WOOD SHRINKAGE PREDICTION USING NIR SPECTROSCOPY

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Abstract. The ability to predict wood shrinkage could help manufacturers avoid lumber with abnormal dimensional stability or match pieces with similar properties in glued assemblies. Near infrared (NIR) spectroscopy is a rapid, nondestructive technique that has been used to predict various wood properties, including extractive content and density. Fifty-seven mahogany (*Swietenia macrophylla*) blocks were scanned using an NIR spectrometer, and were measured for specific gravity, extractives content, and total volumetric swelling. Models were created to predict the wood properties using the NIR data. These models could provide reasonable predictions of shrinkage, density, and extractives content. The use of nonlinear kernel and wavelet statistical techniques improved model performance. It may be possible to use NIR spectroscopy for the on-line sorting of wood according to dimensional stability.

Keywords: Shrinkage, extractives, density, *Swietenia macrophylla*, NIR.

INTRODUCTION

As wood gains or loses water (below the fiber saturation point) it swells and shrinks. This property has important practical consequences for the use of wood because variations in ambient relative humidity and temperature during processing and in service result in moisture content changes. Variations in wood dimensional stability can be particularly challenging for manufacturers that produce glued assemblies, such as laminated veneer lumber, plywood or parallel strand lumber. If bonded pieces shrink or swell differently, warping of the assembly can result.

The swelling and shrinkage of wood vary with grain direction, and among pieces of wood from different locations within a tree and from different trees and wood species. The dimensional stability of wood is a function of density, with denser wood species tending to shrink and swell more for a given change in moisture content (Suchsland 2004). Shrinkage can also be affected by extractive content (Hillis 1987), with

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higher extractive content levels being associated with reduced swelling and shrinkage. High extractive content can also increase the apparent density of the wood, resulting in the observation that denser woods (of the same species) shrink less. Although abnormal shrinkage behavior can be associated with juvenile wood, reaction wood and grain abnormalities (Panshin and de Zeeuw 1980), these indicators are often difficult or impossible to detect in a manufacturing environment.

Mahogany (*Swietenia macrophylla*) is a high-value wood with good wood working properties. Mahogany is used in many applications, including as laminated components of musical instrument bodies. Although the dimensional stability of mahogany is generally good (Forest Products Laboratory 1987), there can be large variation in the wood properties, including density, equilibrium moisture content, and shrinkage of different mahogany boards (Nix and Taylor, unpublished data). This variability can cause significant challenges in utilization.

One possible method for assessing wood properties in manufacturing environments is near infrared (NIR) spectroscopy coupled with multivariate statistical analysis. NIR spectroscopy is a rapid, nondestructive, and relatively inexpensive technology. A number of studies suggest that NIR spectra can be used to predict a variety of wood properties, including extractive content and density (reviewed in So et al 2004 and Tsuchikawa 2007).

This paper reports on an attempt to use NIR spectroscopy to predict the shrinkage of mahogany samples. If NIR-based models can predict dimensional stability, NIR may have the potential to become the basis for a sorting tool for wood manufacturing processes, including kiln drying.

MATERIALS AND METHODS

Sample selection and measurements

Fifty-seven cubes (approximately 40 mm) were cut from defect-free, dry pieces of mahogany lumber scraps from a secondary manufacturing operation. Only one cube was cut from each piece of lumber, although it was not possible to tell if all the off-cuts originally came from different boards. The manufacturer purchases mahogany lumber from several countries in Central and South America.

The end-grain of each cube was scanned with an Analytical Spectral Devices Field Spectrometer at wavelengths between 500–2400 nm. A reflectance fiber optic probe oriented at a right angle to the sample surface was used to collect the reflectance spectra. A piece of Spectralon® was used as a white reference material. Ten scans were collected for each NIR spot (25 mm dia) and averaged into a single spectrum. Two separate NIR spectra were collected for each wood sample.

Each cube was impregnated with water using a combination of vacuum (30 min at 60 kPa) and pressure (90 min at 600 kPa) treatments. After treatment, the cubes were kept submerged for 72 h to permit the blocks to swell completely. The volume of each swollen block was determined by water displacement. The blocks were then oven-dried, weighed, and the volume was re-measured by water displacement. The dry-volume readings were recorded immediately after immersion to avoid interference in the measurements due to water uptake by the wood. Specific gravity was calculated as the dry mass over the swollen volume. Total volumetric shrinkage was calculated as the change in volume after drying over the original (swollen) volume.

