) of radiata pine clear wood. Samples were tested both statically and using a moving spectral scan. The moving spectral scan consisted of a stationary spectrometer scanning the entire length of a 20 x 20 x 300 mm as it moved under the reflectance probe at a constant 900 mm/min. rate. The total number of samples used in the calibration model was 486 and the validation model consisted of 80 samples. Calibration models were formed using partial least squares methods (PLS), and a 1st derivative pre-treatment gave the best predictability. Results indicated that the spectra in the NIR region (1100 to 2500 nm) predicted MOE best ($R^2 = 0.72$). Preliminary results on a small subset of 72 samples showed better prediction of MOE with the moving scan ($R^2 = 0.55$) versus the static scan ($R^2 = 0.38$).

Gindl et al. (2001) used NIR spectroscopy and the PLS regression method to predict the MOE and MOR of European larch. The effects of compression wood on predictability were

explored, since mechanical property correlations are often different for compression wood compared to normal wood. NIR absorbance correlated well with the desired MOR and MOE properties in both the normal samples and compression wood samples. This indicates that additional information about wood characteristics other than density is present in the NIR spectra. For this study, three NIR measurements containing 100 scans were averaged for each sample and no pretreatment was applied to the spectra. Initial results from the cross validation method showed high correlations for predicting both bending strength (correlation coefficient = r = 0.944) and MOE (r = 0.959). However, the limited sample space (51 samples) required the use of a cross-validation method rather than checking the calibration model on a test set, which makes these results only preliminary.

Hoffmeyer and Pederson (1995) evaluated correlations between NIR spectra and several physical properties including bending strength for Norway spruce specimens with a range of natural growth characteristics. Flexural tests were conducted on 45 x 90 x 1800 mm timbers. Reflectance spectra were gathered over a range of 1200 to 2400 nm on discs cut close to the failure point. Each sample was measured twice and averaged prior to statistical handling. No signal correction or pretreatment were conducted on the spectra. Prediction models were formed using the partial least squares (PLS) and principal component regression (PCR) statistical methods. Bending strength of these full-length timbers was predicted with a low correlation (R^2 = 0.29 for a 3 factor model). Because these tests were conducted on samples with normal growth characteristics (knots, splits, slope of grain, etc.) which lower bending strength from that of a "clear" sample, it's not surprising that the NIR spectra did not correlate as strongly to strength.

Schimleck et al. (2001b) explored the use of NIRS to develop a calibration model for density, E_L, and MFA from a wide range of species. NIR spectra from a total of 59 different

species, representing a wide range of properties, were used for the calibration models. A model for predicting longitudinal modulus of elasticity (E_L) was developed with $R^2 = 0.79$ for a 7 factor model. In addition, this calibration model predicted E_L of eucalyptus delegatensis with $R^2 = 0.76$ and pinus radiata with an $R^2 = 0.75$. This study indicates the potential for creating calibration models that are developed from a wide range of species to accurately predict the modulus of elasticity (and other properties) of individual species.

Rials et al. (2002) analyzed the use of NIR spectroscopy techniques to predict the mechanical properties of composite wood panels. Results indicated good correlations for predicting MOR, MOE, and internal bond strength ($R^2 = 0.80$, 0.82 and 0.76, respectively) of medium-density fiberboard. In addition, internal properties of panel manufacturing variables such as resin content, panel temperature, and density were also predicted with reasonable correlations ($R^2 = 0.80$, 0.56 and 0.73, respectively). Regression coefficients from the PLS models were analyzed to determine which wavelengths and subsequent molecular bonds impacted the prediction of internal bond strength and MOE most strongly.

MATERIALS AND METHODS

Materials

A total of 613 clear wood specimens were used in this experiment. These specimens were composed of three softwood species in the Inland Northwest: Douglas-fir (195), grand fir (190), and lodgepole pine (228). To ensure a diverse sampling population, solid sawn lumber was collected from three mills located throughout the Inland Northwest region that specialized in processing small diameter timber: Vaagen Brothers (Northeastern Washington), Plummer Forest Products (Northern Idaho), and Yakama-Forest Mill (Southwestern Washington). The specimens were cut from nominal 2 x 4-in. lumber, with the exception of the Douglas-fir

specimens from the Yakama-Forests Mill, which were cut from nominal 2 x 6-in. lumber. Small diameter derived timber has a preponderance of small knots, making it difficult to obtain clear and straight-grained specimens. As a result, a smaller subset (256 out of the entire 613 samples) of the "clearest" and most straight grained samples was used for comparison to the entire population. This subset contained samples from each of the three species and each of the three mills. Final dimensions of the clear wood specimens were 2.54 x 2.54 x 40.64-cm (1 x 1 x 16-inch) as specified in the secondary method of ASTM D143 (2002). Specimens were conditioned to the desired moisture content of 12% in a temperature and humidity controlled chamber prior to both bending and spectral testing. Final moisture content values of the samples were determined using ASTM D4442 (2002), Method A.

Flexural Testing

Modulus of rupture (MOR) and modulus of elasticity (MOE) were determined by testing the 1 x 1 x 16-inch specimens to failure in a static bending test per ASTM D143 (2002) procedures. Center point deflection of the specimens was measured by the displacement of the load head. This is not in accordance with ASTM D143 (2002) and may have resulted in slightly lower MOE values due to localized deflection at the supports and load head. This potential bias, however, was consistent for all specimens and assumed to have little effect on the predictability of MOE, which was the ultimate goal of this study.

NIR Spectral Acquisition

Near infrared spectra were collected with the Nicolet Nexus 670 FT-IR spectrometer. Accessories included a white light source, an XKBr beam splitter, a liquid nitrogen cooled Thermo Nicolet MCT-A detector, and the Nicolet Smart Near-IR UpDrift probing port. The UpDrift is a top loading; diffuse reflectance port with a sapphire window that allows for a 7 mm sampling diameter. To ensure dryness in the detector, a constant stream of dry air was purged

through the system at a rate of 30 scf h^{-1}, as recommend by the spectrometer manufacturer. Each spectral measurement consisted of 40 averaged scans. A background correction was accomplished on a white ceramic standard at 10-minute intervals. Spectral absorbance values were collected over the range of 1000 to 2500 nm at 1 nm intervals. A total of four spectral measurements were taken on each specimen: two on the compression face and two on the tension face. Spectral measurements were collected on the 2.54 x 2.54 x 43.18-cm (1 x 1 x 17-inch) samples prior to flexural testing. The laser source was concentrated on early wood. Areas of discoloration, checks, or other natural growth features were avoided. Care was taken to ensure that the scanned surfaces were not touched by the hand or by any other contaminant.

Multivariate Statistics

All multivariate analysis (MVA) was conducted using the Unscrambler® 7.6, CAMO software. Two multivariate statistical tools were used to group the data and to develop prediction models. A detailed description of MVA techniques can be found elsewhere (e.g. Esbensen, 2000, Antii, 1999). However, a brief description of the two MVA methods that were used in this experiment is provided below.

Principal component analysis (PCA) is an orthogonal factoring method used to uncover variation in the spectral data (X-matrix). This is a useful tool for breaking down large amounts of correlated data such as spectra (often 1500 or more absorbance variables per sample) into useful trends and clusters. By projecting the variation in spectral data onto principal components (PC) oriented perpendicular to one another, clusters and patterns in the data can be uncovered. The first principal component (PC1) is the vector that describes the largest amount of variation in the data. The second component (PC2) is the vector oriented perpendicular to PC1, that describes the next highest amount of variation. PC3 describes the next highest amount of

variation perpendicular to PC2 and so on. These principal components can then be plotted against one another on score plots to take 2-dimensional snapshots of the data. This study, for example, used the score plot of PC1 vs. PC2 to identify clustering of three species. As a rule of thumb, the PC1 versus PC2 score plot is a useful tool because it plots the two vectors that describe the most variation in the data.

Partial least squares (PLS) is a regression method that is used to regress a response variable (MOR, MOE, density, etc.) onto the decomposed data (spectra) and make a projection on to the perpendicular factors. Similar to PCA, the PLS method allows for the decomposition of large amounts of correlated data (spectra) into perpendicularly oriented vectors. Unlike PCA, this method allows for the regression of the desired property (MOR and MOE) onto the spectral data. For this study, two types of PLS models were constructed. A PLS-2 model is used for simultaneously predicting two correlated variables (MOR and MOE) from the X-matrix (spectra). A PLS-1 model is used to predict only one variable (MOR) from the response matrix.

Data Analysis

The four spectral measurements per specimen were averaged prior to statistical analysis. The spectral data were then mean centered, and a principal component analysis (PCA) performed to look for clustering of species and for potential outliers. Although the species identification was not a specific goal of this study, it was conducted as another possible use for NIR. In addition, PCA was used to look for "drift" in the spectrometer. This was accomplished by looking for clustering of spectral data that were collected on different days.

A partial least squares (PLS-2) multivariate statistical analysis was then conducted to develop models for predicting MOR and MOE from the NIR spectra. Two-thirds of the samples

were randomly selected to develop the calibration (predictive) models, and the remaining one-third was used as the test set to validate the models. Predictive models were also developed with the spectral data that was pre-treated with 1^{st} and 2^{nd} derivatives. Differentiation was accomplished using the Savitsky-Golay (S-G) method, which computes the derivative based on a polynomial approximation of the curve. Five data points were used on each side of the data point and a second-degree polynomial was used for fitting the curve.

Simple regressions between MOR and MOE were conducted. Regression models for predicting MOR from MOE were developed from a calibration set (2/3 of the population). To be consistent with the correlations derived from the PLS models, values from the validation sets (1/3 of the total population) were used for predicting MOR. See Appendix C for a summary of the PLS methods used in this study.

For further comparison, the partial least squares (PLS-1) method was used to develop models to predict MOR from NIR spectra plus MOE. MOE values were divided by the standard deviation to normalize to the same relative scale as the absorbance values. The same calibration and validation sets were used for both the PLS-2 and PLS-1 models.

RESULTS AND DISCUSSION

A statistical summary of flexural properties is given in Table 3-1. Statistics were calculated for a combination of species and mill groupings. In addition, the statistical properties are presented for the "selected samples", which is the group of samples that were selected as the most straight grained and clear. The average moisture content of all of the samples was 11.0 % (dry basis) with a standard deviation of 1.2 %.

Table 3-1 Statistical properties for all of the samples.

Species	Mill (# Samples)	Property	Average (MPa)	COV (%)	Minimum (MPa)	Maximum (MPa)
Douglas-fir	Vaagen (62)	MOR	88.3	14.1	59.9	114.7
		MOE	10418	15.8	6233	13410
	Yakama (81)	MOR	93.8	14.8	48.7	124.0
		MOE	11576	14.4	8128	14948
	Plummer (52)	MOR	98.4	10.9	74.4	125.8
		MOE	11687	10.5	9218	14645
	All (195)	MOR	93.3	14.2	48.7	125.8
		MOE	11239	14.6	6233	14948
Grand fir	Vaagen (75)	MOR	76.5	13.9	46.3	104.5
		MOE	9370	14.8	6295	12804
	Yakama (71)	MOR	70.7	11.9	52.4	96.9
		MOE	8715	12.5	5978	11521
	Plummer (44)	MOR	70.9	20.0	48.9	103.8
		MOE	9143	17.0	6564	12666
	All (190)	MOR	73.0	15.3	46.3	104.5
		MOE	9074	14.9	5978	12804
Lodgepole	Vaagen (75)	MOR	90.3	9.1	64.9	112.0
		MOE	10983	9.9	6771	13148
	Yakama (77)	MOR	81.1	13.3	57.3	108.2
		MOE	9722	15.1	5668	13362
	Plummer (76)	MOR	85.1	10.4	67.7	104.5
		MOE	10666	9.6	8281	12969
	All (228)	MOR	85.5	11.8	57.3	112.0
		MOE	10453	12.6	5668	13362
All samples	All Mills (613)	MOR	84.1	16.7	46.3	125.8
		MOE	10273	16.4	5668	14948
Selected Samples	Selected (256)	MOR	84.2	17.3	46.3	121.4
		MOE	10397	16.8	6295	14645

Near infrared spectra were collected for each of the 613 samples over the range of 1000 to 2500 nm. The raw spectra for each of the individual species were averaged and are shown in Figure 3-1. There are some obvious visual differences between the spectra of Douglas-fir and the other two species, as it is noticeably shifted upward; however, little information can be quantitatively determined from the individual spectra. This is why multivariate statistics is a

useful tool to extract information from NIR spectra. A valuable spectral pretreatment method is the use of 1st or 2nd derivatives. For this study, the 1st derivative pretreatment gave as good or better results for prediction models than that of the raw spectra, while the 2nd derivative pretreatment showed relatively poor results and was subsequently not used. One benefit of 1st derivative pretreatment is a "baseline correction" between spectra where the relative shifts in raw data are normalized and only the changes in slope (derivative) are reflected. This effect can be seen when comparing the raw spectra of Figure 3-1 to the 1st derivative spectra in Figure 3-2.

Figure 3-1 Graphical representation of the average raw spectra of each of three species. The upper spectra is Douglas-fir, the middle spectra is lodgepole pine, and the lowest spectra is grand fir.

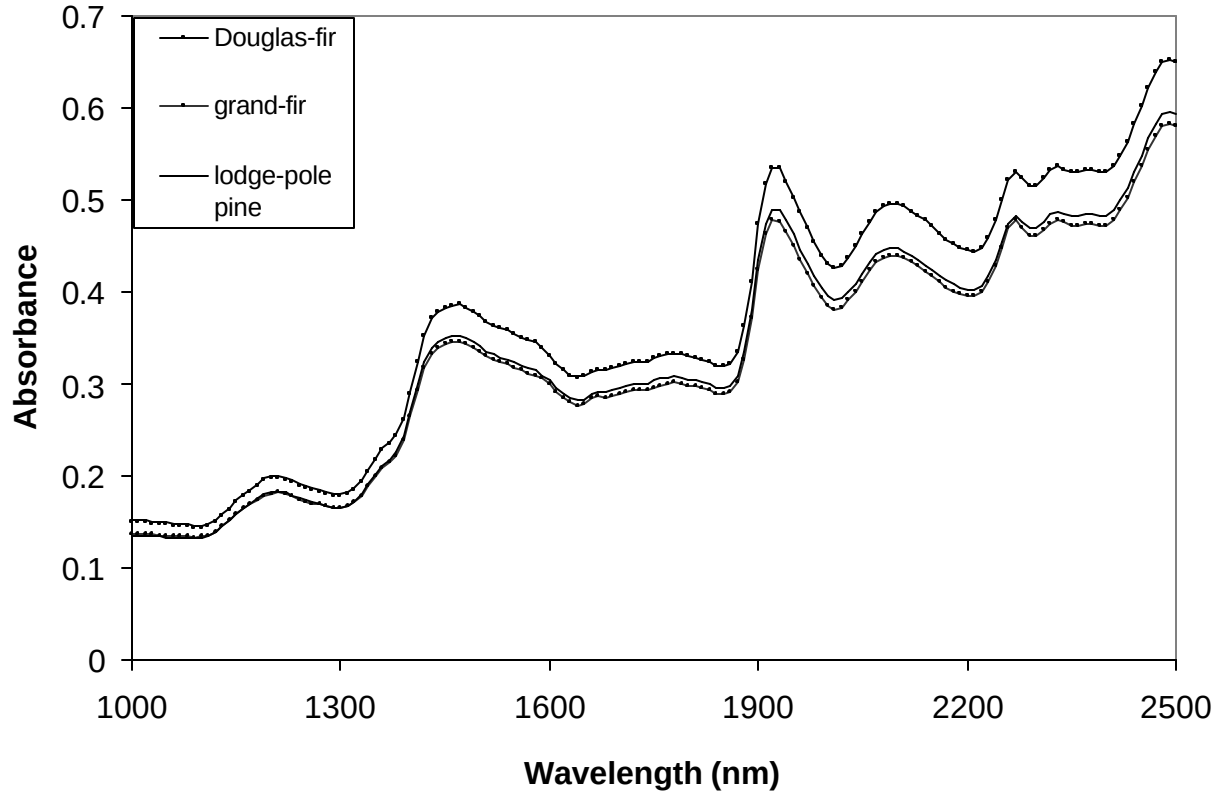
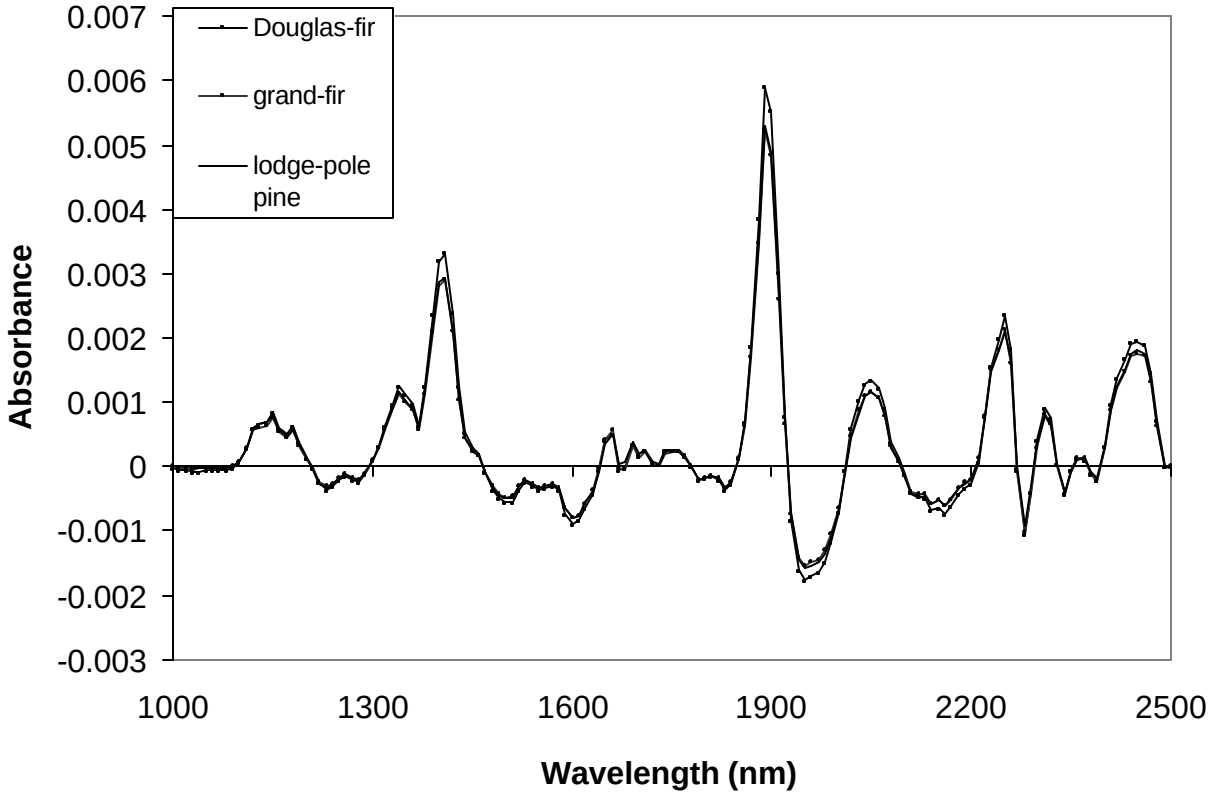


Figure 3-2 Graphical representation of the average 1st Derivative spectra of each of three species.



