Near-infrared technology applications for quality control in wood processing

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Abstract

Wet-pockets are a common processing issue with some wood species in board lamination for gluelam manufacturing and in just simple structural lumber production. Swift in-line detection of wet-pockets before and/or after kiln drying is thus essential to quality control and process optimization.

An in-line pilot-plant near-infrared (NIR) system with line speeds of 0, 500 and 1000 mm $s^{-}1$ combined with the developed partial least square (PLS) models tested the capacity to predict surface moisture content of kiln-dried western hemlock full-length lamination boards. The system showed high prediction ability. It is concluded that NIR spectroscopy has a potential to sort green lumber before drying based on moisture content, and that the NIR system with line speed of 0 to 1000 mm s^{-1} is capable of providing entire surface moisture distribution, and of detecting wet-pockets in lamina for industry applications.

Visible and NIR spectroscopy combined with discriminant analysis was used to distinguish wet-pockets from normal wood in subalpine fir samples. A soft independent modeling of class (SIMCA) model using the wavelength range of 650 to 1150 nm succeeded in 98% distinguishing wet-pockets from normal wood in the green state, while the model resulted in the misclassification for air-dried samples. The discriminant PLS model showed excellent correct classification results of 96% for green samples and 100% for dried samples, respectively. The analysis confirms that wet-pockets could be readily distinguished from normal wood using the discriminant PLS.

1 Introduction

Wet-pockets (also known as "wetwood" or "wet-spots") are commonly referred to as localized areas in heartwood with abnormally high moisture content. Wet-pockets are severe processing problem and causes serious drying defects in lumber. It has been speculated that a wet-pocket is a consequence of bacterial activity (Bauch *et al.* 1975, Ward & Zeikus 1980, Schink & Ward 1984) and causes excessive honeycomb, ring shake and deep surface checks during kiln-drying (Ward & Groom 1983, Ross *et al.* 1994). Due to high moisture and slow drying characteristics compared to normal heartwood (Ward 1986), drying

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lumber containing wet-pockets results in uneven final moisture contents between and within boards, and long drying times (Kozlik & Ward 1981, Simpson 1991). Invariably the areas containing wet-pockets are still wet after drying, and consequently wet-pockets on the surface interfere with the gluing process of lamination stock, ultimately creating zones of weakness and substandard adhesion. Therefore, swift in-line detection of wet-pockets before and/or after kiln drying is thus essential to quality control and process optimization. Watanabe *et al.* (2010) demonstrated that the pilot-plant NIR system was accurate for the detection of wet-pockets on the surface of kiln-dried hemlock. However the achieved line speed is deemed too slow for industrial application. The improvement of line speed is the remained task for wood industry to detect lamina with wet-pockets allowing lumber to be sorted accordingly.

NIR spectroscopy has been used as a nondestructive measurement of material composition because of its accuracy and rapidity. The characteristic physical and chemical properties of wet-pockets, such as moisture (Mackay 1975, Schneider & Zhou 1989) and extractives content (Schroeder & Kozlik 1972, Bauch *et al.* 1975) have been successfully predicted by NIR spectroscopy combined with the power of multivariate statistical modeling. For example, the use of NIR technology to predict moisture content (Hoffmeyer & Pedersen 1995, Karttunen *et al.* 2008, Adedipe & Dawson-Andoh 2008, Watanabe *et al.2010*) and extractives content (Gierlinger *et al.* 2002, Taylor *et al.* 2008, Poke *et al.* 2006) have been evaluated. It is expected that NIR spectroscopy could possibly be used to detect wet-pockets based on wood chemistry, such as extractives content, allowing for more accurate detection than the one based on moisture content.

The objective of this study was to assess NIR technology as a potential non-destructive method to detect wet-pockets. The high-speed detection of surface wet-pockets in kiln-dried western hemlock lumber destined for lamination and the classification of wet-pockets in wood piece of sub-alpine fir were evaluated.

2 Materials and Methods

2.1 High-speed detection of surface wet-pockets

2.1.1 Derivation of calibration models using small samples

Forty-three kiln dried timber pieces (105 x 105 mm in cross-section and 2.5 m long) of western hemlock (*Tsuga heterophylla*) were obtained from two BC coastal sawmills. Thereafter, they were cut into small samples of 100 mm long (fiber direction) 105 mm wide and 45 mm thick. The NIR spectrum was captured from three surfaces, offering the range of grain orientations, namely, flat-grain, edge-grain, and in-between grain. In addition, three types of wood (juvenile, sapwood, and heartwood) were evaluated. This experimental design resulted in a total of nine combinations (3 orientations x 3 wood types) for a total of 270 samples (25 replications for each combination).