Ten mm from the transverse surface of each wood cube was ground and collected for extractives analysis using an end-mill on a milling machine. Samples of the wood powder (~2 g oven-dried) were weighed and enclosed in heat-sealable polyester filter bags (mesh size 25 μm, ANKOM Technology, Macedon, NY). The bags were oven-dried at 103°C for 14 h, and re-weighed. The bags were then extracted according to ASTM Standard 1105 (ASTM 2001), involving successive extraction steps with toluene/ethanol (2:1), 95% ethanol, and hot water. The extracted samples were oven-dried at 103°C for 24 h and reweighed. The extractives content of each sample was determined as the mass lost from the sample and expressed as a percentage of the oven-dry mass.

Model development and evaluation

The spectral data set (57 samples × 2 scans per block) was randomly divided into two subsets for model building and testing. The training set contained 66 spectra (33 samples with 2 replications) and the test set contained the remaining 48 spectra (24 samples with 2 replications).

Models were developed relating the spectral data (independent variables) to each of the three response variables (shrinkage, basic relative density, and extractives). Because the spectra contained a large number of (correlated) variables compared with the number of samples, multivariate statistical methods were used, including wavelet data precompression, partial least squares (PLS) (Jong 1993), and kernel partial least squares (KPLS) (Rosipal and Trejo 2001).

A wavelet-based reduction technique was applied first to reduce the dimensionality of the spectral data. The wavelet reduction technique is achieved by selecting wavelet coefficients that include the valuable information and assigning zero to unimportant data, using thresholding procedures. In this paper, a wavelet vertical energy thresholding (VET) method (Jung et al 2006) was used for the data reduction procedure. The KPLS method was then used to build the models, using the reduced wavelet coefficients as the explanatory variables. The KPLS method is a nonlinear version of PLS that can accommodate nonlinear variations in the data. The nonlinear data in the input space are mapped into high-dimensional, linear data in feature space with kernel functions. The KPLS algorithm is directly derived from PLS (Rosipal and Trejo 2001, and Rosipal 2003). The Kernel partial least squares regression and wavelet-based reduction technique were implemented in the MATLAB programming environment, using the KPLS code and WaveLab802 toolbox[1].

TABLE 1. *Selected properties of mahogany wood blocks.*

	Specific gravity	Total volumetric shrinkage (%)	Extractives content (%)
Average	0.50	8.1	18.1
Minimum	0.39	5.1	11.8
Maximum	0.80	11.1	28.1
Standard deviation	0.09	1.2	3.1

Prediction models were created using the training set data. The models were then evaluated using the test set data. This split-sample method (ie, separate 'training' and 'test' data sets) is a common approach to avoid over-fitting models to the data (Duan et al 1983; Baker et al 2002, Naes et al 2004).

Model performance was evaluated by comparing the RMS of prediction (RMSEP, the prediction error) and the correlation (R^2) between measured and predicted values using the test set data.

NIR spectrometers that can scan are broad range of wavelengths (from 500–2400nm) are relatively expensive (~$60,000). Less expensive (<$5,000) spectrometers are available but they scan only limited regions in the NIR spectrum (eg, 500–1100nm). To test the possibility that the less expensive units could provide useful prediction capability, the model building exercises described above were repeated using a subset (from 500–1100 nm) of the original dataset.

RESULTS

The samples varied widely in density, extractive content, and shrinkage values (Table 1). Higher extractive content in the blocks was associated with lower volumetric shrinkage levels (Fig 1) and higher specific gravity (Fig 2). Specific gravity was negatively correlated with shrinkage (Fig 3).

Models based on the full spectral data provided good predictions of shrinkage ($R^2 = 0.67$,), spe-

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[1] Available from http://www-stat.stanford.edu/~wavelab/index_wavelab802.html