Principal component analysis (PCA) was conducted on both the raw and 1st derivative spectral data to look for clustering of species and for any trends in the spectral data. This was accomplished more to affirm that the spectral data were reasonable and constant (no drift). Although the species clustering was not a specific goal of this study, the results provided some insight into the best choice for pretreatment of the data. The score plots PC1-PC2 for the raw and 1st derivative spectra data of the wood from the Plummer mill are shown in Figure 3-3 and Figure 3-4, respectively. Although it's difficult to quantify, the species in the 1st derivative data are clearly more tightly clustered than the raw spectra with the Douglas-fir species clearly separating along PC1 and the lodgepole and grand fir species are clustered more along PC2. It

should be noted that the plots from the Plummer mill were chosen primarily for ease of seeing the clusters. The larger number of samples in the entire sample population and the other mills made it more difficult to read. See the Appendix for the score plots of all of the samples.

Figure 3-3 Score plot of PC1 vs PC2 looking for clustering of species in Plummer – raw spectra. D = Douglas-fir, G = grand fir, and L = lodgepole pine.

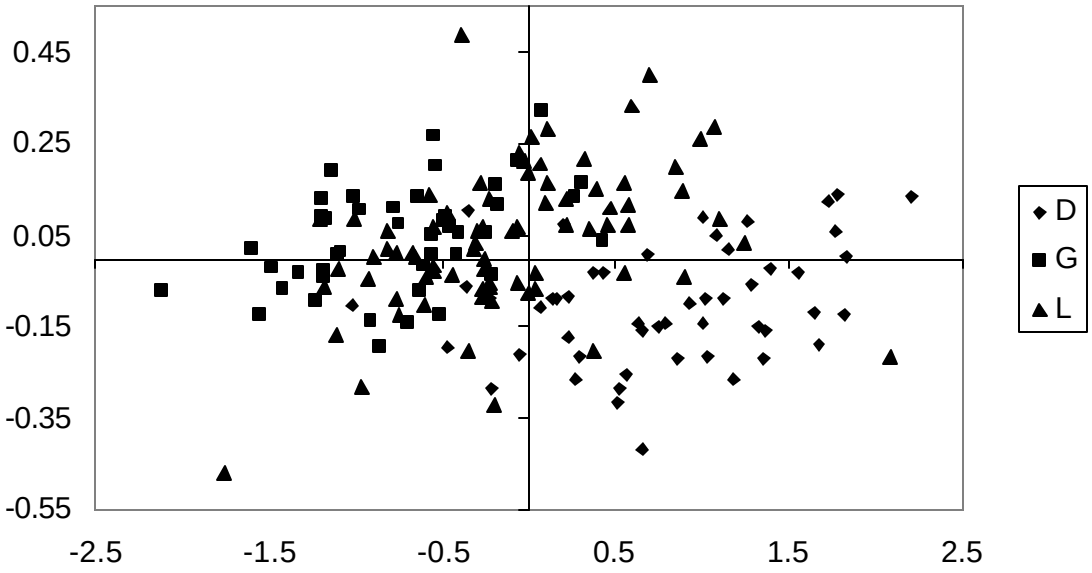
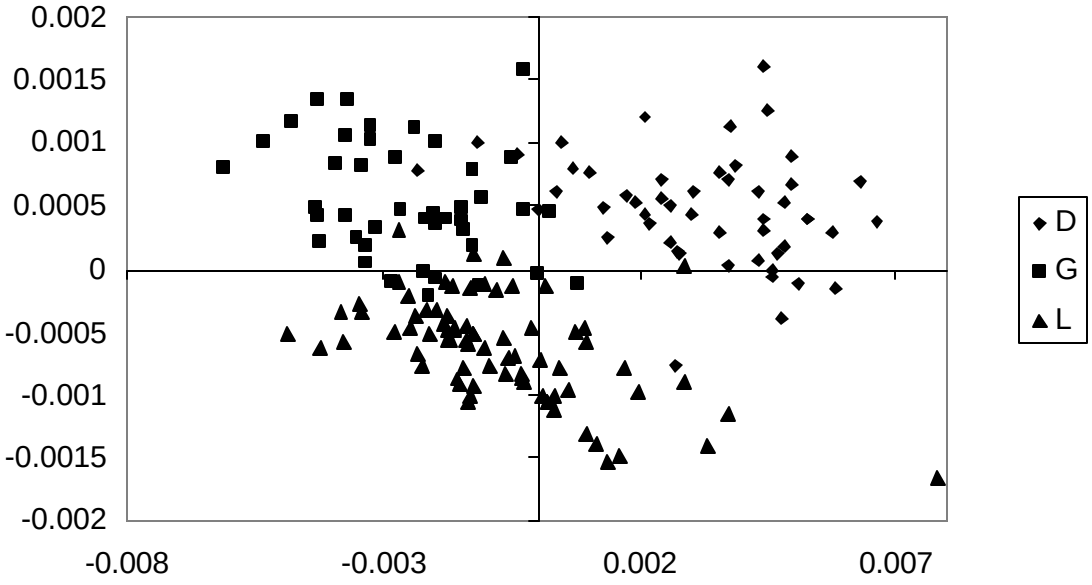


Figure 3-4 Score plot of PC1 vs PC2 looking for clustering of species in Plummer – 1st Derivative. D = Douglas-fir, G = grand fir, and L = lodgepole pine.



Linear regression models were developed using the PLS-2 method for predicting MOR and MOE strictly from the spectral data. Results of the raw spectral data and the 1st derivative pretreated spectra are shown in Table 3-2 and Table 3-3, respectively. With few exceptions, the 1st derivative NIR spectra produced higher correlations with a smaller number of factors. In addition, the models for individual species generally did not predict MOR or MOE as well as the models compiled from a mixture of the three species. The selected sample group consisting of the clearest and most straight grained samples provided the best prediction model for both MOR and MOE.

Table 3-2 Summary of PLS-2 prediction of MOR and MOE of the various species using raw NIR spectra with RMSEP values in MPa.

		Douglas-Fir	Grand Fir	Lodgepole	Selected Clears*	All
MOR	R	0.64	0.75	0.68	0.87	0.78
	RMSEP	9.27	7.45	7.22	7.98	9.03
	Factors in model	6	8	4	8	8
MOE	R	0.75	0.82	0.72	0.89	0.82
	RMSEP	1076	800	883	903	1007
	Factors in model	6	8	7	8	8

*Selected clears consist of 83 Douglas-fir, 93 grand fir, and 80 lodgepole pine for a total of 256 samples.

Table 3-3 Summary of PLS-2 prediction of MOR and MOE of the various species using 1st derivative pretreated NIR spectra with RMSEP values in MPa.

		Douglas-Fir	Grand Fir	Lodgepole	Selected Clears	All
MOR	R	0.7	0.75	0.65	0.86	0.80
	RMSEP	8.66	7.25	7.54	8.02	8.65
	Factors in model	5	4	3	5	5
MOE	R	0.77	0.81	0.74	0.90	0.84
	RMSEP	1014	807	855	862	938
	Factors in model	5	4	2	5	5

A graphical representation of the PLS-2 calibration models developed to predict MOR of all of the samples from raw and 1st derivative spectra are shown in Figure 3-5 and Figure 3-6, respectively. Although the models appear quite different upon first glance, it is of some interest that the absorbance bands that tend to carry the most weight (highest peaks and valleys) for predicting MOR are similar for both the raw and 1st derivative model. Previous studies (Rials, et al., 2002) have used calibration model peaks to identify molecular components that contribute the most to predicting a desired property.

Figure 3-5 Regression coefficients for the calibration model for all of the species. Spectra were untreated.

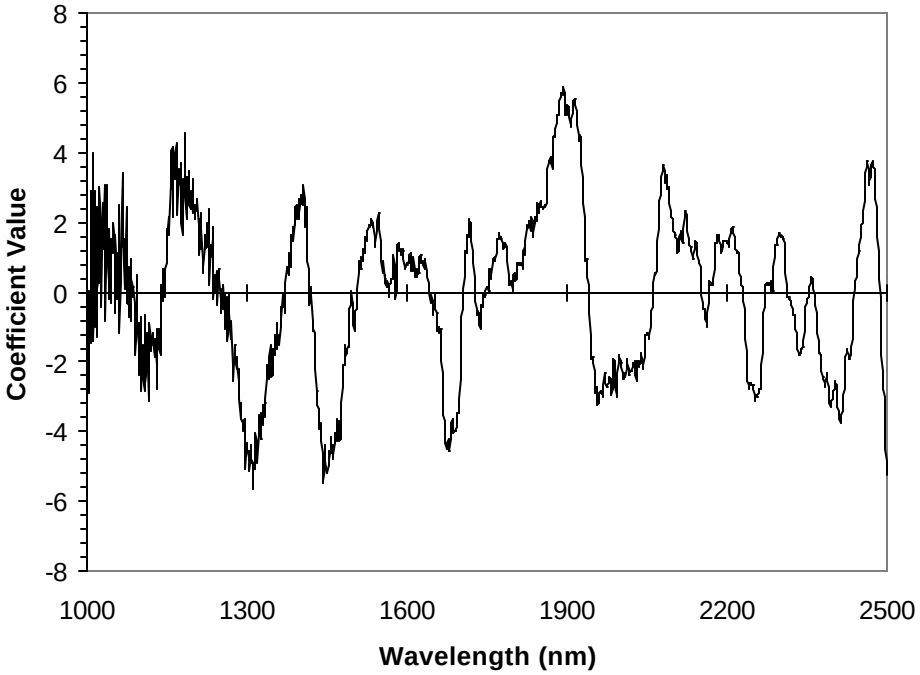
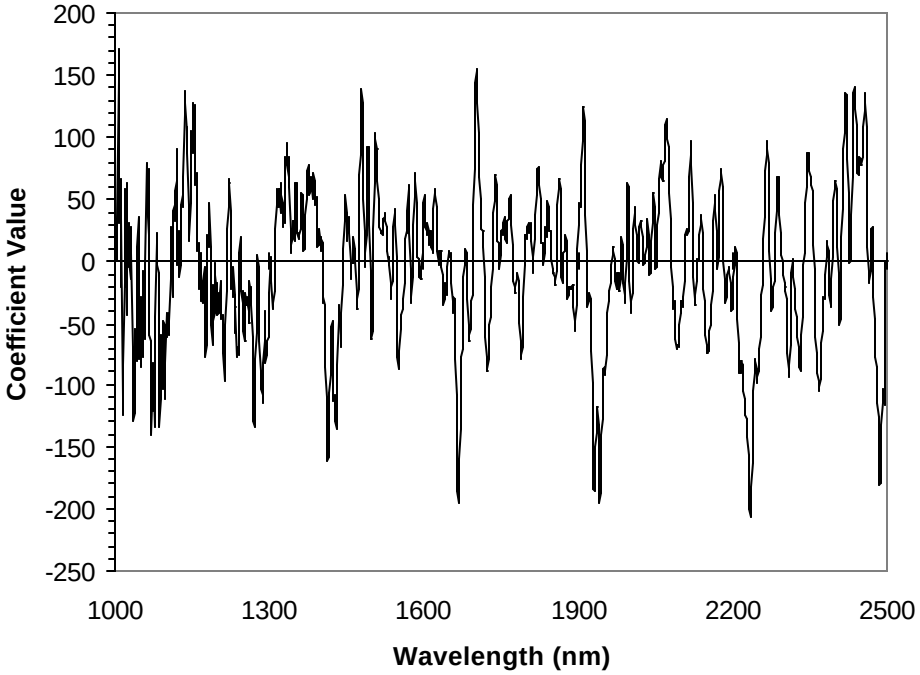


Figure 3-6 Regression coefficients for the calibration model for predicting MOR of all the species. Spectra were pretreated with 1st derivative.



For comparison to the PLS-2 prediction models, a simple scatter plot between MOR and MOE was accomplished for each of the sampling groups. As would be expected for clear wood samples, the correlations were quite high (see Table 3-4 for results). For every case, static MOE was a better predictor of MOR than the PLS-2 regression models.

PLS-1 models were also developed to see how well MOR could be predicted from both NIR spectra and static MOE. From Table 3-5 it can be seen that the addition of the NIR spectra to the regression model resulted in little to no increase in correlation from the MOR versus MOE correlations.

Table 3-4 Correlation coefficient (R) values for prediction of MOR from static MOE of the various species groupings

	Douglas-Fir	Grand Fir	Lodgepole	Selected Clears	All
R	0.85	0.91	0.88	0.90	0.94

Table 3-5 Results from the PLS-1 models for predicting MOR from NIR spectra plus MOE with RMSEP values in MPa.

		Douglas-Fir	Grand Fir	Lodgepole	Selected Clears*	All
Raw Spectra	R	0.88	0.92	0.9	0.95	0.94
	RMSEP	5.81	5.41	5.44	4.83	5.07
	Factors in model	4	4	2	2	2
1st Derivative	R	0.92	0.94	0.9	0.95	0.95
	RMSEP	5.89	5.53	5.40	4.89	5.16
	Factors in model	5	4	4	2	4

*Selected clears consist of 83 Douglas-fir, 93 grand fir, and 80 lodgepole pine for a total of 256 samples.

The results for predicting MOR of all of the samples are shown for each method (PLS-2, PLS-1, and MOR vs MOE) in Figure 3-7 through Figure 3-9, respectively.

Figure 3-7 Results of the PLS2 regression model for predicting MOR of all samples from NIR spectra that were pre-treated with 1st derivative.

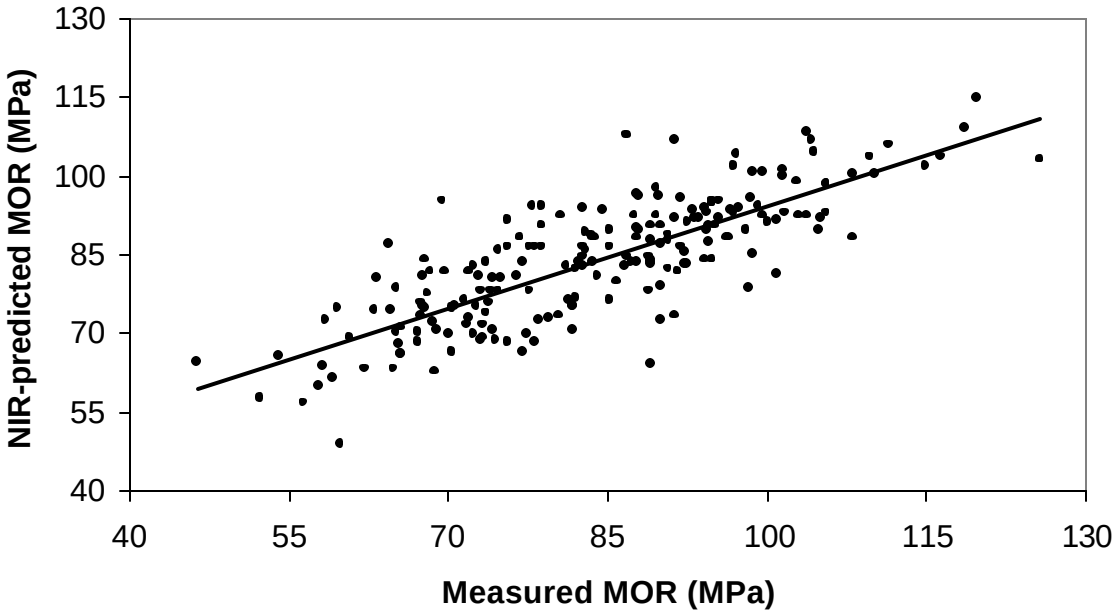


Figure 3-8 Results of predicting MOR from Static MOE for all samples.

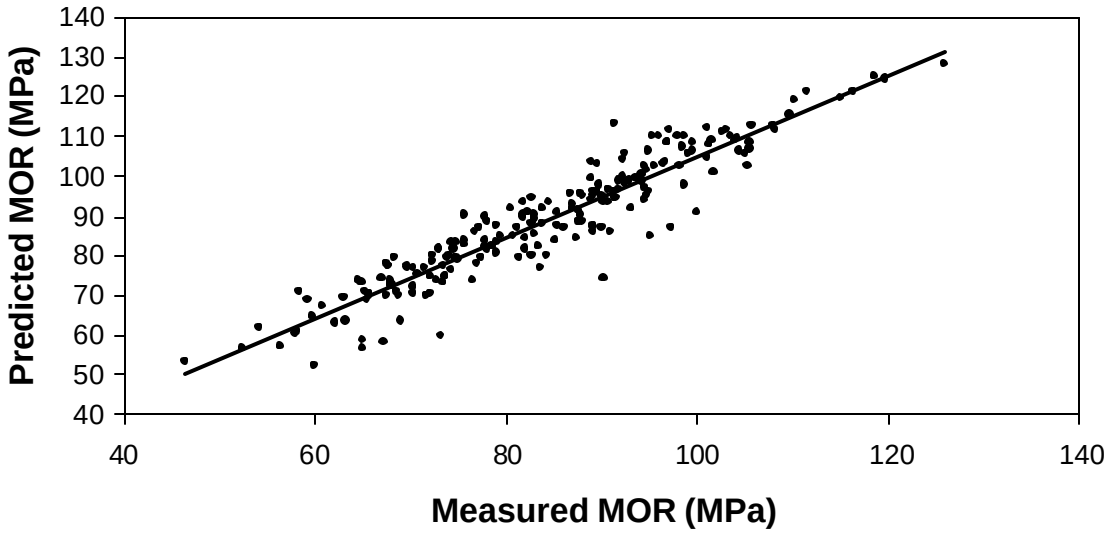
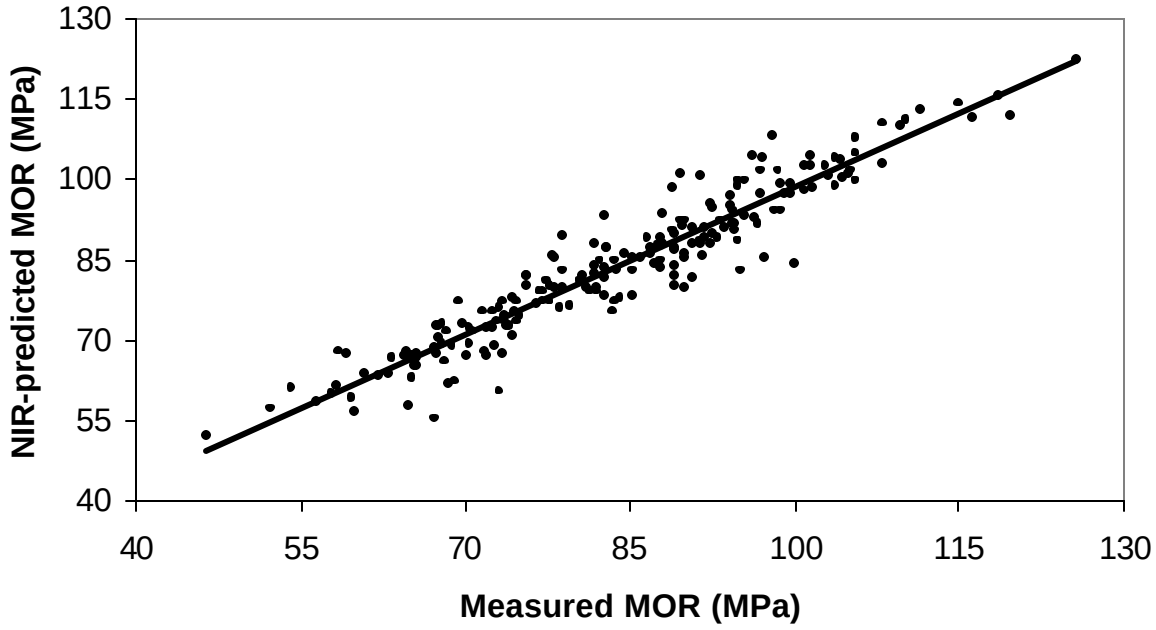


Figure 3-9 Results of the PLS-1 regression model for predicting MOR all of the samples from MOE plus NIR spectra that were pre-treated with 1st derivative.