The samples were oven-dried at 103±2°C for 24 hours and their weight was measured with a digital balance. They were then evenly divided into six groups and conditioned in special chambers (Parameter Generation and Control Inc.) to various moisture contents. The temperature, relative humidity and the target equilibrium moisture for each group are listed in Table 1. Two groups of the samples above 28% were then soaked in distilled water for 20 seconds or 10 minutes, respectively, and thereafter placed in sealed bags for couple weeks for the water to diffuse and redistribute within their mass. Subsequently, they were weighed prior to NIR measurement and their final moisture was calculated.

Table 1: Average measured moisture content of samples after conditioning

Target moisture (%)	Temperature (°C)	Relative humidity (%)	Actual MC (%)	
			Average	Standard deviation
5	40	27	5.2	0.2
12	20	65	12.9	0.3
19	40	77	19.5	0.4
26	40	97	26.0	0.9
Above 28%*	50	99	63.9	20.2

*The samples with target moisture above 28% were soaked in distilled water after conditioning.

NIR spectra were collected with the LF-1900 spectrometer (Spectral Evolution, Inc., North Andover, MA. USA) operating in a diffuse reflectance mode at 4-nm intervals between 1300 and 2050nm. The spectrometer (spot area 77 x 20 mm^2) was oriented at 90° above each sample surface. The distance between the sample surface and the NIR spectrometer was 200mm. A piece of commercial micro-porous Telfon was used as reference. A single spectrum was obtained by averaging 10 scans. Two spectra collected from upper and bottom surface, respectively, were averaged into a single spectrum. Thereafter, 324 out of total 540 spectra captured were used as the calibration set, while the remaining 216 spectra were used in the validation set.

The spectra were pre-processed by the Savitzky-Golay second derivatives with 7 convolution points (Savitzky and Golay 1964) using the Unscrambler (version 9.1, CAMO, Corvallis, OR, USA) software package. A multivariate regression, namely, partial least squares regression, was utilized by means of complete cross-validation method to construct two types of calibration models that predict moisture content ranging from 5 to 105% and within hygroscopic range (5-28%), respectively.

The moisture content of each sample in the validation set was predicted by the calibration models. Predictive quality was evaluated by comparing the predicted values to the measured ones. The coefficient of determination (R^2), root mean square error of prediction (RMSEP) and ratio of performance to deviation (RPD) served as statistical measures (Williams and Sobering 1993).

2.1.2 Evaluation of the pilot-plant system using "wet" lam-stock

Kiln-dried pieces deemed by inline industrial moisture meters as "wet" lam-stock lumber of 90 mm x 50 mm x 2225 mm in dimensions, provided from a local sawmill, served as full-size specimens for the assessment of the pilot-plant NIR system. In preliminary experiments, some of lumbers were dried and their average moisture content was less than 12%. In addition, the lumbers contained little local wet-spots on surface. Therefore, wet-spots were created on surface artificially, Fifteen kiln-dried pieces of lam-stock lumber were used as specimens. They were divided into three groups (5 specimens for each group), namely, dried, partially dried and wet. The partially dried and wet specimens were prepared by spraying 16 ml of distilled water locally or all-over the top and bottom surfaces, respectively, every two days for three weeks. Thereafter, the specimens were covered by plastic sheet for more than three weeks.

A variable speed table was built and the NIR spectrometer was mounted on it to produce a pilot-plant in-line NIR system. The top and bottom surfaces of each specimen were scanned by passing it under the NIR spectrometer at a fixed speed. The conveyor system was moving at 500 and 1000 mm/s during which time 82 and 41 scans were taken per pass, respectively. Next, the specimen was scanned at 50 mm intervals along longitudinal direction under static condition (called “line speed 0 mm/s”). A single spectrum was obtained from one scan instead of averaging 10 scans. This trial resulted in a time reduction between each scan, so that only approximately 0.06 seconds were required to obtain a single spectrum.

After acquiring the spectra, slices of 40 mm in thickness were cut from the upper and bottom surfaces of each specimen, respectively. These slices were then re-cut into thin slices at 50 mm intervals along the longitudinal direction. Once the weight of all thin slices was measured, they were oven-dried and their moisture content was calculated gravimetrically. A total of 1382 data points of surface moisture from the thin slices were obtained.