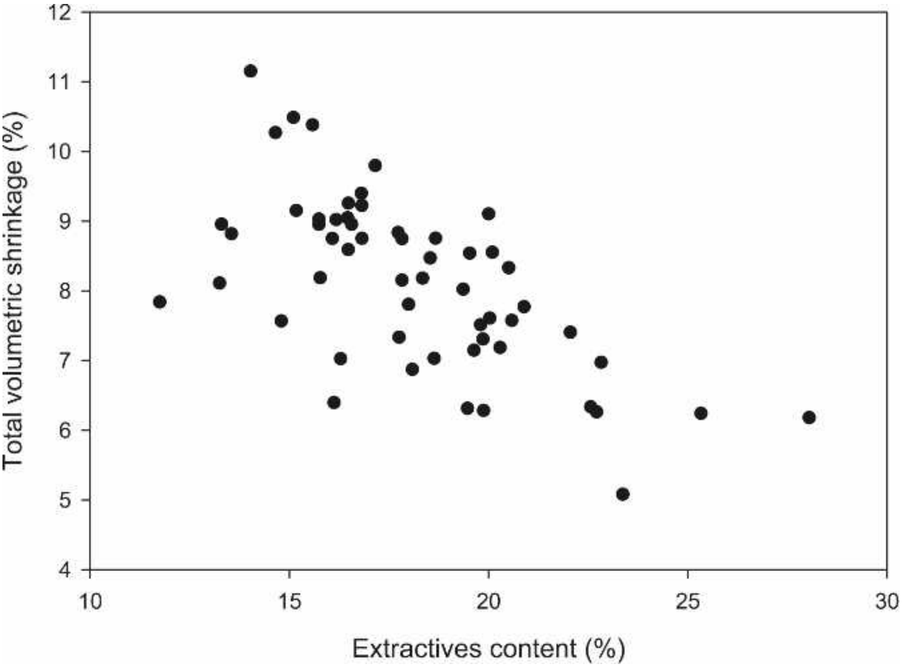

FIGURE 1. Extractives content vs total volumetric shrinkage for the mahogany samples. $R^2 = 0.42$

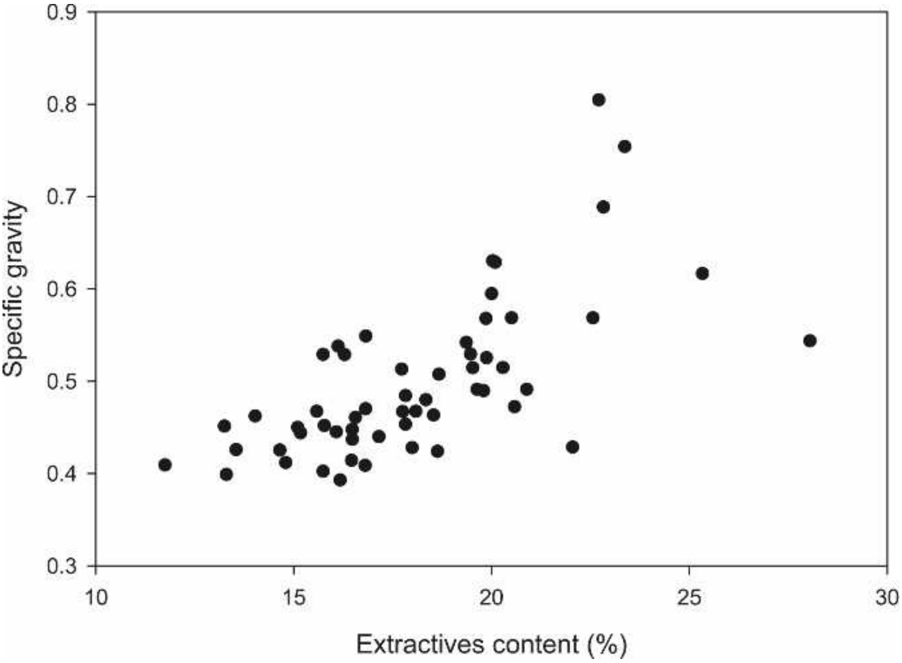

FIGURE 2. Extractives content vs specific gravity for the mahogany samples. $R^2 = 0.44$