Prediction models for MOR were developed for the selected clear sample set for three ranges of the spectra at 500 nm to look at the sensitivity. The results shown below in Table 3-6 indicate that there is no significant difference in predictability between the entire NIR range and the smaller spectral ranges. This indicates that a less expensive spectrometer with a limited spectral range may still be able to predict MOR with reasonable accuracy.

Table 3-6. Results for predicting MOR from varying ranges of the spectra for solid samples of the Selected Clears.

Parameter	Spectral Range (nm)			
	1000-2500	1000-1500	1501-2000	2001-2500
R	0.87	0.83	0.78	0.81
RMSEP (MPa)	7.98	8.93	9.89	9.34
No. of factors	8	5	8	8

SUMMARY AND CONCLUSIONS

NIR spectroscopy along with multivariate analysis techniques was used to develop predictive models of flexural properties of clear wood for three commercially relevant species in the Inland Northwest (Douglas-fir, grand fir, and lodgepole pine). Clear wood specimens were studied with the rationale that lumber properties could be predicted by applying standard strength ratios to predicted clear wood strengths. Samples were machined from lumber cut from small diameter timber, making it difficult to obtain truly clear, straight-grained specimens. Reasonable correlations were observed for a large sample size (613 samples) that contained "semi" clear as well as clear specimens (R = 0.80 for MOR and 0.84 for MOE). When a subset (256 samples) of the population containing the clearest and straightest grained samples was analyzed, bending properties were predicted with noticeably improved results (R = 0.87 for MOR and 0.90 for MOR).

MOR predictions from the NIRS technique were similar to those using MOE as a predictor variable. This comparison is relevant because the MOE-MOR correlation is the basis for mechanical lumber grading. For this study, static MOE was a slightly better predictor of MOR than the NIR spectral models. Although static MOE tests are quite easily obtained and commonly used for lumber grading in a production environment, they are not often a viable option for nondestructive evaluation in the field due to support conditions and access to the member being measured. Conversely, portable, lightweight, NIR field probes are available that could offer the ability to take localized bending properties of a wood sample in the field.

NIRS models that were developed from grouped individual species data did not predict individual species properties any better than a model developed from all three species combined. However, PCA analysis showed that the individual species were easily identified in a score plot

cluster analysis. This indicates that although differences in the chemical and/or physical make-up of the individual species could be detected in the spectral data, the particular wavelengths that contribute to bending strength properties are consistent between the three species chosen for this study. This has practical significance for a field measurement tool, as it would indicate that a calibration model developed from a wide range of species could accurately predict bending properties of individual species. This is consistent with the findings of Schimleck (2001b).

Using NIR spectra and MOE predictor variables did not significantly improve the accuracy of predicting MOR. There does not appear to be much reason to collect spectra along with MOE measurements for the use of predicting MOR.

1st derivative pretreatment gave slightly better results than raw spectra. Species were more easily clustered in PCA and the regression models gave a little higher correlation with fewer orthogonal factors. 2nd derivative pretreatment did not improve results and was not used for this study.

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Chapter 4: Overall Conclusions and Summary

Near infrared spectroscopy (NIRS) with the use of multivariate statistical analysis provides a useful tool for predicting flexural properties of clear wood specimens. This thesis was divided into two separate papers. The first paper (Chapter 2) explored the feasibility of using near infrared spectroscopy for predicting bending properties of a limited sample size of Inland Northwest species and to analyze and compare typical NIRS and multivariate statistical techniques to evaluate which methods may work best for future studies. With the knowledge of statistical tools and probing techniques from the first paper, the second study (Chapter 3) developed statistically robust prediction models for MOR and MOE for three commercially relevant Inland Northwest species: Douglas-fir, grand-fir, and lodge pole pine.

Results of the first study, Chapter 2, indicated that each of the three probing techniques used in the study predicted both MOR and MOE with good correlations with R values ranging from 0.88 to 0.92 for untreated spectra. The derivative pre-treatments showed little to no improvement for prediction values. Solid wood samples gave similar results to powder samples for predicting MOR, and were more accurate than powder samples for predicting MOE. This limited study indicated a good potential for the use of NIRS for the prediction of MOR and MOE, although a larger and more comprehensive sampling population would be needed to draw definitive results.

Results of the second paper, Chapter 3, indicated that correlations for the subset of clear samples were significantly higher than the total population with R values of MOR and MOE of 0.86 and 0.90 for the clear samples as compared to R values of 0.80 and 0.84 for all the samples. Individual species showed no improvement in predictability and the 1st derivative pretreated spectra produced slightly better results than untreated spectra. MOR predictions from the

NIRS technique were similar to those using MOE as a predictor variable. This comparison is relevant because the MOE-MOR correlation is the basis for mechanical lumber grading. For this study, static MOE was a slightly better predictor of MOR than the NIR spectral models. Although static MOE tests are quite easily obtained and commonly used for lumber grading in a production environment, they are not often a viable option for non-destructive evaluation in the field due to support conditions and access to the member being measured. Conversely, portable, NIR field probes are available that could offer the ability to take localized bending properties of a wood sample in the field. Results from both Chapter 2 and 3 indicate that good prediction results may be obtained from a smaller range of the spectral region, eliminating the expense required for detection and optical systems that cover the entire NIR spectral region.

APPENDIX A - Chapter 2 - Bending Properties

Mechanical and Physical Properties - Chapter 2 Samples

Sample No.	Species[a]	Width (in)	Thickness (in)	Max Load (lb)	MOR (psi)	MOE (static) (psi x 10^6)	MOR (MPa)	MOE (static) (MPa)
1	LP	1.007	1.018	786.6	15829	1.632	109.1	11252
2	LP	0.976	0.986	629.8	13939	1.399	96.1	9646
3	LP	0.986	0.983	714.9	15757	1.693	108.6	11673
4	LP	1.014	0.982	576.1	12372	1.253	85.3	8639
5	LP	1.001	1.009	754.9	15556	1.686	107.3	11625
6	LP	0.994	1.015	669.3	13725	1.464	94.6	10094
7	LP	0.978	1.000	636.5	13667	1.325	94.2	9136
8	LP	0.988	0.990	718.4	15580	1.592	107.4	10976
9	LP	1.020	1.020	779.9	15433	1.68	106.4	11583
10	LP	0.982	0.988	584.7	12809	1.383	88.3	9535
11	LP	0.987	0.985	639.2	14017	1.488	96.6	10259
12	LP	0.969	0.990	782.5	17303	1.762	119.3	12149
13	LP	1.019	1.020	651.5	12905	1.39	89.0	9584
14	LP	0.980	0.970	749.5	17070	1.749	117.7	12059
15	LP	0.979	0.972	767.5	17425	1.842	120.1	12700
16	LP	0.974	0.980	729.7	16381	1.717	112.9	11838
17	LP	0.984	0.981	551.4	12228	1.513	84.3	10432
18	LP	0.988	0.998	554.4	11831	1.203	81.6	8294
19	LP	0.988	1.003	487	10289	1.114	70.9	7681
20	LP	0.988	1.003	419.6	8865	1.083	61.1	7467
21	LP	1.003	0.988	627.9	13468	1.308	92.9	9018
22	LP	0.980	0.996	532.3	11498	1.11	79.3	7653
23	LP	0.978	0.990	521.3	11421	1.245	78.7	8584
24	LP	0.983	0.970	491	11148	1.0215	76.9	7043
25	LP	1.005	1.002	511.4	10643	0.999	73.4	6888
26	LP	1.002	1.014	581.5	11853	1.234	81.7	8508
27	LP	0.987	0.982	517.6	11420	1.191	78.7	8212
28	AF	0.985	0.983	426.8	9417	0.959	64.9	6612
29	AF	1.014	0.982	378.1	8120	0.624	56.0	4302
30	AF	1.007	0.950	345.4	7981	0.5226	55.0	3603
31	AF	0.975	1.013	474.9	9968	1.012	68.7	6977
32	AF	0.996	0.986	481.3	10438	0.965	72.0	6653
33	AF	0.981	1.005	466.6	9889	1.129	68.2	7784
34	AF	0.995	0.989	498.5	10756	0.74	74.2	5102
35	AF	1.027	1.012	411.3	8212	0.77	56.6	5309
36	AF	1.012	1.006	409.7	8401	0.9355	57.9	6450
37	AF	1.038	1.037	461.7	8686	1.03	59.9	7102
38	AF	1.029	1.046	492.9	9194	1.072	63.4	7391
39	AF	1.036	1.024	498.3	9633	1.099	66.4	7577
40	AF	1.003	1.016	457.4	9277	1.1006	64.0	7588
41	AF	0.995	1.022	431.7	8723	0.998	60.1	6881
42	AF	0.978	0.993	397	8645	1.057	59.6	7288
43	AF	1.027	1.026	455.3	8844	1.012	61.0	6977
44	AF	1.005	1.022	377.6	7554	0.879	52.1	6060
45	AF	1.036	1.045	472.8	8776	0.985	60.5	6791
46	AF	1.016	1.010	397.9	8062	0.863	55.6	5950
47	AF	1.011	1.038	439.7	8477	0.8043	58.4	5545
48	AF	1.035	1.007	475.4	9512	0.936	65.6	6453
49	ES	0.976	0.980	460.9	10326	1.247	71.2	8598
50	ES	0.980	0.994	522.7	11336	1.25	78.2	8618
51	ES	0.998	1.000	524	11026	1.303	76.0	8984
52	ES	0.976	0.996	489.1	10608	1.1155	73.1	7691
53	ES	0.983	0.997	518.7	11148	1.2425	76.9	8567
54	ES	0.981	0.992	463.6	10085	1.248	69.5	8605
55	ES	0.973	0.993	444.3	9725	1.185	67.1	8170
56	ES	0.974	0.992	461.2	10105	1.1565	69.7	7974

Sample No.	Species[a]	Width (in)	Thickness (in)	Max Load (lb)	MOR (psi)	MOE (static) (psi x 10^6)	MOR (MPa)	MOE (static) (MPa)
57	ES	0.990	0.991	351.9	7601	1.129	52.4	7784
58	ES	0.991	0.983	449.1	9849	1.155	67.9	7963
59	ES	0.993	0.990	505	10897	1.25	75.1	8618
60	ES	0.978	0.978	423.9	9516	1.1008	65.6	7590
61	ES	1.004	1.012	504.7	10308	1.1693	71.1	8062
				Ave	11238	1.1987	77.5	8264.7940
				Median	10608	1.1565	73.1	7973.7899
				Min	7554	0.5226	52.1	3603.2016
				Max	17425	1.8420	120.1	12700.1479
				COV	23.7137558	23.96646611	23.7	23.96646611

a. Species: LP = Lodge pole pine, AF = subalpine fir, ES = engleman spruce
b. Specific Gravity = ovendry weight/volume at ambient MC
c. Specific Gravity = ovendry wt./ovendry volume. Volume is calculated from published (Wood Handbook) volumetric shrinkage rates.
Volumetric shrinkage rates (%): LP = 11.1, AF = 9.4, ES = 11.0

Flexural Test accomplished per ASTM D143
Moisture Content determined from ASTM D4442, Method A
Specific Gravity determined from ASTM D2395, Method A

APPENDIX B - Chapter 2 Moisture Content

Moisture Content for 6 % M.C. (Target)

Specimen	Initial Wt (grams)	Final Wt (grams)	MC (%)
1	8.9441	8.4203	6.221
2	7.1234	6.7018	6.291
3	8.6270	8.1208	6.233
4	7.1940	6.7759	6.170
5	8.3232	7.8445	6.102
6	8.1279	7.6567	6.154
7	7.0905	6.6766	6.199
8	7.9498	7.4773	6.319
9	8.7679	8.2334	6.492
10	7.3794	6.9345	6.416
11	7.6203	7.1579	6.460
12	8.5446	8.0077	6.705
13	8.7121	8.1585	6.786
14	8.6028	8.0546	6.806
15	8.2634	7.7433	6.717
16	7.6931	7.1986	6.869
17	8.0686	7.5620	6.699
18	6.6663	6.2439	6.765
19	6.4991	6.0773	6.941
20	6.4199	6.0380	6.325
21	7.3030	6.8555	6.528
22	6.4713	6.0935	6.200
23	6.8094	6.4024	6.357
24	6.2342	5.8664	6.270
25	6.2640	5.8885	6.377
26	6.9650	6.5340	6.596
27	6.4442	6.0446	6.611
28	5.2854	4.9654	6.445
29	5.9696	5.5806	6.971
30	6.0379	5.6274	7.295
31	5.2086	4.8684	6.988
32	5.5818	5.2219	6.892
33	5.1401	4.8133	6.790
34	6.4606	6.0806	6.249
35	5.2908	4.9665	6.530
36	5.0012	4.6962	6.495
37	5.5460	5.2136	6.376
38	5.3892	5.0705	6.285
39	5.5041	5.1741	6.378
40	5.3	4.9834	6.4
41	5.2	4.8937	6.3
42	4.9	4.6647	5.0
43	5.4	5.0877	6.1
44	5.2	4.8563	7.1

Specimen	Initial Wt (grams)	Final Wt (grams)	MC (%)
45	5.5	5.1432	6.9
46	5.6	5.2560	6.5
47	5.5	5.1171	7.5
48	5.5	5.1078	7.7
49	5.7	5.4092	5.4
50	5.9	5.5512	6.3
51	6.1	5.7446	6.2
52	5.7	5.3450	6.6
53	6.6	6.1930	6.6
54	6.2	5.8343	6.3
55	5.6	5.2080	7.5
56	6.5	6.0708	7.1
57	6.0	5.5582	7.9
58	5.5	5.1878	6.0
59	5.9	5.4562	8.1
60	5.3	4.9721	6.6
61	6.0	5.6329	6.5
		Average	6.573

Moisture Content for 8% M.C. (Target)

Specimen	Height	Width	Thickness	Initial Wt (grams)	Final Wt (grams)	MC (%)
1	0.9600	1.0070	1.0255	8.5473	7.8803	8.464
2	0.9540	0.9820	0.9940	7.0699	6.5038	8.704
3	0.9600	0.9940	0.9920	8.5717	7.9197	8.233
4	0.9730	1.0240	0.9740	7.3231	6.7660	8.234
5	0.9750	1.0050	1.0160	8.6039	7.9531	8.183
6	0.9680	0.9870	1.0180	8.2519	7.6206	8.284
7	0.9830	0.9890	1.0110	7.0606	6.5254	8.202
8	0.9540	0.9890	0.9930	7.8885	7.2824	8.323
9	0.9580	1.0180	1.0280	8.8026	8.1015	8.654
10	0.9700	0.9790	0.9820	7.6338	7.0397	8.439
11	0.9610	0.9740	0.9925	7.6447	7.0595	8.290
12	0.9745	0.9755	0.9930	8.5947	7.9631	7.932
13	0.9820	1.0240	1.0290	8.9418	8.2591	8.266
14	0.9830	0.9800	0.9690	8.5150	7.8557	8.393
15	0.9640	0.9810	0.9785	8.4885	7.8622	7.966
16	0.9700	0.9735	0.9780	7.7847	7.1756	8.488
17	0.9755	0.9790	0.9940	8.0433	7.4245	8.335
18	0.9660	0.9880	0.9910	6.6810	6.1734	8.222
19	0.9740	0.9890	1.0100	6.7355	6.2175	8.331
20	0.9780	0.9930	1.0035	6.6886	6.1694	8.416
21	0.9960	1.0040	0.9840	7.4916	6.9054	8.489
22	0.9605	0.9760	0.9970	6.3922	5.9084	8.188
23	0.9595	0.9880	0.9940	7.0838	6.5323	8.443
24	0.9740	0.9730	0.9780	6.4239	5.9412	8.125
25	0.9790	1.0055	1.0060	6.4501	5.9484	8.434
26	0.9515	1.0030	1.0110	6.9516	6.4141	8.380
27	0.9725	0.9860	0.9825	6.6773	6.1603	8.392
28	0.9680	0.9890	1.0000	5.4249	5.0539	7.341
29						
30	0.9710	1.0035	0.9495	5.8585	5.4024	8.443
31	0.9920	0.9750	1.0150	5.4020	5.0126	7.768
32	1.0010	0.9950	0.9820	5.7520	5.3353	7.810
33	0.9670	0.9775	1.0090	5.1723	4.7905	7.970
34	0.9640	0.9870	0.9970	6.6678	6.1752	7.977
35	0.9710	1.0275	1.0185	5.4550	5.0323	8.400
36	0.9615	1.0130	1.0080	5.1754	4.7772	8.335
37	0.9920	1.0455	1.0370	5.6664	5.2368	8.203
38	0.9795	1.0260	1.0425	5.5352	5.1123	8.272
39	0.9575	1.0250	1.0270	5.4638	5.0560	8.066
40	0.9830	1.0030	1.0175	5.4712	5.0480	8.384
41	0.9795	0.9990	1.0290	5.3466	4.9317	8.413
42	0.9610	0.9760	0.9950	4.9685	4.5850	8.364
43	0.9735	1.0280	1.0290	5.5523	5.1355	8.116
44	0.9750	1.0155	1.0240	5.2826	4.8741	8.381
45	0.9660	1.0345	1.0495	5.6044	5.1811	8.170
46						
47	0.9690	1.0130	1.0330	5.5140	5.1000	8.118

Specimen	Height	Width	Thickness	Initial Wt (grams)	Final Wt (grams)	MC (%)
48	0.9630	1.0315	1.0100	5.5618	5.1440	8.122
49	0.9700	0.9750	0.9760	5.6122	5.1795	8.354
50	0.9910	0.9815	0.9930	5.7037	5.2710	8.209
51	0.9695	0.9875	0.9890	5.8744	5.4217	8.350
52						
53	0.9625	0.9895	0.9900	6.0688	5.5831	8.699
54	0.9760	0.9820	0.9910	5.8591	5.4075	8.351
55	0.9740	0.9800	0.9940	5.5314	5.1040	8.374
56	0.9810	0.9755	0.9910	6.1414	5.6794	8.135
57	0.9750	0.9840	0.9990	5.9968	5.5317	8.408
58	0.9820	0.9915	0.9760	5.6631	5.2348	8.182
59	0.9750	0.9850	0.9910	5.8296	5.3730	8.498
60	0.9810	0.9760	0.9705	5.4209	4.9991	8.438
61	0.9830	0.9965	1.0200	6.1064	5.6342	8.381
					Average	**8.273**

Moisture Content for 12 % M.C. (Target)

Specimen	Initial 1	Initial 2	Initial Wt (ave)	Final Wt (grams)	MC (%)
1	9.3096	9.2998	9.3047	8.4203	10.503
2	7.4165	7.4055	7.4110	6.7018	10.582
3	8.9861	8.9778	8.9820	8.1208	10.604
4	7.4906	7.4838	7.4872	6.7759	10.497
5	8.6527	8.645	8.6489	7.8445	10.254
6	8.4605	8.4525	8.4565	7.6567	10.446
7	7.3777	7.369	7.3734	6.6766	10.436
8	8.2695	8.2607	8.2651	7.4773	10.536
9	9.11	9.1024	9.1062	8.2334	10.601
10	7.6701	7.6633	7.6667	6.9345	10.559
11	7.911	7.9027	7.9069	7.1579	10.463
12	8.8566	8.8477	8.8522	8.0077	10.545
13	9.0207	9.013	9.0169	8.1585	10.521
14	8.9014	8.8951	8.8983	8.0546	10.474
15	8.54	8.5309	8.5355	7.7433	10.230
16	7.9537	7.9472	7.9505	7.1986	10.444
17	8.34	8.3158	8.3279	7.5620	10.128
18	6.895	6.8869	6.8910	6.2439	10.363
19	6.781	6.7085	6.7448	6.0773	10.983
20	6.6819	6.6742	6.6781	6.0380	10.600
21	7.5952	7.5872	7.5912	6.8555	10.732
22	6.7275	6.7194	6.7235	6.0935	10.338
23	7.0853	7.0757	7.0805	6.4024	10.591
24	6.4776	6.4704	6.4740	5.8664	10.357
25	6.5128	6.5045	6.5087	5.8885	10.532
26	7.229	7.2181	7.2236	6.5340	10.553
27	6.6876	6.6794	6.6835	6.0446	10.570
28	5.4656	5.4551	5.4604	4.9654	9.968
29	6.1817	6.1744	6.1781	5.5806	10.706
30	6.2412	6.2335	6.2374	5.6274	10.839
31	5.3765	5.3678	5.3722	4.8684	10.347
32	5.7595	5.7528	5.7562	5.2219	10.231
33	5.3099	5.3035	5.3067	4.8133	10.251
34	6.7148	6.7062	6.7105	6.0806	10.359
35	5.4946	5.4868	5.4907	4.9665	10.555
36	5.1983	5.1896	5.1940	4.6962	10.599
37	5.7579	5.7494	5.7537	5.2136	10.358
38	5.6052	5.596	5.6006	5.0705	10.455
39	5.7239	5.7156	5.7198	5.1741	10.546
40	5.5093	5.5026	5.5060	4.9834	10.486
41	5.4035	5.3962	5.3999	4.8937	10.343
42	5.159	5.1527	5.1559	4.6647	10.529
43	5.6217	5.6087	5.6152	5.0877	10.368
44	5.3704	5.3633	5.3669	4.8563	10.513

Specimen	Initial 1	Initial 2	Initial Wt (ave)	Final Wt (grams)	MC (%)
45	5.6823	5.6708	5.6766	5.1432	10.370
46	5.8172	5.8092	5.8132	5.2560	10.601
47	5.665	5.5656	5.6153	5.1171	9.736
48	5.6658	5.6578	5.6618	5.1078	10.846
49	5.9649	5.9571	5.9610	5.4092	10.201
50	6.1347	6.1264	6.1306	5.5512	10.436
51	6.354	6.3437	6.3489	5.7446	10.519
52	5.9148	5.9076	5.9112	5.3450	10.593
53	6.8381	6.8283	6.8332	6.1930	10.337
54	6.4433	6.4348	6.4391	5.8343	10.365
55	5.7535	5.7439	5.7487	5.2080	10.382
56	6.7148	6.7055	6.7102	6.0708	10.532
57	6.1535	6.1428	6.1482	5.5582	10.614
58	5.7387	5.7298	5.7343	5.1878	10.533
59	6.0273	6.0183	6.0228	5.4562	10.385
60	5.4844	5.4746	5.4795	4.9721	10.205
61	6.236	6.2186	6.2273	5.6329	10.552
					10.461

Moisture Content for 20 % M.C. (Target)

Specimen	Initial Wt (ave)	Final Wt (grams)	MC (%)
1	10.0780	8.4203	19.687
2	8.0740	6.7018	20.475
3	9.7390	8.1208	19.927
4	8.1070	6.7759	19.645
5	9.3730	7.8445	19.485
6	9.1260	7.6567	19.190
7	7.9760	6.6766	19.462
8	8.9760	7.4773	20.043
9	9.8220	8.2334	19.295
10	8.2790	6.9345	19.389
11	8.5500	7.1579	19.448
12	9.5570	8.0077	19.348
13	9.8230	8.1585	20.402
14	9.5850	8.0546	19.000
15	9.1920	7.7433	18.709
16	8.5990	7.1986	19.454
17	9.0010	7.5620	19.029
18	7.5010	6.2439	20.133
19	7.2900	6.0773	19.955
20	7.2080	6.0380	19.377
21	8.2520	6.8555	20.371
22	7.2650	6.0935	19.225
23	7.6530	6.4024	19.533
24	7.0130	5.8664	19.545
25	7.0900	5.8885	20.404
26	7.8450	6.5340	20.064
27	7.2200	6.0446	19.445
28	5.8690	4.9654	18.198
29	6.6370	5.5806	18.930
30	6.6990	5.6274	19.043
31	5.7680	4.8684	18.478
32	6.1900	5.2219	18.539
33	5.7350	4.8133	19.149
34	7.2190	6.0806	18.722
35	5.9200	4.9665	19.199
36	5.6250	4.6962	19.778
37	6.2160	5.2136	19.227
38	6.0500	5.0705	19.318
39	6.1970	5.1741	19.770
40	5.9550	4.9834	19.497
41	5.8290	4.8937	19.112
42	5.5700	4.6647	19.407
43	6.0930	5.0877	19.759
44	5.7910	4.8563	19.247

Specimen	Initial Wt (ave)	Final Wt (grams)	MC (%)
45	6.1520	5.1432	19.614
46	6.3020	5.2560	19.901
47	6.0950	5.1171	19.110
48	6.1400	5.1078	20.208
49	6.4770	5.4092	19.740
50	6.6630	5.5512	20.028
51	6.8960	5.7446	20.043
52	6.4540	5.3450	20.748
53	7.4680	6.1930	20.588
54	7.0230	5.8343	20.374
55	6.2470	5.2080	19.950
56	7.3260	6.0708	20.676
57	6.6930	5.5582	20.417
58	6.2250	5.1878	19.993
59	6.5650	5.4562	20.322
60	5.9450	4.9721	19.567
61	6.7800	5.6329	20.364
			19.624

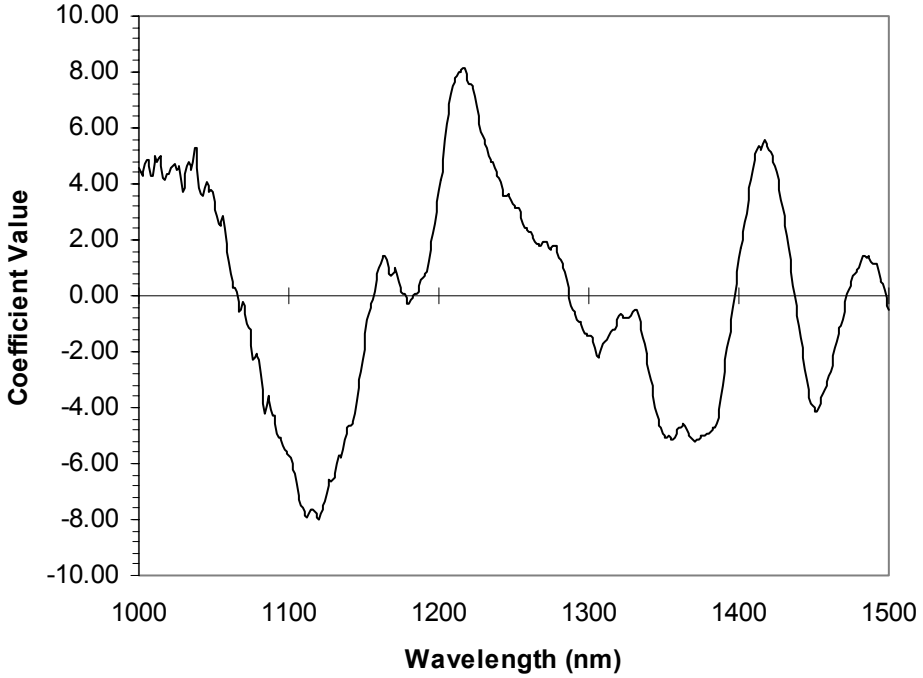
APPENDIX C – Summary of PLS procedures

Summary of PLS Modeling Procedure

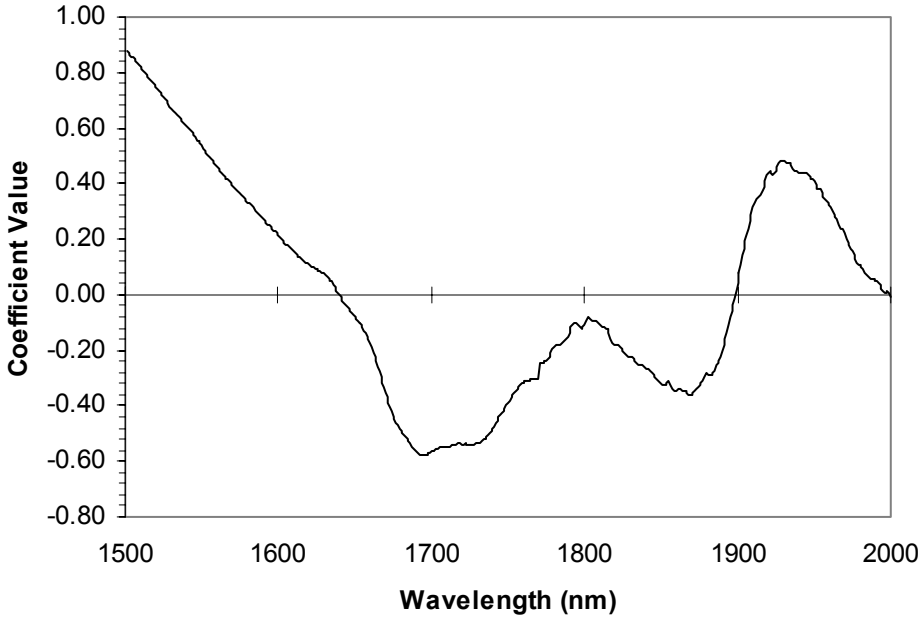
1. Randomly select approximately 2/3 of the sample population for the calibration model.
2. Prior to PLS analysis, mean center both the X-data (spectra) and Y-data (MOR and/or MOE).
3. Weight the Y-data by the inverse of their standard of deviation (no weighting factor is applied to the X-data).
4. Perform a full cross-validation, PLS analysis with a minimum of 8 factors. (Leveraged correction is much faster and is a useful starting tool to get a quick look at a model).
5. Look over the regression overview for irregularity in the calibration model (look for outliers, etc.).
6. If an outlier(s) exist, check spectral and physical data to see if there is a valid reason to remove from the sampling population or to re-test (ie. Spectra is visually different to the other spectra or the sample has a physical irregularity such as a knot, blue-stain, or slope of grain issue)
7. Remove valid outliers (if they exist) or redo the spectral analysis and repeat steps 1 through 6.
8. Use the remaining 1/3 of the sample population to validate the calibration model.
9. Choose the number of factors to be used in the model based on the minimum value for RMSEP. This can be done in by varying the number of factors and plotting the prediction result statistics until the minimum RMSEP is found.

APPENDIX D – Chapter 2 – Regression Coefficient Plots

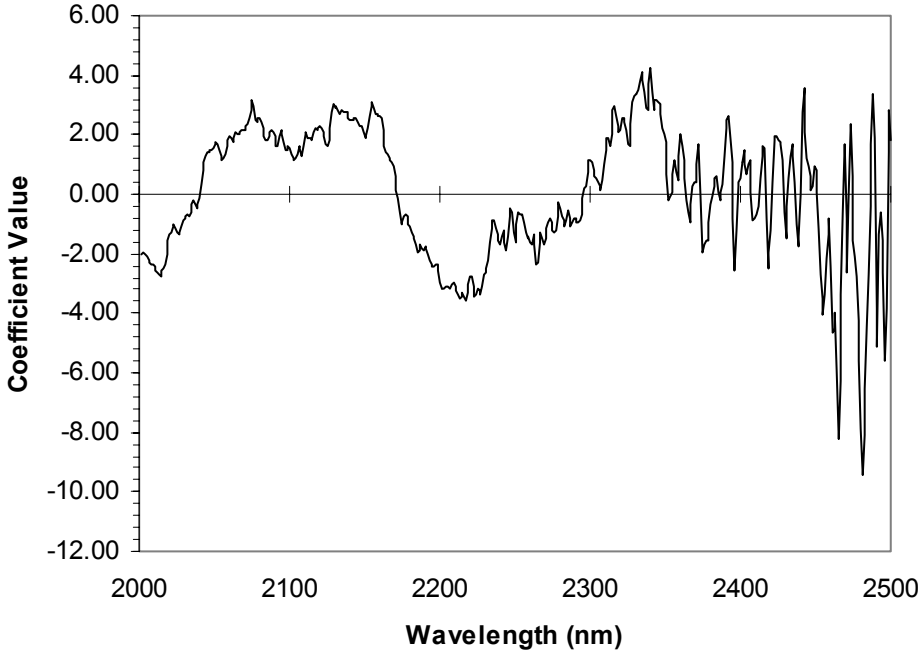
Regression coefficients for the ASD probe for predicting MOR from 1000 to 1500 nm (raw spectra)



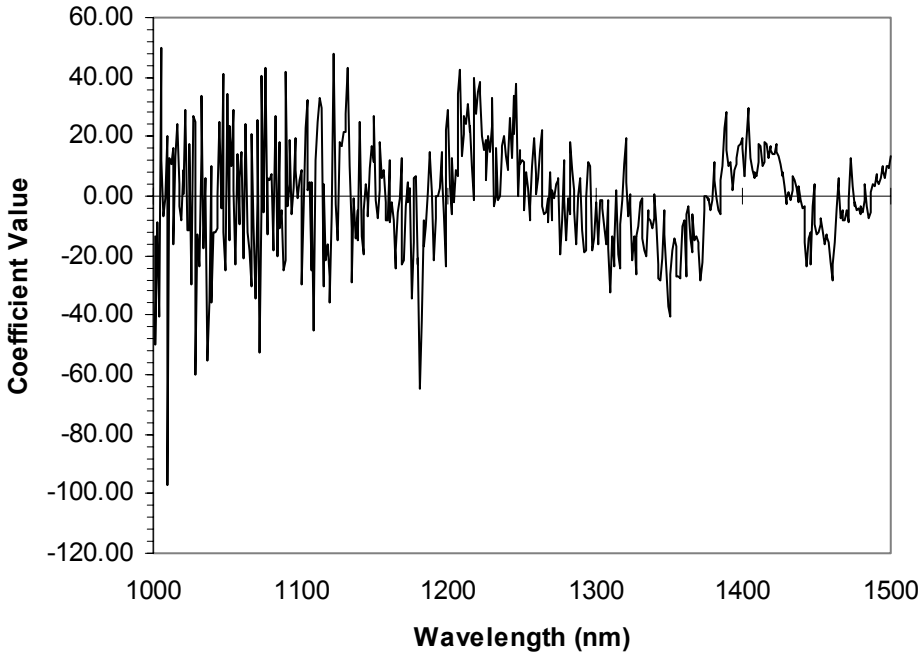
Regression coefficients for the ASD probe for predicting MOR from 1501-2000 nm (raw spectra)



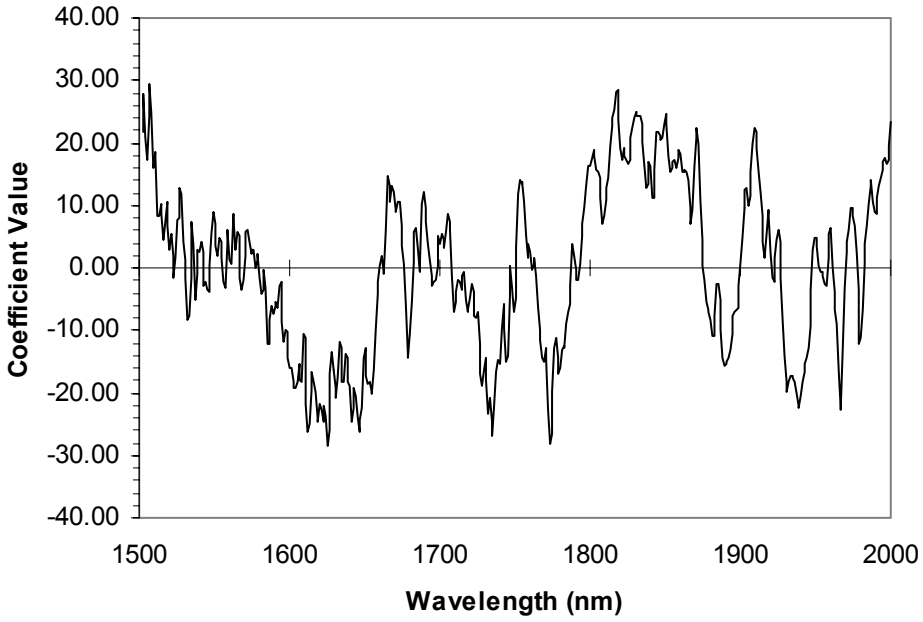
Regression coefficients for the ASD probe for predicting MOR from 2000-2500 nm (raw spectra)



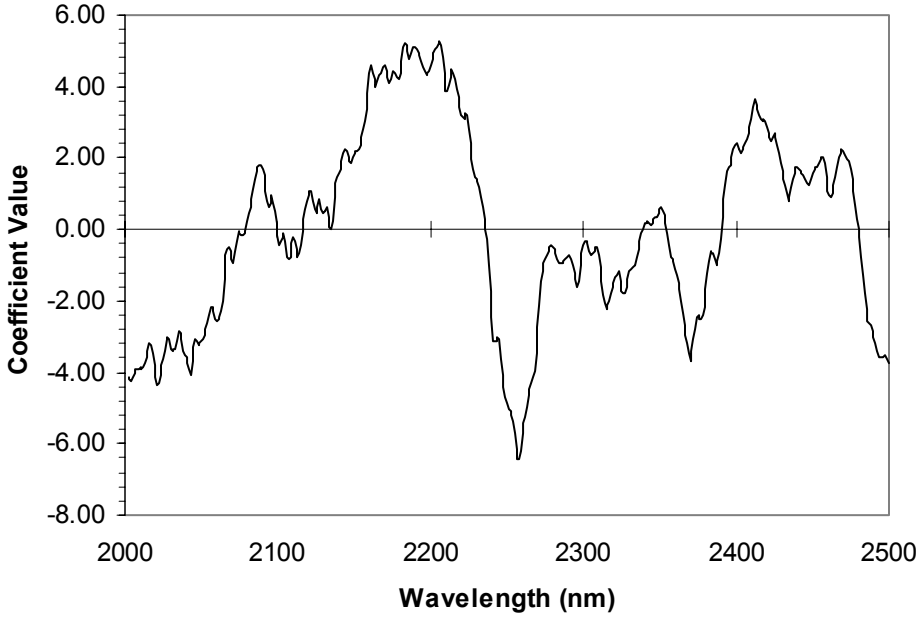
Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 1000-1500 nm (raw spectra)



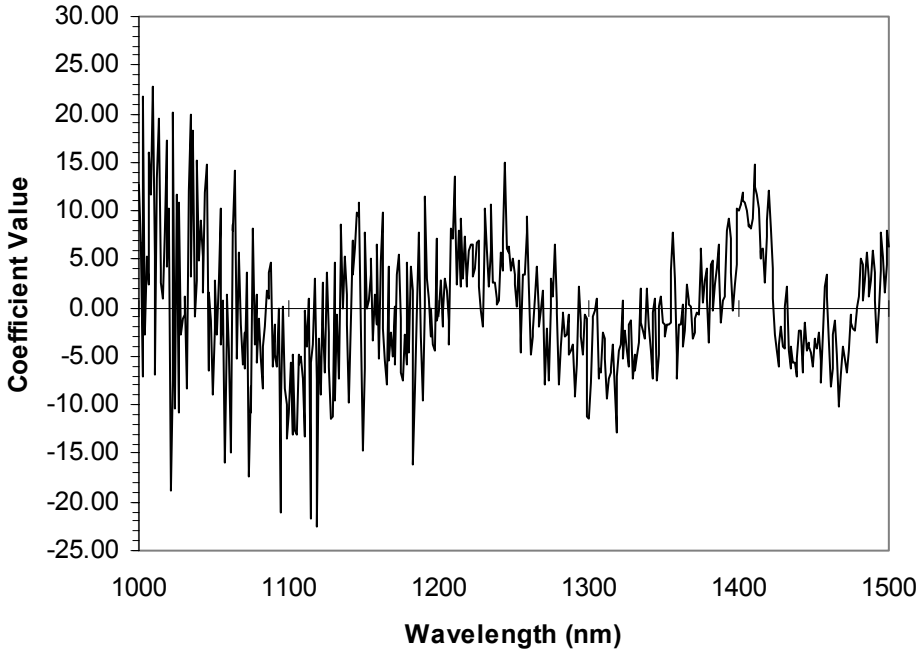
Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 1501-2000 nm (raw spectra)