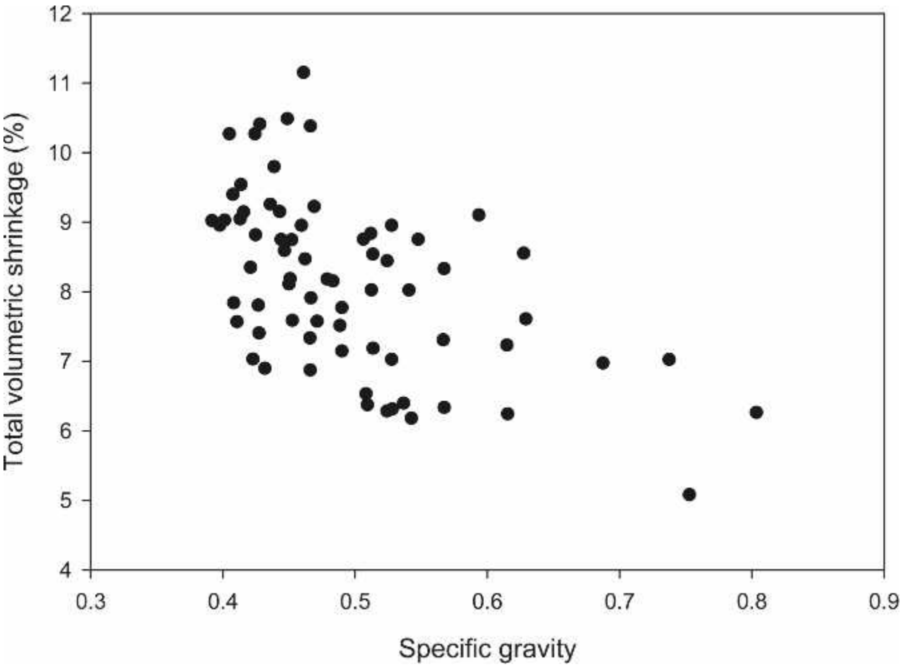

FIGURE 3. Specific gravity vs shrinkage for the mahogany samples. $R^2 = 0.29$

cific gravity ($R^2 = 0.81$), and extractives content ($R^2 = 0.68$) (Table 2). Models based on the limited wavelength data (from 500–1100 nm) performed less well. In all cases, models that made use of both wavelet (Symmlet 8) and kernel PLS technique, with kernel of radial basis function (RBF) performed the best.

DISCUSSION

The 2-fold variations in the range of density and shrinkage values that were observed in these samples highlight the challenge faced by wood manufacturers when working with mahogany. This species has good woodworking properties in general (Forest Products Laboratory 1987), but such extreme variations in properties can result in problems, especially when different pieces are combined in a single assembly.

The extractive content of mahogany is high, and these extractives appear to 'bulk' the cell wall and prevent shrinkage, as has been found in

TABLE 2. *Summary of results for NIR-based models for predicting wood characteristics. Separate models were created using data from the full NIR spectrum (500–2500 nm) and data from a limited range (500–1000 nm) that corresponds to the output from less-expensive spectrometers.*

Wavelength range used		Specific gravity	Total volumetric shrinkage (%)	Extractives content (%)
500–2400 nm	R^2	0.81	0.67	0.68
	# of PCs	9	14	10
	Kernel (Parameter)	RBF($\sigma = 20$)	RBF($\sigma = 42$)	RBF($\sigma = 66$)
	RMSEP	0.04	0.006	0.02
500–1000 nm	R^2	0.69	0.23	0.41
	# of PCs	9	5	4
	Kernel (Parameter)	RBF($\sigma = 52$)	RBF($\sigma = 7$)	RBF($\sigma = 7$)
	RMSEP	0.05	0.009	0.03

other species (Choong 1969; Choong and Achmadi 1991). These extractives also increase the density of the wood (Fig 2), so that there is an inverse relationship between density and shrinkage in these samples (Fig 3), rather than the positive association between shrinkage and density that is generally seen among various wood species (Suchsland 2004).

That the NIR spectra could be used to predict density and extractive content is consistent with previous work with various softwoods (Thygesen 1994; Hoffmeyer and Pedersen 1995; Gierlinger et al. 2002; Schimleck et al. 2003; Flaete and Haartveit 2004; Tsuchikawa et al. 2005; Via et al. 2005). Because of the relationship of density and extractive content to wood shrinkage, it is perhaps not surprising that NIR spectra could also provide good predictions of total volumetric shrinkage.

Wood is almost always dried before manufacture to moisture levels that are close to the in-service condition; thus the swelling and shrinkage encountered during and after the manufacturing process is only a fraction of the total volumetric shrinkage. However, because the shrinkage rate is a linear function of change in moisture content below the fiber saturation point (Suchsland 2004), total volumetric shrinkage will be directly related to the dimensional stability of individual pieces during, and after manufacture. Thus, if an NIR-based tool could be developed that consistently predicted total volumetric shrinkage, it would be useful for sorting wood into groups with similar dimensional stability behavior within the range of moisture contents normally encountered during processing and in service.

The relatively poor predictive performance encountered with the limited-wavelength models highlights the possible tradeoffs between equipment cost and capability. If NIR technology were to be applied to predicting shrinkage in a manufacturing process, this tradeoff would need to be explored further, so that acceptable prediction accuracy could be achieved at a reasonable cost.

CONCLUSIONS

Mahogany wood samples varied widely in extractive content, density, and total volumetric shrinkage. Samples with higher extractive contents were denser but shrank less. Shrinkage, basic relative density, and extractives content could be predicted using models based on NIR spectra. Kernel and wavelet statistical techniques improved model performance. An NIR-based shrinkage prediction tool could be helpful to manufacturers by permitting them to group pieces with similar properties and eliminating samples with extreme properties.

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