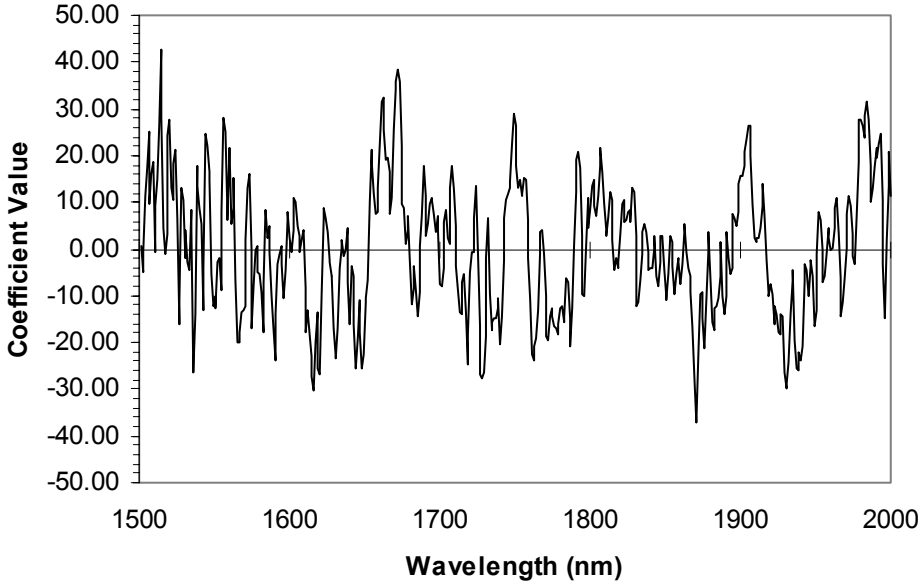
Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 2001-2500 nm (raw spectra)



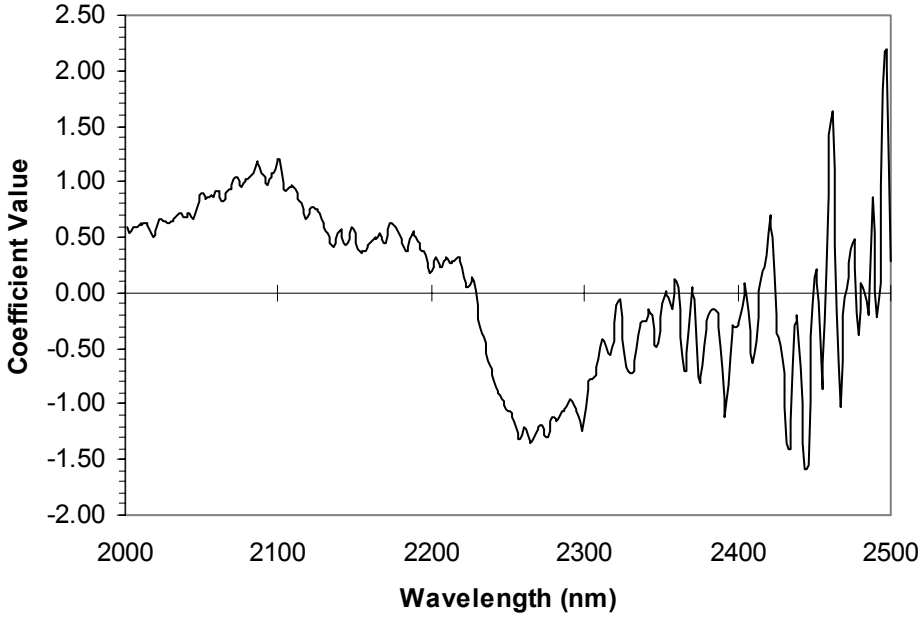
Regression coefficients for the Nicolet Fiberport probe for predicting MOR from 1000-1500 nm (raw spectra)



Regression coefficients for the Nicolet Fiberport probe for predicting MOR from 1501-2000 nm (raw spectra)



Regression coefficients for the Nicolet Fiberport probe for predicting MOR from 2001-2500 nm (raw spectra)



APPENDIX E – Chapter 3 – Bending and Moisture Content

First letter = Species - D = Doug-fir, G = Grand fir, L = lodgepole pine
Second letter = Mill - V = Vaagen Bros (Colville), Y = Yakama-Forest (White Swan), P = Plummer Forest (Plummer)
Third space = Sample number

Bending Data

Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
DV 1	16	1.007	1.005	642.7	13243	1.398	91.3	9639	7.54	6.83	10.4
DV 2	16	1.0045	1.0055	562.7	11647	1.45	80.3	9997	6.99	6.31	10.8
DV 5	16	1.0065	1.006	556.2	11461	1.394	79.0	9611	6.69	6.01	11.3
DV 7	16	1.005	1.0045	713.8	14775	1.854	101.9	12783			
DV 8	16	1.003	1.003	539.9	11236	1.228	77.5	8467			
DV 9	16	1.0055	1.0015	649.9	13479	1.846	92.9	12728	9.16	8.31	10.2
DV 11	16	1.0035	1.007	557.3	11541	1.359	79.6	9370	7.47	6.79	10.0
DV 12	16	1.006	1.007	663.1	13664	1.658	94.2	11432	9.32	8.45	10.3
DV 13	16	1.003	1.0025	663.4	13814	1.525	95.2	10515			
DV 14	16	1.006	1.0035	420.1	8687	0.904	59.9	6233			
DV 15	16	1.004	1.0025	627.1	13032	1.463	89.9	10087	7.01	6.36	10.2
DV 16	16	1.005	1.003	635.4	13171	1.646	90.8	11349			
DV 17	16	1.0045	1.0025	765.6	15894	1.93	109.6	13307	8.59	7.77	10.6
DV 19	16	1.004	1.002	599.5	12464	1.542	85.9	10632	7.32	6.53	12.1
DV 20	16	1.005	1.003	534.2	11074	1.272	76.4	8770	7.84	7.07	10.9
DV 21	16	1.004	1.004	704.4	14616	1.665	100.8	11480	9.93	8.94	11.1
DV 23	16	1.0055	1.005	575.3	11890	1.376	82.0	9487	7.77	7.01	10.8
DV 24	16	1.0055	1.006	563	11624	1.374	80.1	9473	7.07	6.44	9.8
DV 25	16	1.004	1.003	721.9	14994	1.711	103.4	11797	7.91	7.23	9.4
DV 26	16	1.006	1.005	585.5	12089	1.201	83.4	8281	7.33	6.61	10.9
DV 27	16	1.005	1.006	483.8	9994	1.111	68.9	7660	5.23	4.72	10.8
DV 28	16	1.005	1.0065	678.1	14008	1.759	96.6	12128	7.94	7.22	10.0
DV 29	16	1.005	1.005	478.7	9903	1.181	68.3	8143	6.69	6.07	10.2
DV 40	16	1.004	1.0045	802.4	16642	1.945	114.7	13410	8.93	8.02	11.3
DV 42	16	1.0025	1.003	702	14625	1.699	100.8	11714	7.96	7.23	10.1
DV 43	16	1.005	1.001	681.6	14157	1.516	97.6	10452	8.26	7.48	10.4
DV 44	16	1.0025	1.004	540.9	11257	1.3	77.6	8963	6.14	5.57	10.2
DV 45	16	1.005	1.002	638.1	13241	1.648	91.3	11363			
DV 46	16	1.002	1.002	724	15113	1.801	104.2	12417	9.11	8.17	11.5
DV 47	16	1.0045	1.004	576.9	11959	1.338	82.5	9225	6.8	6.14	10.7
DV 49	16	1.006	1.007	584.2	12038	1.442	83.0	9942			
DV 50	16	1.0045	1.005	579.9	12009	1.59	82.8	10963	7.08	6.37	11.1
DV 51	16	1.004	1.005	478.7	9923	1.192	68.4	8219	6.5	5.9	10.2
DV 52	16	1.003	1.0005	658	13667	1.518	94.2	10466	7.32	6.61	10.7
DV 53	16	1.005	1.003	679.7	14090	1.865	97.1	12859	7.66	6.84	12.0
DV 54	16	1.006	1.004	643.8	13306	1.661	91.7	11452	6.91	6.2	11.5
DV 55	16	1.003	1.002	778.8	16225	1.708	111.9	11776	7.7	6.9	11.6
DV 58	16	1.003	1.003	725.4	15097	1.83	104.1	12617	6.71	6.09	10.2
DV 60	16	1.005	1.0025	551.7	11442	1.473	78.9	10156	7.67	6.94	10.5
DV 61	16	1.004	1.0055	580.9	12036	1.446	83.0	9970	7.01	6.3	11.3
DV 62	16	1.004	1.002	728.6	15149	1.843	104.4	12707	8.44	7.56	11.6
DV 63	16	1.006	1.0055	540.7	11158	1.354	76.9	9336	8.67	7.83	10.7
DV 64	16	1.004	1.0045	623.6	12933	1.477	89.2	10184	8.44	7.54	11.9
DV 67	16	1.008	1.0025	761.9	15708	1.884	108.3	12990			
DV 68	16	1.0045	1.0045	543.6	11263	1.165	77.7	8032	8.44	7.57	11.5
DV 69	16	1.0035	1.0045	437.9	9091	1.284	62.7	8853	7.13	6.46	10.4
DV 70	16	1.0045	1.0045	487.2	10094	1.303	69.6	8984	6.86	6.15	11.5
DV 71	16	1.006	1.005	586.6	12112	1.454	83.5	10025	7.46	6.77	10.2
DV 72	16	1.004	1.002	612.9	12743	1.493	87.9	10294			
DV 73	16	1.005	1.0055	625.8	12940	1.541	89.2	10625			
DV 75	16	1.006	1.0045	540.7	11169	1.273	77.0	8777	6.48	5.87	10.4
DV 76	16	1.004	1.003	629.3	13071	1.265	90.1	8722	7.26	6.5	11.7
DV 78	16	1.004	1.0045	687.5	14259	1.636	98.3	11280	6.64	6.05	9.8
DV 81	16	1.0015	1.002	704.4	14719	1.818	101.5	12535	7.19	6.47	11.1
DV 82	16	1.004	1.0045	546.3	11319	1.392	78.0	9598	5.83	5.29	10.2
DV 85	16	1.004	1.005	748.5	15500	1.807	106.9	12459	8.52	7.71	10.5
DV 88	16	1.0045	1.001	498.8	10672	1.31	73.6	9032			
DV 90	16	1.035	1.005	651.8	13525	1.634	93.3	11266	7.92	7.18	10.3
DV 91	16	1.0015	1.004	549	11449	1.452	78.9	10011			
DV 92	16	1.0025	1.0025	612.3	12762	1.493	88.0	10294			
DV 93	16	1.0035	1.003	600.5	12485	1.144	86.1	7888	7.85	7.1	10.6
DV 96	16	1.004	1.0015	682.7	14201	1.839	97.9	12679	8.09	7.29	11.0
				Ave	12797.56	1.510967742	88.2	10418			
				COV(%)	14.1335	15.77898643	14.1	16			
				MIN	8687	0.904	59.9	6233			
				MAX	16642	1.945	114.7	13410			
GV 1	16	1.0045	1.004	470.9	9766	1.196	67.3	8246	6.58	5.92	11.1
GV 2	16	1.0035	1.004	544.7	11319	1.497	78.0	10321	7.49	6.72	11.5
GV 3	16	1.006	1.0035	448.3	9270	0.995	63.9	6860	8.14	7.35	10.7
GV 4	16	1.005	1.0045	594.1	12297	1.333	84.8	9191	7.43	6.66	11.6
GV 5	16	1.003	1.002	639.2	13316	1.69	91.8	11652	7.99	7.22	10.7
GV 6	16	1.0065	1.006	513	10571	1.387	72.9	9563	6.26	5.7	9.8
GV 8	16	1.007	1.005	575.3	11855	1.484	81.7	10232	6.82	6.16	10.7
GV 9	16	1.0035	1.0065	564	11686	1.474	80.6	10163	6.76	6.1	10.8
GV 10	16	1.006	1.006	447.8	9237	1.162	63.7	8012	6.79	6.2	9.5
GV 11	16	1.004	1.003	581.2	12072	1.633	83.2	11259	7.84	7.01	11.8
GV 12	16	1.005	1.003	593.6	12305	1.539	84.8	10611	7.36	6.63	11.0
GV 13	16	1.005	1.0055	663.1	13711	1.704	94.5	11749	8.55	7.71	10.9
GV 15	16	1.005	1.003	484	10033	1.303	69.2	8984	7.38	6.63	11.3
GV 16	16	1.007	1.006	520	10704	1.245	73.8	8584	6.88	6.2	11.0
GV 19	16	1.003	1.004	666.8	13857	1.714	95.5	11818	8.48	7.65	10.8
GV 20	16	1.0075	1.004	458.3	9439	1.016	65.1	7005	7.44	6.69	11.2
GV 21	16	1.005	1.0045	607.5	12574	1.578	86.7	10880	7.1	6.41	10.8
GV 22	16	1.0065	1.007	532.3	10958	1.429	75.6	9853	6.56	5.99	9.5
GV 25	16	1.0035	1.002	527.5	10978	1.402	75.7	9666	7.31	6.58	11.1
GV 26	16	1.0055	1.0065	601.6	12415	1.352	85.6	9322	7.59	6.86	10.6
GV 27	16	1.0025	1.004	492.6	10252	1.277	70.7	8805	6.9	6.21	11.1
GV 28	16	1.0045	1.0035	546	11324	1.566	78.1	10797	6.86	6.18	11.0
GV 29	16	1.004	1.0025	479.7	9969	1.198	68.7	8260	5.57	5	11.4
GV 30	16	1.0055	1.005	505.8	10454	1.208	72.1	8329	6.2	5.59	10.9
GV 32	16	1.003	1.003	635.2	13220	1.679	91.1	11576	6.71	6.05	10.9
GV 34	16	1.006	1.0055	479.7	9899	1.095	68.3	7550	5.29	4.85	9.1
GV 36	16	1.003	1.0005	726.4	15156	1.857	104.5	12804	7.96	7.17	11.0

Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
GV 39	16	1.002	1.002	539.9	11270	1.424	77.7	9818	7.89	7.09	11.3
GV 41	16	1.005	1.0045	557	11529	1.436	79.5	9901	6.34	5.75	10.3
GV 42	16	1.002	1.0035	571.5	11912	1.422	82.1	9804	6.85	6.17	11.0
GV 43	16	1.004	1.004	470.1	9755	1.262	67.3	8701	6.45	5.79	11.4
GV 44	16	1.004	1.004	563	11682	1.541	80.5	10625	7.348	6.73	9.2
GV 45	16	1.003	1.002	644.3	13416	1.602	92.5	11045	7.99	7.2	11.0
GV 46	16	1.005	1.0025	390.3	8095	1.123	55.8	7743	6.47	5.86	10.4
GV 48	16	1.004	1.001	433.8	9028	1.435	62.2	9894	6.31	5.66	11.5
GV 50	16	1.004	1.0035	394.1	8182	0.99	56.4	6826	6.78	6.12	10.8
GV 51	16	1.0055	1.0035	324.5	6717	0.93	46.3	6412	4.61	4.17	10.6
GV 54	16	1.006	1.003	420.4	8697	1.127	60.0	7770	5.38	4.85	10.9
GV 55	16	1.005	1.002	622.3	12913	1.455	89.0	10032	6.78	6.12	10.8
GV 56	16	1.006	1.004	514.1	10636	1.348	73.3	9294	6.53	5.89	10.9
GV 57	16	1.0055	1.002	596	12355	1.417	85.2	9770	7.24	6.52	11.0
GV 58	16	1.004	1.003	477.3	9914	1.249	68.4	8612	6.42	5.78	11.1
GV 59	16	1.003	1.0015	521.3	10866	1.341	74.9	9246	7.18	6.45	11.3
GV 60	16	1.005	1.001	645.6	13410	1.679	92.5	11576	7.82	7	11.7
GV 61	16	1.0055	1.003	524.8	10868	1.372	74.9	9460	6.98	6.37	9.6
GV 62	16	1.003	1.007	587.9	12187	1.467	84.0	10115	7.23	6.59	9.7
GV 63	16	1.0055	1.004	653.4	13518	1.61	93.2	11101	7.31	6.56	11.4
GV 64	16	1.004	1.003	472.8	9820	1.311	67.7	9039	6.24	5.6	11.4
GV 65	16	1.006	1.005	465.2	9605	1.24	66.2	8550	5.8	5.23	10.9
GV 66	16	1.004	1.005	437.6	9071	1.191	62.5	8212	5.47	4.95	10.5
GV 68	16	1.0025	1.0015	514.4	10732	1.357	74.0	9356			#DIV/0!
GV 69	16	1.004	1.001	567.2	11805	1.294	81.4	8922	6.92	6.19	11.8
GV 70	16	1.003	1.004	509.8	10599	1.031	73.1	7108	6.03	5.45	10.6
GV 74	16	1.004	1.0055	443.2	11652	1.321	80.3	9108	6.49	5.87	10.6
GV 75	16	1.004	1.001	551.7	11482	1.438	79.2	9915	6.55	5.87	11.6
GV 76	16	1.003	1.002	604.8	12600	1.56	86.9	10756	7.49	6.74	11.1
GV 77	16	1.0045	1.002	553.6	11499	1.297	79.3	8943	7.94	7.21	10.1
GV 78	16	1.0035	1.005	491.8	10205	1.206	70.4	8315	7.87	7.06	11.5
GV 79	16	1.004	1.005	561.6	11642	1.044	80.3	7198	8.36	7.46	12.1
GV 81	16	1.0085	1.007	464.7	9528	1.206	65.7	8315	5.75	5.78	-0.5
GV 82	16	1.004	1.0025	490.5	10193	1.303	70.3	8984	6.11	5.48	11.5
GV 83	16	1.003	1.006	590.9	12261	1.505	84.5	10377	6.46	5.79	11.6
GV 84	16	1.002	1.0035	537.7	11196	1.436	77.2	9901	6.54	5.87	11.4
GV 86	16	1.0025	1.005	585.2	12167	1.568	83.9	10811	6.74	6.12	10.1
GV 89	16	1.0045	1.0035	514.6	10673	1.273	73.6	8777	6	5.36	11.9
GV 90	16	1.004	1.004	419.6	8694	0.913	59.9	6295	5.13	4.59	11.8
GV 92	16	1.004	1.004	441.6	9150	1.088	63.1	7501	5.19	4.65	11.6
GV 93	16	1.0045	1.0045	538.8	11163	1.321	77.0	9108	6.22	5.54	12.3
GV 94	16	1.0035	1.0045	596.8	12390	1.58	85.4	10894	6.61	5.96	10.9
GV 95	16	1.0075	1.0065	516.5	10617	1.305	73.2	8998	5.6	5.04	11.1
GV 96	16	1.003	1.004	599.5	12464	1.479	85.9	10197	6.82	6.12	11.4
GV 97	16	1.006	1.005	585	12079	1.298	83.3	8949	6.78	6.21	9.2
GV 98	16	1.0045	1.004	469.8	9739	1.218	67.1	8398	6.29	5.68	10.7
GV 99	16	1.005	1.005	519.2	10741	1.356	74.1	9349	6.64	5.98	11.0
GV 100	16	1.0055	1.003	593.3	12287	1.564	84.7	10783	7.94	7.16	10.9
				Ave	11088.55	1.35928	76.5	9372			
				COV(%)	13.92777	14.84070778	13.9	15			
				MIN	6717	0.913	46.3	6295			
				MAX	15156	1.857	104.5	12804			
LV 2	16	1.0035	1.0045	643.8	13366	1.565	92.2	10790			
LV 3	16	1.003	1.003	687	14298	1.79	98.6	12342	8.06	7.23	11.5
LV 4	16	1.002	1.0025	778.3	16239	1.907	112.0	13148	9.21	8.22	12.0
LV 6	16	1.0035	1.004	622.3	12926	1.644	89.1	11335	7	6.29	11.3
LV 8	16	1.0015	1.006	649.4	13515	1.547	93.2	10666	8.08	7.25	11.4
LV 9	16	1.0065	1.004	489.9	10115	1.312	69.7	9046	5.6	5.02	11.6
LV 10	16	1.008	1.006	648.3	13319	1.625	91.8	11204	7.11	6.4	11.1
LV 11	16	1.005	1.004	676	13999	1.723	96.5	11880	7.56	6.82	10.9
LV 13	16	1.007	1.003	566.7	11701	1.437	80.7	9908	6.31	5.67	11.3
LV 14	16	1.0045	1.006	588.5	12175	1.467	83.9	10115	6.32	5.75	9.9
LV 15	16	1.004	1.005	655	13578	1.663	93.6	11466	6.79	6.17	10.0
LV 16	16	1.004	1.0025	560.3	11644	1.432	80.3	9873	6.15	5.5	11.8
LV 18	16	1.004	1.003	639.2	13277	1.682	91.5	11597	7.19	6.45	11.5
LV 19	16	1.003	1.006	660.9	13714	1.665	94.6	11480	7.34	6.6	11.2
LV 20	16	1.001	1.0045	626.6	13073	1.573	90.1	10845	7.5	6.75	11.1
LV 21	16	1.004	1.004	561.3	11647	1.426	80.3	9832	6.87	6.15	11.7
LV 22	16	1.0015	1.0025	627.9	13114	1.478	90.4	10190	8.12	7.32	10.9
LV 23	16	1.004	1.006	608.6	12603	1.553	86.9	10708	7.66	6.93	10.5
LV 24	16	1.0065	1.008	640.5	13172	1.454	90.8	10025	6.98	6.32	10.4
LV 25	16	1.002	1.004	629.5	13114	1.598	90.4	11018	7.61	6.87	10.8
LV 26	16	1.006	1.003	555.2	11486	1.486	79.2	10246	6.73	6.07	10.9
LV 27	16	1.003	1.005	688.6	14303	1.723	98.6	11880	7.27	6.56	10.8
LV 28	16	1.005	1.0025	621.7	12894	1.662	88.9	11459	6.55	5.91	10.8
LV 29	16	1.003	1.005	573.4	11910	1.518	82.1	10466	6.23	5.61	11.1
LV 30	16	1.006	1.007	638.7	13148	1.588	90.7	10949	6.51	5.88	10.7
LV 34	16	1.006	1.004	740.1	15296	1.788	105.5	12328	6.28	5.71	10.0
LV 35	16	1.009	1.0065	654	13403	1.62	92.4	11170	6.5	5.82	11.7
LV 36	16	1.01	1.011	462.5	9418	0.982	64.9	6771	6.54	5.89	11.0
LV 37	16	1.009	1.005	740.1	15190	1.758	104.7	12121	8.33	7.49	11.2
LV 38	16	1.0055	1.0045	587.1	12140	1.545	83.7	10652	6.33	5.7	11.1
LV 39	16	1.005	1.006	571	11801	1.353	81.4	9329	5.92	5.35	10.7
LV 40	16	1.008	1.011	631.4	12908	1.58	89.0	10894	6.16	5.51	11.8
LV 42	16	1.0045	1.0035	612.9	12711	1.494	87.6	10301	6.48	5.79	11.9
LV 43	16	1.005	1.0045	641.9	13286	1.585	91.6	10928	5.98	5.38	11.2
LV 45	16	1.0025	1.001	618.5	12911	1.467	89.0	10115	5.92	5.33	11.1
LV 46	16	1.0075	1.0085	622.3	12766	1.479	88.0	10197	5.69	5.09	11.8
LV 48	16	1.004	1.004	591.7	12278	1.384	84.7	9542	4.99	4.43	12.6
LV 49	16	1.0065	1.003	644.3	13316	1.608	91.8	11087	6.84	6.11	11.9
LV 50	16	1.004	1.005	702.8	14569	1.729	100.4	11921	7.84	7.09	10.6
LV 53	16	1.005	1.006	655.3	13543	1.707	93.4	11769	7.25	6.49	11.7
LV 54	16	1.004	1.007	708.2	14651	1.867	101.0	12873	8.05	7.21	11.7
LV 55	16	1.0015	1.0025	658.3	13749	1.617	94.8	11149	7.75	6.92	12.0
LV 56	16	1.005	1.0065	654	13510	1.645	93.1	11342	8.41	7.58	10.9
LV 57	16	1.001	1.005	589.3	12289	1.543	84.7	10639	7.25	6.49	11.7
LV 58	16	1.007	1.003	626.3	12931	1.538	89.2	10604	7.92	7.09	11.7
LV 59	16	1.007	1.007	740.1	15220	1.767	104.9	12183	9.59	8.72	10.0
LV 60	16.06	1.0065	1.0035	618.5	12777	1.701	88.1	11728	5.48	4.92	11.4
LV 61	16.06	1.003	1.003	713.3	14845	1.697	102.4	11700	6.16	5.49	12.2

Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
LV 62	16.06	1.007	1.005	496.9	10239	1.343	70.6	9260	5.38	4.83	11.4
LV 65	16.06	1.008	1.006	617.2	12680	1.492	87.4	10287	6.4	5.73	11.7
LV 67	16.06	1.004	1.005	639.5	13243	1.59	91.3	10963	6.55	5.84	12.2
LV 68	16.06	1.0045	1.003	632.5	13124	1.646	90.5	11349	6.83	6.11	11.8
LV 69	16.06	1.009	1.005	592.2	12155	1.488	83.8	10259	7.01	6.3	11.3
LV 71	16.06	1.003	1.005	645.9	13416	1.769	92.5	12197	7.27	6.51	11.7
LV 72	16.06	1.0045	1.007	649.4	13422	1.648	92.5	11363	7.45	6.64	12.2
LV 74	16	1.004	1.004	635.4	13191	1.635	90.9	11273	6.62	5.92	11.8
LV 75	16	1.008	1.0035	645.4	13293	1.723	91.7	11880	7.32	6.54	11.9
LV 76	16	1.006	1.007	578	11910	1.424	82.1	9818	6.41	5.76	11.3
LV 77	16	1.004	1.003	702.3	14573	1.867	100.5	12873	7.71	6.91	11.6
LV 78	16	1.0045	1.004	589	12210	1.357	84.2	9356	7.28	6.44	13.0
LV 80	16	1.007	1.01	589.3	12083	1.392	83.3	9598	7.12	6.4	11.3
LV 81	16	1.003	1.008	560	11597	1.464	80.0	10094	6.55	5.87	11.6
LV 84	16	1.0085	1.004	666	13696	1.715	94.4	11825	7.96	7.11	12.0
LV 87	16	1.001	1.007	683.2	14219	1.815	98.0	12514	8.8	7.89	11.5
LV 89	16	1.008	1.006	574.8	11809	1.545	81.4	10652	7.77	6.98	11.3
LV 90	16	1.003	1.004	640	13313	1.696	91.8	11694	7.82	7.03	11.2
LV 91	16	1.008	1.0035	640	13181	1.672	90.9	11528	7.28	6.62	10.0
LV 92	16	1.003	1.007	692.6	14357	1.547	99.0	10666	8.14	7.31	11.4
LV 93	16	1.007	1.005	681.1	14035	1.807	96.8	12459	8.6	7.71	11.5
LV 94	16	1.005	1.0075	735.8	15185	1.752	104.7	12080	9.42	8.47	11.2
LV 95	16	1.004	1.0085	645.4	13332	1.819	91.9	12542	8.77	7.85	11.7
LV 96	16	1.0095	1.003	560.5	11515	1.328	79.4	9156	6.68	6.07	10.0
LV 97	16	1.007	1.005	651.8	13431	1.573	92.6	10845	7.87	7.07	11.3
LV 99	16	1.004	1.004	675.4	14015	1.73	96.6	11928	8.59	7.69	11.7
LV 100	16	0.996	0.996	634.1	13477	1.66	92.9	11445	8.3	7.43	11.7
				Ave	13100.52	1.59292	90.3	10983			
				COV(%)	9.134712	9.878581141	9.1	10			
				MIN	9418	0.982	64.9	6771			
				MAX	16239	1.907	112.0	13148			
DY 1	16	1.0135	1.016	630.3	12689	1.539	87.5	10611	7.72	6.92	11.6
DY 2	16	1.0135	1.0155	597.6	12031	1.506	83.0	10384	6.95	6.28	10.7
DY 3	16	1.017	1.014	658.8	13191	1.669	90.9	11507	8.12	7.25	12.0
DY 4	16	1.013	1.013	711.7	14378	1.906	99.1	13141	8.44	7.55	11.8
DY 6	16	1.013	1.015	565.4	11400	1.433	78.6	9880	6.07	5.52	10.0
DY 7	16	1.014	1.0115	749.5	15134	1.778	104.3	12259	8.44	7.59	11.2
DY 8	16	1.013	1.014	698.3	14093	1.811	97.2	12486	7.73	6.95	11.2
DY 9	16	1.013	1.0155	627.4	12643	1.555	87.2	10721	7.46	6.67	11.8
DY 10	16	1.013	1.0165	635.4	12792	1.347	88.2	9287	8.15	7.39	10.3
DY 11	16	1.015	1.014	684.6	13762	1.774	94.9	12231	7.48	6.72	11.3
DY 12	16	1.0145	1.021	702.5	14039	1.812	96.8	12493	7.63	6.85	11.4
DY 13	16	1.015	1.015	681.6	13688	1.546	94.4	10659	7.54	6.85	10.1
DY 14	16	1.0135	1.0125	662.5	13377	1.656	92.2	11418	7.56	6.89	9.7
DY 15	16	1.016	1.016	605.9	12132	1.308	83.6	9018	6.87	6.23	10.3
DY 17	16	1.0115	1.01	670.6	13682	1.779	94.3	12266	8.29	7.52	10.2
DY 18	16	1.012	1.01	719.7	14611	1.78	100.7	12273	8.69	7.84	10.8
DY 19	16	1.013	1.013	737.4	14897	1.854	102.7	12783	8.2	7.39	11.0
DY 20	16	1.016	1.0125	710.9	14284	1.789	98.5	12335	8.19	7.41	10.5
DY 22	16	1.013	1.012	598.8	12111	1.677	83.5	11563	6.31	5.77	9.4
DY 23	16	1.014	1.014	849.4	17119	2.006	118.0	13831	8.69	7.91	9.9
DY 24	16	1.013	1.015	728.1	14680	1.591	101.2	10970	7.84	7.08	10.7
DY 26	16	1.0125	1.017	350.5	7060	1.373	48.7	9467	8.79	7.97	10.3
DY 27	16	1.0135	1.016	488.1	9817	1.248	67.7	8605	7.58	6.92	9.5
DY 28	16	1.016	1.0165	867.4	17360	2.062	119.7	14217	9.42	8.5	10.8
DY 29	16	1.016	1.017	549	10982	1.416	75.7	9763	7.37	6.7	10.0
DY 30	16	1.013	1.01	557.6	11298	1.51	77.9	10411	7.3	6.62	10.3
DY 31	16	1.013	1.012	575.8	11638	1.426	80.2	9832	7.13	6.51	9.5
DY 32	16	1.01	1.0125	608.6	12374	1.672	85.3	11528	7.78	7.07	10.0
DY 34	16	1.015	1.014	542	10896	1.205	75.1	8308	7.1	6.42	10.6
DY 35	16	1.015	1.014	663.9	13346	1.402	92.0	9666	8.37	7.59	10.3
DY 38	16	1.015	1.012	649.4	13080	1.682	90.2	11597	7.55	6.9	9.4
DY 39	16	1.016	1.017	632.5	12652	1.473	87.2	10156	6.57	6.04	8.8
DY 40	16	1.011	1.014	660.4	13381	1.739	92.3	11990	10.04	9.11	10.2
DY 42	16	1.013	1.013	772.9	15614	1.931	107.7	13314	8.57	7.76	10.4
DY 43	16	1.0125	1.015	609.7	12305	1.334	84.8	9198	7.09	6.47	9.6
DY 44	16	1.0135	1.0165	637.6	12824	1.905	88.4	13135	8.77	7.91	10.9
DY 46	16	1.016	1.018	591.4	11819	1.508	81.5	10397	7.45	6.76	10.2
DY 47	16	1.014	1.014	591.9	11922	1.569	82.2	10818	7.28	6.64	9.6
DY 49	16	1.023	1.024	711.1	13935	1.833	96.1	12638	8.73	7.89	10.6
DY 51	16	1.0255	1.025	602.4	11736	1.491	80.9	10280	7.62	7.77	-1.9
DY 52	16	1.0265	1.026	558.4	10847	1.465	74.8	10101	7.67	6.97	10.0
DY 53	16	1.027	1.025	585	11363	1.381	78.3	9522	7.25	6.52	11.2
DY 55	16	1.0265	1.024	654.2	12720	1.241	87.7	8556	8.89	7.93	12.1
DY 56	16	1.027	1.026	695.8	13503	1.572	93.1	10839	8.66	7.76	11.6
DY 57	16	1.027	1.0285	909.5	17607	1.998	121.4	13776	9.67	8.75	10.5
DY 60	16	1.027	1.023	717.3	13961	1.769	96.3	12197	7.98	7.25	10.1
DY 61	16	1.026	1.026	625.5	12162	1.465	83.9	10101	7.85	7.13	10.1
DY 62	16	1.027	1.0285	533.4	10326	1.179	71.2	8129	6.17	5.52	11.8
DY 63	16	1.028	1.0275	671.4	12978	1.61	89.5	11101	7.72	6.95	11.1
DY 64	16	1.026	1.028	815.3	15822	1.999	109.1	13783	9.68	8.7	11.3
DY 65	16	1.024	1.0215	880	17194	2.075	118.5	14307	9.73	8.74	11.3
DY 66	16	1.024	1.021	816.9	16024	1.95	110.5	13445	9.38	8.41	11.5
DY 67	16	1.026	1.0245	841.3	16382	2.124	112.9	14644	10.22	9.19	11.2
DY 68	16	1.023	1.0225	761.9	14952	1.901	103.1	13107	8.81	7.97	10.5
DY 69	16	1.025	1.028	758.9	14756	1.749	101.7	12059	8.9	8.03	10.8
DY 70	16	1.027	1.025	668.2	12980	1.571	89.5	10832	8.05	7.25	11.0
DY 72	16	1.026	1.024	794.9	15486	1.958	106.8	13500	8.49	7.73	9.8
DY 74	16	1.024	1.024	677	13241	1.883	91.3	12983	9.21	8.26	11.5
DY 75	16	1.025	1.024	621.2	12126	1.539	83.6	10611	7.4	6.68	10.8
DY 77	16	1.029	1.027	665.5	12852	1.658	88.6	11432	8.04	7.2	11.7
DY 78	16	1.0285	1.028	639.2	12344	1.494	85.1	10301	7.52	6.83	10.1
DY 79	16	1.024	1.0235	700.9	13715	1.595	94.6	10997	8.66	7.83	10.6
DY 80	16	1.029	1.0275	589.5	11373	1.477	78.4	10184	6.94	6.23	11.4
DY 81	16	1.026	1.023	717.3	13988	1.812	96.4	12493	8.52	7.66	11.2
DY 82	16	1.0235	1.001	867.6	17035	2.066	117.5	14245	9.96	9.08	9.7
DY 83	16	1.024	1.0255	771	15057	1.89	103.8	13031	9.02	8.15	10.7
DY 84	16	1.0275	1.028	704.7	16635	1.536	114.7	10590	8.19	7.43	10.2
DY 85	16	1.025	1.022	642.7	12570	1.674	86.7	11542	8.28	7.47	10.8
DY 86	16	1.027	1.026	832.7	16159	2.015	111.4	13893	9.9	9.03	9.6

Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
DY 87	16	1.0255	1.02	918.4	17980	2.168	124.0	14948	9.88	8.88	11.3
DY 88	16	1.0235	1.023	662.3	12978	1.72	89.5	11859	8.17	7.35	11.2
DY 89	16	1.026	1.026	602.4	11713	1.367	80.8	9425	6.77	6.13	10.4
DY 90	16	1.0275	1.026	758.1	14697	1.788	101.3	12328	8.17	7.4	10.4
DY 91	16	1.027	1.025	739.1	14357	1.705	99.0	11756	7.99	7.12	12.2
DY 92	16	1.025	1.025	662.5	12919	1.611	89.1	11107	7.23	6.56	10.2
DY 93	16	1.024	1.025	645.9	12620	1.583	87.0	10914	8.03	7.31	9.8
DY 95	16	1.023	1.028	802.4	15663	2.03	108.0	13996	9.82	8.83	11.2
DY 96	16	1.027	1.026	668.2	12967	1.542	89.4	10632	8.36	7.6	10.0
DY 97	16	1.025	1.025	785.5	15318	1.874	105.6	12921	8.79	7.9	11.3
DY 99	16	1.0235	1.023	872.7	17101	2.066	117.9	14245	10.57	9.48	11.5
DY 100	16	1.025	1.025	864.4	16856	2.012	116.2	13872	9.51	8.71	9.2
				Ave	13606.16	1.679098765	93.8	11577			
				COV(%)	14.83817	14.37530499	14.8	14			
				MIN	7060	1.179	48.7	8129			
				MAX	17980	2.168	124.0	14948			
GY 1	16	1.017	1.0245	674.9	13375	1.671	92.2	11521	8.16	7.39	10.4
GY 2	16	1.0175	1.019	511.9	10190	1.226	70.3	8453	5.58	5.1	9.4
GY 6	16	1.017	1.0165	454.5	9078	1.055	62.6	7274	5.91	5.3	11.5
GY 7	16	1.017	1.014	552.2	11057	1.425	76.2	9825	7.32	6.59	11.1
GY 8	16	1.017	1.02	477.3	9501	1.18	65.5	8136	5.63	5.1	10.4
GY 9	16	1.017	1.017	505	10082	1.228	69.5	8467	5.25	4.72	11.2
GY 10	16	1.0185	1.015	521.3	10397	1.086	71.7	7488	5.67	5.11	11.0
GY 11	16	1.0175	1.0175	423.6	8444	1.053	58.2	7260	4.92	4.44	10.8
GY 12	16	1.017	1.015	604.8	12098	1.51	83.4	10411	6.66	6.01	10.8
GY 13	16	1.019	1.018	530.5	10539	1.255	72.7	8653	6.21	5.62	10.5
GY 14	16	1.017	1.017	488.6	9755	1.007	67.3	6943	5.78	5.29	9.3
GY 15	16	1.017	1.017	488.1	9735	1.237	67.1	8529	5.9	5.3	11.3
GY 16	16	1.0165	1.0165	487.8	9729	1.263	67.1	8708	5.58	5.03	10.9
GY 17	16	1.0175	1.0175	525.6	10442	1.269	72.0	8749	5.4	4.89	10.4
GY 18	16	1.018	1.018	522.7	10394	1.283	71.7	8846	5.95	5.37	10.8
GY 19	16	1.017	1.017	576.4	11496	1.447	79.3	9977	5.86	5.3	10.6
GY 20	16	1.018	1.018	469.8	9352	1.256	64.5	8660	5.6	5.01	11.8
GY 21	16	1.02	1.02	529.4	10476	1.371	72.2	9453	5.59	5.07	10.3
GY 22	16	1.018	1.018	633.8	12641	1.593	87.2	10983	8.07	7.3	10.5
GY 24	16	1.015	1.015	536.9	10761	1.295	74.2	8929	6.75	6.08	11.0
GY 28	16	1.019	1.019	584.7	11605	1.421	80.0	9797	6.73	6.04	11.4
GY 29	16	1.019	1.019	554.1	10992	1.438	75.8	9915	6.69	6.05	10.6
GY 31	16	1.02	1.02	480.5	9518	1.132	65.6	7805	5.61	5.09	10.2
GY 32	16	1.019	1.019	542.8	10784	1.41	74.4	9722	7.27	6.54	11.2
GY 33	16	1.019	1.019	500.7	9947	1.213	68.6	8363	5.64	5.06	11.5
GY 34	16	1.018	1.018	494.5	9853	1.237	67.9	8529	5.82	5.23	11.3
GY 35	16	1.018	1.018	571.8	11393	1.395	78.6	9618	6.31	5.7	10.7
GY 38	16	1.02	1.02	384.7	7605	0.984	52.4	6784	4.83	4.35	11.0
GY 39	16	1.018	1.018	485.1	9637	1.2	66.4	8274	5.6	5.04	11.1
GY 41	16	1.018	1.018	477.3	9510	1.194	65.6	8232	5.46	4.89	11.7
GY 43	16	1.0175	1.017	452.9	9033	1.107	62.3	7632	5.5	4.96	10.9
GY 45	16	1.0165	1.0165	522.7	10451	1.351	72.1	9315	6.4	5.72	11.9
GY 46	16	1.015	1.018	531.3	10638	1.246	73.3	8591	6.81	6.1	11.6
GY 47	16	1.016	1.015	492.3	9867	1.24	68.0	8550	5.62	5.09	10.4
GY 48	16	1.017	1.0155	488.9	9775	1.32	67.4	9101	6.35	5.7	11.4
GY 49	16	1.0155	1.017	449.7	9005	1.086	62.1	7488	5.3	4.84	9.5
GY 50	16	1.016	1.0175	528.6	10558	1.349	72.8	9301	6.47	5.84	10.8
GY 52	16	1.0165	1.017	481.6	9624	1.368	66.4	9432	6.61	5.94	11.3
GY 54	16	1.016	1.015	562.7	11278	1.416	77.8	9763	7.23	6.54	10.6
GY 55	16	1.015	1.016	489.4	9819	1.304	67.7	8991	6.63	6	10.5
GY 56	16	1.017	1.0145	601.6	12040	1.274	83.0	8784	7.75	6.94	11.7
GY 57	16	1.017	1.017	481.6	9615	1.302	66.3	8977	6.28	5.65	11.2
GY 61	16	1.016	1.018	500.9	10010	1.091	69.0	7522	8.49	7.59	11.9
GY 63	16	1.0175	1.018	459.3	9152	1.19	63.1	8205	5.81	5.24	10.9
GY 64	16	1.016	1.0135	508.7	10211	1.307	70.4	9011	6.12	5.53	10.7
GY 65	16	1.016	1.018	480.3	9598	1.217	66.2	8391	6.15	5.54	11.0
GY 66	16	1.016	1.017	387.1	7743	0.867	53.4	5978	5.7	5.14	10.9
GY 67	16	1.017	1.0155	494.5	9887	1.223	68.2	8432	6.2	5.57	11.3
GY 68	16	1.016	1.0145	531.3	10654	1.093	73.5	7536	6.2	5.59	10.9
GY 70	16	1.017	1.0135	553.8	11094	1.186	76.5	8177	6.71	5.99	12.0
GY 71	16	1.017	1.016	456.4	9121	1.196	62.9	8246	5.29	4.78	10.7
GY 72	16	1.016	1.016	488.1	9773	1.242	67.4	8563	6.02	5.43	10.9
GY 75	16	1.017	1.013	701.2	14054	1.643	96.9	11328	7.51	6.77	10.9
GY 76	16	1.016	1.0145	492.9	9884	1.298	68.1	8949	6.82	6.14	11.1
GY 78	16	1.015	1.016	531.3	10665	1.222	73.5	8425	5.88	5.3	10.9
GY 79	16	1.0155	1.0155	505.2	10131	1.277	69.9	8805	7.68	6.87	11.8
GY 80	16	1.0175	1.0185	471.7	9394	1.16	64.8	7998	6.89	6.19	11.3
GY 82	16	1.016	1.017	531.3	10628	1.275	73.3	8791	6.78	6.09	11.3
GY 83	16	1.018	1.019	527	10826	1.351	74.6	9315	7.3	6.4	14.1
GY 84	16	1.018	1.019	589.8	11729	1.502	80.9	10356	6.33	5.79	9.3
GY 86	16	1.018	1.0155	463.1	9241	1.103	63.7	7605	5.47	5.03	8.7
GY 89	16	1.017	1.0165	543.1	10848	1.41	74.8	9722	6.92	6.22	11.3
GY 90	16	1.017	1.018	441.1	8802	1.075	60.7	7412	6.06	5.46	11.0
GY 91	16	1.018	1.0175	402.7	8020	1.011	55.3	6971	5.34	4.82	10.8
GY 92	16	1.016	1.015	431.1	8641	1.018	59.6	7019	5.75	5.16	11.4
GY 94	16	1.016	1.015	448.6	8991	1.151	62.0	7936	4.9	4.49	9.1
GY 95	16	1.0185	1.017	527	10490	1.304	72.3	8991	5.73	5.26	8.9
GY 96	16	1.0165	1.017	662.5	13239	1.615	91.3	11135	7.46	6.79	9.9
GY 97	16	1.017	1.015	535.3	10708	1.347	73.8	9287	6.71	6.09	10.2
GY 98	16	1.017	1.017	619.3	12364	1.375	85.2	9480	6.16	5.69	8.3
GY 99	16	1.017	1.015	538.3	10768	1.276	74.2	8798	5.54	5.07	9.3
				Ave	10264.15	1.263690141	70.8	8713			
				COV(%)	11.94475	12.48510468	11.9	12			
				MIN	7605	0.867	52.4	5978			
				MAX	14054	1.671	96.9	11521			
LY 1	16	1.003	1.004	541.5	11259	1.295	77.6	8929	6.15	5.56	10.6
LY 2	16	1.005	1.005	590.9	12225	1.417	84.3	9770	6.28	5.59	12.3
LY 4	16	1.005	1.0025	630.3	13072	1.743	90.1	12018	7.24	6.48	11.7
LY 5	16	1	1.005	597.3	12481	1.302	86.1	8977	7.26	6.51	11.5
LY 6	16	1.0015	1.004	531.8	11090	1.254	76.5	8646	6.92	6.2	11.6
LY 7	16	1.0035	1	677.3	14124	1.471	97.4	10142	10.4	9.21	12.9
LY 9	16	1	0.999	612.6	12877	1.729	88.8	11921	8.63	7.74	11.5
LY 10	16	1.003	0.998	469.5	9820	1.306	67.7	9005	6.44	5.76	11.8

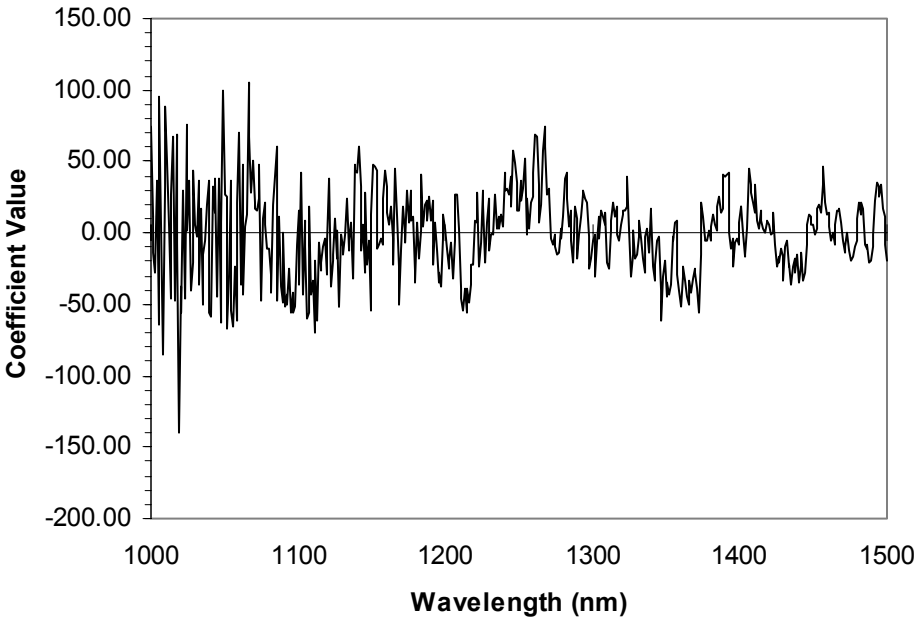
Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
LY 11	16	1.002	0.998	590.1	12367	1.592	85.3	10976	8.34	7.44	12.1
LY 14	16	1.003	1.0035	517.9	10773	1.319	74.3	9094	7.13	6.4	11.4
LY 15	16	1.0025	1.002	574.8	11987	1.354	82.6	9336	7.19	7.09	1.4
LY 16	16	1.0015	1	636.2	13320	1.658	91.8	11432	8.49	7.6	11.7
LY 17	16	0.9995	1	584.7	12279	1.507	84.7	10390	8.28	7.38	12.2
LY 19	16	1.003	1.004	507.9	10560	1.215	72.8	8377	6.63	5.96	11.2
LY 21	16	1.0035	1.001	561.1	11689	1.399	80.6	9646	7.74	6.89	12.3
LY 22	16	1.003	1.0045	441.9	9183	1.095	63.3	7550	6.05	5.43	11.4
LY 23	16	1.004	1.003	400.3	8306	0.979	57.3	6750	6.14	5.53	11.0
LY 24	16	1.0045	1.002	518.1	10761	1.257	74.2	8667	7.7	6.9	11.6
LY 26	16	1.003	0.9995	533.7	11146	1.225	76.8	8446	7.44	6.66	11.7
LY 28	16	1.0025	1.002	656.9	13706	1.634	94.5	11266	7.59	6.84	11.0
LY 29	16	1.002	1.002	471.9	9856	1.253	68.0	8639	6.67	5.97	11.7
LY 31	16	1.003	1.0015	544.7	11353	1.401	78.3	9660	6.86	6.17	11.2
LY 32	16	1.0015	1	523.5	10966	1.454	75.6	10025	7.17	6.43	11.5
LY 34	16	1.002	1	684	14314	1.831	98.7	12624	8.62	7.72	11.7
LY 35	16	1	0.9995	581.5	12230	1.648	84.3	11363	7.83	6.99	12.0
LY 36	16	0.9995	1	561.4	11822	1.341	81.5	9246	6.85	6.11	12.1
LY 37	16	1.004	1.002	533.4	11096	1.186	76.5	8177	7.02	6.27	12.0
LY 38	16	1.0025	1.0015	661.2	13795	1.438	95.1	9915	8.53	7.59	12.4
LY 39	16	1.0045	1.0025	515.7	10706	1.319	73.8	9094	7.11	6.35	12.0
LY 40	16	1	1.0035	749.5	15685	1.863	108.1	12845	9	8.08	11.4
LY 43	16	1.004	1.003	657.7	13661	1.685	94.2	11618	8.36	7.48	11.8
LY 44	16	1.002	1.0025	568.9	11870	1.507	81.8	10390	7.16	6.37	12.4
LY 45	16	1.001	1.0005	621.5	13019	1.395	89.8	9618	8.4	7.52	11.7
LY 47	16	1.0015	1	546.6	11444	1.411	78.9	9729	7.05	6.32	11.6
LY 50	16	0.999	1	587.4	12360	1.316	85.2	9074	7.53	6.72	12.1
LY 51	16	1.0025	1.002	749.5	15630	1.656	107.8	11418	8.84	7.89	12.0
LY 52	16	1	0.9975	488.6	10286	1.263	70.9	8708	5.93	5.31	11.7
LY 53	16	1.006	1.0035	511.7	10581	1.169	73.0	8060	6.51	5.86	11.1
LY 54	16	1.004	1.0035	571.3	11860	1.499	81.8	10335	7.19	6.43	11.8
LY 55	16	1.004	1.005	438.7	9094	1.081	62.7	7453	5.78	5.25	10.1
LY 56	16	1.0015	1	532.1	11141	1.383	76.8	9535	7.11	6.37	11.6
LY 57	16	1.0015	0.9985	551.4	11562	1.418	79.7	9777	7.1	6.37	11.5
LY 58	16	1.0035	0.996	459.1	9612	1.205	66.3	8308	7.03	6.27	12.1
LY 60	16	0.9995	1.0015	536.1	11252	1.355	77.6	9342	7.82	7	11.7
LY 61	16	1.004	1.0015	598.7	12454	1.353	85.9	9329	8.3	7.44	11.6
LY 62	16	1.004	1.004	436.2	9051	1.112	62.4	7667	6.92	6.22	11.3
LY 63	16	1.001	1.002	576.4	12056	1.259	83.1	8681	8.78	7.85	11.8
LY 64	16	0.998	1.002	484	10184	1.353	70.2	9329	6.44	5.78	11.4
LY 65	16	1.0045	1.0035	641.1	13296	1.61	91.7	11101	7.23	6.5	11.2
LY 66	16	1.002	0.999	599.5	12552	1.534	86.5	10577	7.01	6.26	12.0
LY 67	16	1	0.998	723.5	15224	1.898	105.0	13086	8.15	7.24	12.6
LY 68	16	1.001	1.0045	557.3	11628	1.309	80.2	9025	6.68	5.97	11.9
LY 69	16	1.0015	1.0015	725.1	15159	1.938	104.5	13362	8.89	7.97	11.5
LY 72	16	1.004	1.004	539.3	11190	1.536	77.2	10590	6.93	6.25	10.9
LY 73	16	1.0025	1.005	449.4	9344	1.064	64.4	7336	6.03	5.44	10.8
LY 74	16	1.004	1.004	465.8	9665	1.085	66.6	7481	6.1	5.92	3.0
LY 76	16	0.999	1.002	493.4	10361	1.116	71.4	7695	6.11	5.47	11.7
LY 77	16	1.003	1.003	522.1	10866	1.289	74.9	8887	5.93	5.32	11.5
LY 78	16	1.002	1.002	571.5	11930	1.487	82.3	10253	7.01	6.25	12.2
LY 79	16	0.999	0.999	560	11795	1.507	81.3	10390	7.14	6.38	11.9
LY 80	16	1.0015	1.002	608.3	12704	1.589	87.6	10956	7.66	6.8	12.6
LY 81	16	1.001	1.0025	593	12397	1.658	85.5	11432	8.02	7.18	11.7
LY 82	16	1.003	1.005	538.3	11181	1.421	77.1	9797	6.93	6.17	12.3
LY 83	16	1.0025	1.002	601.1	12535	1.604	86.4	11059	7.39	6.59	12.1
LY 84	16	1.002	1.001	510.6	10669	1.274	73.6	8784	6.99	6.23	12.2
LY 85	16	1.002	1.0015	530.2	11073	1.321	76.3	9108	6.56	5.89	11.4
LY 87	16	1.005	1.003	506	10489	1.354	72.3	9336	6.17	5.51	12.0
LY 88	16	1.001	0.998	551.7	11586	1.486	79.9	10246	6.75	6.03	11.9
LY 89	16	1.0025	1.0035	627.4	13064	1.468	90.1	10122	7.89	7.1	11.1
LY 90	16	1.003	1.002	508.7	10598	1.386	73.1	9556	7.26	6.49	11.9
LY 91	16	1.002	1.001	569.1	11892	1.383	82.0	9535	6.68	6	11.3
LY 94	16	1	1.001	626.8	13150	1.618	90.7	11156	7.91	7.07	11.9
LY 95	16	1.002	1	581.5	12163	1.436	83.9	9901	8.04	7.19	11.8
LY 96	16	1	1	506.8	10643	1.311	73.4	9039	6.9	6.18	11.7
LY 97	16	1.0015	1.0025	454.2	9486	0.822	65.4	5667	6.26	5.62	11.4
LY 99	16	1.002	0.998	676.6	14117	1.618	97.3	11156	7.92	7.08	11.9
LY 100	16	1.0005	1	611	12818	1.562	88.4	10770	7.53	6.71	12.2
				Ave	11760.26	1.410246753	81.1	9723			
				COV(%)	13.30266	15.09556885	13.3	15			
				MIN	8306	0.822	57.3	5667			
				MAX	15685	1.938	108.1	13362			
DP 2	16	0.98	1.0025	656.4	14310	1.641	98.7	11314	7.06	6.36	11.0
DP 4	16	1.003	1.006	629.8	13068	1.592	90.1	10976	7.11	6.4	11.1
DP 5	16	1.0015	1.002	873	18242	2.124	125.8	14644	9.62	8.65	11.2
DP 6	16	1.004	1.0085	663.6	13708	1.727	94.5	11907	7.64	6.87	11.2
DP 9	16	1.005	1.005	664.2	13741	1.698	94.7	11707	7.63	6.86	11.2
DP 10	16	1.0045	1.004	773.4	16032	1.811	110.5	12486	8.04	7.23	11.2
DP 12	16	1.01	0.9985	554.6	11434	1.367	78.8	9425	5.99	5.39	11.1
DP 13	16	1.004	0.997	732.3	15302	1.812	105.5	12493	8.52	7.66	11.2
DP 15	16	1	1.001	746.8	15667	1.876	108.0	12935	8.15	7.37	10.6
DP 17	16	1.002	1.0035	589.3	12283	1.438	84.7	9915	6.67	5.99	11.4
DP 19	16	0.9945	0.999	730.2	15520	1.784	107.0	12300	7.51	6.79	10.6
DP 21	16	1.002	1	610.5	12769	1.598	88.0	11018	8	7.15	11.9
DP 24	16	1.001	0.997	651.8	13702	1.645	94.5	11342	7.77	6.96	11.6
DP 25	16	0.998	1.0015	577.4	12156	1.55	83.8	10687	6.71	6.04	11.1
DP 27	16	1	1.0025	723.2	15149	1.764	104.4	12162	8.08	7.28	11.0
DP 28	16	1.001	1.002	583.1	12190	1.604	84.0	11059	7.4	6.62	11.8
DP 29	16	1.004	1.0015	518.9	10794	1.337	74.4	9218	6.08	5.46	11.4
DP 31	16	1.004	0.999	702.3	14646	1.749	101.0	12059	6.98	6.28	11.1
DP 32	16	0.998	1.003	752.2	15812	1.797	109.0	12390	7.74	6.99	10.7
DP 34	16	1.002	1	734.8	15369	1.739	106.0	11990	7.66	6.92	10.7
DP 37	16	1.001	1.001	621.5	13012	1.485	89.7	10239	7.13	6.41	11.2
DP 39	16	1.002	1.001	732.3	15302	1.809	105.5	12473	7	6.27	11.6
DP 40	16	1.003	1	597.6	12475	1.505	86.0	10377	6.22	5.57	11.7
DP 45	16	1.001	1.001	667.4	13973	1.717	96.3	11838	6.81	6.1	11.6
DP 47	16	1.001	0.999	757.9	15900	1.924	109.6	13266	7.11	6.37	11.6
DP 48	16	0.9975	1.001	574.5	12113	1.549	83.5	10680	5.97	5.4	10.6
DP 51	16	0.997	1.0005	666.3	14070	1.734	97.0	11956	6.83	6.1	12.0

Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
DP 52	16	1.0015	0.999	699.6	14662	1.792	101.1	12355	7.42	6.67	11.2
DP 53	16	1	0.998	740.1	15573	1.767	107.4	12183	7.05	6.4	10.2
DP 54	16	1	0.998	643.5	13541	1.587	93.4	10942	6.89	6.22	10.8
DP 58	16	1	0.9985	792.7	16672	1.986	114.9	13693	8.12	7.29	11.4
DP 62	16	1.002	1.001	596.5	12464	1.351	85.9	9315	5.68	5.11	11.2
DP 63	16	1.005	0.9985	634.6	13333	1.628	91.9	11225	5.9	5.32	10.9
DP 67	16	0.9975	0.999	723.5	15293	1.867	105.4	12873	8.12	7.29	11.4
DP 68	16	0.997	0.994	751.1	15964	1.977	110.1	13631	8.75	7.82	11.9
DP 70	16	0.9965	1.001	621.7	13134	1.57	90.6	10825	6.94	6.21	11.8
DP 74	16	1	1.0015	610.5	12801	1.582	88.3	10908	7.5	6.74	11.3
DP 78	16	1	0.999	651.5	13695	1.583	94.4	10914	7.57	6.79	11.5
DP 79	16	0.999	0.9965	723.2	15271	1.766	105.3	12176	7.7	6.92	11.3
DP 80	16	0.9975	1.0025	724.6	15255	1.714	105.2	11818	7.69	6.92	11.1
DP 82	16	0.9965	1	697.2	14744	1.687	101.7	11631	7.12	6.43	10.7
DP 84	16	1	0.9975	623.1	13118	1.587	90.4	10942	7.69	6.86	12.1
DP 85	16	0.9975	0.999	683.5	14440	1.463	99.6	10087	8.48	7.58	11.9
DP 86	16	1	0.999	724.8	15236	1.861	105.0	12831	7.97	7.18	11.0
DP 87	16	1	1	699.9	14698	1.799	101.3	12404	7.7	6.89	11.8
DP 88	16	1.001	1	595.2	12474	1.467	86.0	10115	6.51	5.87	10.9
DP 89	16	1.001	0.997	716.5	15062	1.815	103.8	12514	7.67	6.95	10.4
DP 90	16	1	0.997	601.6	12672	1.428	87.4	9846	6.4	5.77	10.9
DP 91	16	1	0.998	725.1	15258	1.721	105.2	11866	7.5	6.76	10.9
DP 92	16	0.998	0.999	746	15745	1.799	108.6	12404	7.75	7	10.7
DP 93	16	0.9995	1	713.3	14994	1.907	103.4	13148	7.31	6.61	10.6
DP 96	16	0.999	0.998	822	17331	2.074	119.5	14300	7.68	6.93	10.8
				Ave	14272.48	1.695269231	98.4	11688			
				COV(%)	10.87491	10.54328611	10.9	11			
				MIN	10794	1.337	74.4	9218			
				MAX	18242	2.124	125.8	14644			
GP 2	16	1.001	1.002	476.8	9973	1.328	68.8	9156	5.69	5.13	10.9
GP 4	16	1.001	0.999	587.1	12317	1.563	84.9	10777	7.03	6.29	11.8
GP 5	16	1.002	1.0005	473.3	9895	1.349	68.2	9301	5.47	4.93	11.0
GP 6	16	1	1.001	372.3	7810	1.028	53.8	7088	4.08	3.68	10.9
GP 7	16	1.0025	0.999	448.6	9383	1.25	64.7	8618	6	5.39	11.3
GP 9	16	1.001	0.9995	568.3	11916	1.529	82.2	10542	6.63	5.95	11.4
GP 10	16	1.001	1.0005	496.6	10403	1.198	71.7	8260	6.02	5.45	10.5
GP 12	16	1.001	1.0015	420.9	8808	1.156	60.7	7970	5.83	5.27	10.6
GP 14	16	1	1.0015	607.2	12732	1.698	87.8	11707	6.76	6.09	11.0
GP 16	16	0.999	0.9985	613.7	12933	1.645	89.2	11342	6.56	5.9	11.2
GP 18	16	0.998	1.0015	557	11726	1.45	80.8	9997	6.66	5.96	11.7
GP 20	16	1.001	1	451.5	9463	1.212	65.2	8356	5.31	4.81	10.4
GP 22	16	1.0015	1	448.6	9392	1.226	64.8	8453	5.01	4.51	11.1
GP 23	16	1.0005	1.002	566.4	11859	1.519	81.8	10473	5.79	5.21	11.1
GP 25	16	1.001	1.001	375.7	7866	1.07	54.2	7377	4.77	4.33	10.2
GP 27	16	1.0015	1.002	385.2	8049	1.047	55.5	7219	4.67	4.22	10.7
GP 30	16	0.9985	1.003	386.6	8119	1.084	56.0	7474	4.91	4.43	10.8
GP 32	16	0.999	1.0015	513.6	10802	1.385	74.5	9549	6.18	5.55	11.4
GP 34	16	1.001	1.0025	524	10955	1.334	75.5	9198	5.84	5.27	10.8
GP 36	16	1.002	1.001	498.8	10423	1.351	71.9	9315	6.26	5.63	11.2
GP 41	16	1.002	1.001	411.3	8594	1.182	59.3	8150	5.54	5	10.8
GP 45	16	0.9995	1.003	400.8	8400	1.044	57.9	7198	4.75	4.29	10.7
GP 46	16	1.0015	0.999	500.9	10498	1.335	72.4	9205	5.36	4.8	11.7
GP 51	16	0.999	1.0005	677.6	14251	1.714	98.3	11818	7.42	6.66	11.4
GP 52	16	1.001	1.0015	357	7471	1.003	51.5	6915	4.39	3.95	11.1
GP 57	16	1.001	1.0015	494	10338	1.303	71.3	8984	5.69	5.15	10.5
GP 58	16	1.0005	0.9975	714.4	15025	1.837	103.6	12666	7.86	7.09	10.9
GP 60	16	0.999	1.0005	469.8	9881	1.233	68.1	8501	5.26	4.74	11.0
GP 63	16	1	1	717	15049	1.757	103.8	12114	7.54	6.75	11.7
GP 65	16	0.9995	1	352.1	7398	0.952	51.0	6564	4.25	3.85	10.4
GP 68	16	1.0025	1.001	399.7	8344	1.124	57.5	7750	5.5	4.97	10.7
GP 69	16	0.9995	0.999	473.6	9966	1.332	68.7	9184	6.12	5.5	11.3
GP 70	16	0.999	0.998	447.5	9435	1.246	65.1	8591	5.14	4.62	11.3
GP 71	16	1.001	1	630.9	13222	1.686	91.2	11625	7.4	6.61	12.0
GP 74	16	0.998	1.0025	596	12535	1.469	86.4	10128	6.66	6.02	10.6
GP 75	16	0.999	1.0025	424.2	8904	1.19	61.4	8205	3.93	3.55	10.7
GP 78	16	1.002	1.002	440.3	9260	1.298	63.8	8949	4.56	4.13	10.4
GP 80	16	1.0005	0.999	337.6	7090	1.082	48.9	7460	3.36	3.06	9.8
GP 85	16	1	1	521.1	10932	1.353	75.4	9329	4.6	4.17	10.3
GP 90	16	1.0005	1	458.8	9625	1.27	66.4	8756	4.01	3.65	9.9
GP 93	16	1.002	0.9985	404.6	8475	1.213	58.4	8363	4.25	3.85	10.4
GP 97	16	1.001	1.001	600.3	12569	1.607	86.7	11080	6.14	5.53	11.0
GP 98	16	1.001	1	565.9	11860	1.571	81.8	10832	5.47	4.92	11.2
GP 99	16	1.0005	0.9995	411.8	8643	1.114	59.6	7681	4.85	4.34	11.8
				Ave	10286.11	1.325840909	70.9	9141			
				COV(%)	19.9579	17.01160925	20.0	17			
				MIN	7090	0.952	48.9	6564			
				MAX	15049	1.837	103.8	12666			
LP 1	16	0.994	0.997	598.9	12767	1.687	88.0	11631	8.02	7.19	11.5
LP 2	16	0.9985	0.998	576.6	12169	1.432	83.9	9873	8.84	7.93	11.5
LP 3	16	0.999	0.998	567	11967	1.563	82.5	10777	7.42	6.65	11.6
LP 4	16	0.996	0.998	533.7	11321	1.383	78.1	9535	7.59	6.81	11.5
LP 6	16	0.997	0.997	609.9	12924	1.598	89.1	11018	8.26	7.41	11.5
LP 7	16	0.9965	0.9935	715.4	15159	1.77	104.5	12204	9.59	8.65	10.9
LP 8	16	0.9975	0.999	557	11767	1.468	81.1	10122	6.4	5.77	10.9
LP 11	16	0.998	0.9975	518.7	10975	1.522	75.7	10494	6.81	6.11	11.5
LP 12	16	0.996	0.9945	702.5	14953	1.861	103.1	12831	8.02	7.18	11.7
LP 14	16	0.994	0.99	656.1	14086	1.617	97.1	11149	7.54	6.75	11.7
LP 15	16	0.997	0.9955	581.2	12334	1.421	85.0	9797	7.55	6.75	11.9
LP 17	16	0.997	0.997	593.8	12583	1.542	86.8	10632	7.08	6.35	11.5
LP 19	16	0.997	0.996	565.6	11997	1.487	82.7	10253	6.71	6.02	11.5
LP 22	16	0.994	0.991	645.1	13836	1.838	95.4	12673	8.42	7.54	11.7
LP 23	16	0.9925	0.9925	672.2	14439	1.778	99.6	12259	8.54	7.63	11.9
LP 25	16	0.997	0.995	555.2	11788	1.603	81.3	11052	8.06	7.21	11.8
LP 26	16	0.994	0.997	559.5	11928	1.525	82.2	10515	7.11	6.41	10.9
LP 27	16	0.997	0.995	607.2	12893	1.545	88.9	10652	7.35	6.62	11.0
LP 28	16	0.994	0.9915	680.8	14594	1.881	100.6	12969	8.68	7.76	11.9
LP 29	16	0.998	0.993	557.3	11833	1.398	81.6	9639	6.9	6.2	11.3
LP 32	16	0.995	0.992	521.1	11142	1.449	76.8	9991	7.69	6.88	11.8
LP 33	16	0.9975	0.99	637.9	13599	1.639	93.8	11301	8.9	7.98	11.5

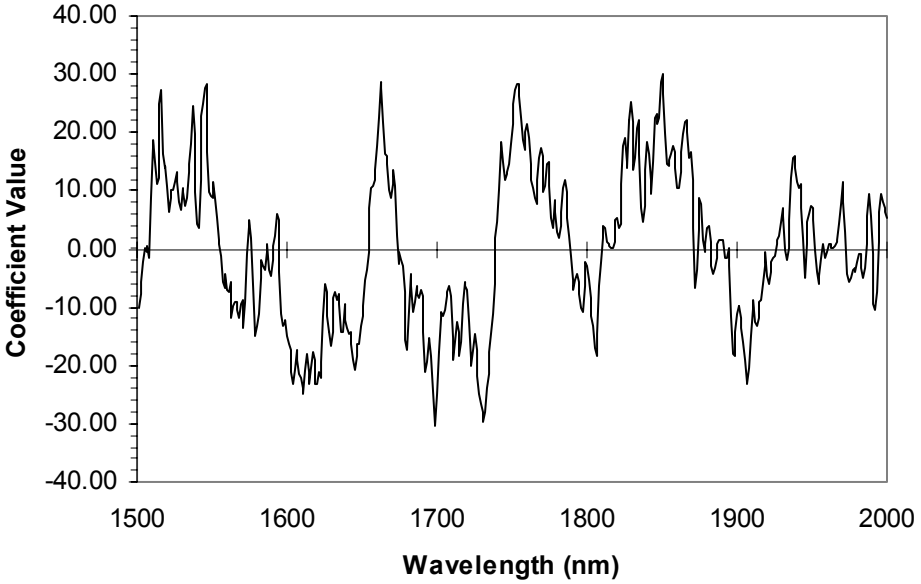
Specimen	Length (inch)	Height (inch)	Width (inch)	Max Load (lbs)	MOR (psi)	MOE (psi X 10^6)	MOR (MPa)	MOE (MPa)	Block Weight (grams)	Final Weight (grams	Moisture Content (%)
LP 34	16	0.9925	0.99	676.5	14568	1.648	100.4	11363	9.77	8.73	11.9
LP 35	16	0.994	0.992	563	12063	1.577	83.2	10873	7.68	6.89	11.5
LP 36	16	0.997	0.995	465	9873	1.241	68.1	8556	6.43	5.82	10.5
LP 37	16	0.997	0.997	601.3	12742	1.52	87.9	10480	8.09	7.23	11.9
LP 38	16	1	0.9985	498.3	10480	1.201	72.3	8281	6.55	5.9	11.0
LP 39	16	0.998	0.994	533.4	11314	1.476	78.0	10177	6.02	5.4	11.5
LP 40	16	0.9965	0.9915	695	14824	1.717	102.2	11838	8.7	7.83	11.1
LP 41	16	0.9965	0.9965	531.3	11275	1.395	77.7	9618	6.09	5.49	10.9
LP 42	16	0.992	0.989	619.9	13376	1.663	92.2	11466	7.34	6.56	11.9
LP 44	16	0.993	0.999	539.4	11510	1.405	79.4	9687	6.91	6.18	11.8
LP 45	16	0.995	0.995	486.2	10365	1.302	71.5	8977	6.34	5.71	11.0
LP 46	16	0.999	0.999	521.9	10993	1.395	75.8	9618	7.28	6.53	11.5
LP 47	16	0.996	0.9965	596	12661	1.536	87.3	10590	7.86	7.06	11.3
LP 51	16	0.994	0.991	521.6	11187	1.255	77.1	8653	6.23	5.6	11.3
LP 52	16	0.993	0.995	578	12372	1.532	85.3	10563	6.42	5.75	11.7
LP 53	16	0.994	0.99	577.7	12403	1.586	85.5	10935	6.63	5.95	11.4
LP 54	16	0.996	0.9935	589.8	12567	1.466	86.6	10108	6.08	5.45	11.6
LP 55	16	0.994	0.991	523	11217	1.351	77.3	9315	5.21	4.67	11.6
LP 57	16	0.997	0.996	566.4	12014	1.522	82.8	10494	6.5	5.81	11.9
LP 59	16	0.9955	0.997	598.8	12729	1.606	87.8	11073	7.48	6.67	12.1
LP 60	16	0.999	0.997	603.8	12743	1.604	87.9	11059	7.11	6.35	12.0
LP 61	16	0.999	0.995	493.2	10430	1.43	71.9	9860	6.29	5.62	11.9
LP 62	16	0.994	0.9945	555.4	11870	1.474	81.8	10163	6.9	6.19	11.5
LP 63	16	0.989	0.9915	505.2	10939		75.4		6.8	6.09	11.7
LP 64	16	0.991	0.99	671.2	14497	1.531	100.0	10556	6.88	6.2	11.0
LP 65	16	0.993	0.992	586.6	12594	1.549	86.8	10680	6.48	5.86	10.6
LP 66	16	0.9945	0.989	543.6	11671	1.718	80.5	11845	7.65	6.88	11.2
LP 68	16	0.997	0.992	629.3	13402	1.597	92.4	11011	6.82	6.14	11.1
LP 69	16	0.997	0.996	466.3	9891	1.379	68.2	9508	6.09	5.47	11.3
LP 71	16	0.998	0.991	650.2	13833	1.722	95.4	11873	7.87	7.06	11.5
LP 73	16	0.99	0.988	579.9	12576	1.603	86.7	11052	6.87	6.13	12.1
LP 74	16	0.991	0.99	556.5	12020	1.604	82.9	11059	6.88	6.42	7.2
LP 76	16	0.994	0.994	535.8	11457	1.508	79.0	10397	6.56	5.86	11.9
LP 77	16	0.997	0.994	617.4	13122	1.593	90.5	10983	7.39	6.64	11.3
LP 78	16	0.998	0.99	465.8	9920	1.272	68.4	8770	6.08	5.5	10.5
LP 79	16	0.999	0.995	545	11526	1.427	79.5	9839	5.88	5.28	11.4
LP 81	16	0.997	0.9925	560.8	11937	1.527	82.3	10528	6.37	5.7	11.8
LP 82	16	0.9965	0.9955	526.4	11183	1.465	77.1	10101	6.73	5.99	12.4
LP 83	16	0.989	0.988	661.2	14368	1.768	99.1	12190	9.02	8.03	12.3
LP 84	16	0.9925	0.993	612.1	13141	1.573	90.6	10845	7.41	6.62	11.9
LP 85	16	0.993	0.991	587.9	12647	1.684	87.2	11611	7.32	6.54	11.9
LP 86	16	0.9935	0.992	589.8	12650	1.671	87.2	11521	7.41	6.62	11.9
LP 87	16	0.9905	0.992	669.3	14442	1.813	99.6	12500	8.43	7.52	12.1
LP 88	16	0.993	0.9905	569.7	12249	1.571	84.5	10832	8.41	7.51	12.0
LP 89	16	0.999	0.9985	465.8	9816	1.313	67.7	9053	6.15	5.51	11.6
LP 90	16	0.9955	0.9935	610.5	13021	1.638	89.8	11294	7.47	6.7	11.5
LP 91	16	0.999	0.999	530.2	11168	1.436	77.0	9901	6.66	5.98	11.4
LP 92	16	0.9955	0.993	557.9	11905	1.613	82.1	11121	7.84	7.01	11.8
LP 93	16	0.994	0.9945	644.3	13770	1.808	94.9	12466	8.27	7.39	11.9
LP 95	16	0.997	0.9945	560.8	11913	1.54	82.1	10618	7.32	6.56	11.6
LP 96	16	0.999	0.999	553.3	11654	1.438	80.4	9915	6.41	5.79	10.7
LP 97	16	1	0.9935	667.6	14111	1.722	97.3	11873	7.93	7.09	11.8
LP 98	16	0.998	0.9945	558.4	11839	1.6	81.6	11032	7.99	7.08	12.9
LP 99	16	1	0.999	578.3	12156	1.523	83.8	10501	7.24	6.49	11.6
LP 100	16	1.005	1	589.5	12367	1.481	85.3	10211	7.14	6.43	11.0
				Ave	12343.05	1.547315789	85.1	10668		Average (all)	11.0
				COV(%)	10.40121	9.569190144	10.4	10		Std Deviation (all)	1.2
				MIN	9816	1.201	67.7	8281			
				MAX	15159	1.881	104.5	12969			

APPENDIX F – Chapter 3 – Regression Coefficients

Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 1000-1500 nm (raw spectra) on the selected clears.



Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 1501-2000 nm (raw spectra) on the selected clears.



Regression coefficients for the Nicolet UpDrift probe for predicting MOR from 2001-2500 nm (raw spectra) on the selected clears.