Surface moisture content of the full-size specimens was predicted from the collected spectra using the calibration models. The predicted moisture was then compared with the calculated ones to assess the accuracy of the new NIR system.

2.2 Wet-pockets classification

Small samples of 40 x 40 x 4 mm in thickness were cut and planed from the heartwood zone of green subalpine fir lumbers. Wet-pocket areas in each sample were immediately identified visually and marked. The samples were then classified into two groups, namely, “wet wood (WW)” of which more than half of its surface was covered by wet-pockets and “normal wood (NW)” that was completely free of any wet-pockets. One hundred samples were prepared for each WW and NW group, respectively. Three-quarters of the samples were randomly selected and assigned to the calibration set, while the remaining quarter was employed as the validation set.

Visible and near infrared (Vis-NIR) spectra of samples in the green state were collected with a QualitySpec Pro (Analytical Spectral Devices Inc. Boulder, CO, USA) operating in a reflectance mode at 1 nm intervals between 650 and 1150 nm. Previously visible range plus only a short NIR range are shown to be useful for the prediction of chemical components in wood (Kelly *et al*. 2004) and the discrimination of wood-based materials (Tsuchikawa *et al*. 2003). NIR spot area had approximately 20 mm diameter. Twenty scans were collected and averaged into a single spectrum for each sample. Thereafter, each sample was weighed and air-dried in a conditioning room (20±3^{o}C and 50±2% relative humidity). Again Vis-NIR spectra of the samples in the dried state were collected and their sample weight was re-measured to calculate moisture content gravimetrically. More details of the hardware are given in Watanabe *et al.* (2010).

Prior to discriminant analysis, the reflectance spectra were converted to absorbance spectra, and pre-processed with second derivatives with 23 convolution points. Two different discriminant analyses, soft independent modeling of class analogy (SIMCA) and partial least squares (PLS) discriminant analysis were performed by Unscrambler software. SIMCA is one of the most common discriminant tools that was introduced by Wold (Wold 1976), and has successfully been applied on wood-based materials (Tsuchikawa *et al.* 2003). PLS discriminant analysis is not inherently designed for problems of classification (Geladi 1988), however, it is routinely used for classification and there is substantial empirical evidence to suggest that it performs well for these purposes (Barker & Rayens 2003).

Principal component analysis (PCA) with full cross-validation was performed for the four types of wood samples, namely, NW in the green state, WW in the green state, NW in the dried state and WW in the dried state, respectively, to construct four individual PCA models. The PCA models were used in the SIMCA classification of the samples in the validation set, with an alpha level of 0.5.

A PLS regression model was constructed with the calibration set using full cross-validation. The γ variables for WW and NW were labelled with +1 and 0, respectively. The models were then used to distinguish wet-pockets from normal wood in the validation set by means of discriminant PLS. Correct classification of wet-pockets was arbitrarily assigned to samples with predicted $\gamma > 0.5$, and correct classification of normal wood was assigned when $\gamma < 0.5$. The percentage correct classification is defined as the proportion of number of wet-pockets and normal wood predicted correctly to the total number of each class for green and dried sample, respectively.

3 Results and Discussion

3.1 High-speed detection of surface wet-pockets

Table 2 shows the summary regression statistics of the calibration models for the hygroscopic range of moisture (5-28%) and the wide moisture range (5-105%), respectively. Both models resulted in high R^2 of 0.98 and 0.96 in the validation set. The RPD values were over 5, which mean that the models are adequate for quality control.

Table 2: Calibration statistics for the hygroscopic range of moisture (5-28%) and wide range of moisture (5-105%), respectively

Calibration model			Calibration set				Validation set			
MC range (%)	Wavelength (nm)	Number of optimum PCs	n	R^2	RMSECV (%)	RPD	n	R^2	RMSEP (%)	RPD
5-28	1300-2050	2	216	0.98	0.98	7.89	144	0.98	0.96	8.17
5-105	1300-2050	2	324	0.96	4.96	5.39	216	0.96	5.12	5.25

PCs: Principal components, RMSECV: Root mean square error of cross validation, RMSEP: Root mean square error of prediction, RPD: Ratio of performance to deviation.

The results of the gravimetrically measured surface moisture content versus the estimated values with line speed 1000 mm s^{-1} determined by the calibration model for the wide range of moisture are presented in Figure 1 (a). The measured surface moisture ranged from 10 to 82%. The model showed high R^2 values of 0.87, 0.87 and 0.85, and low RMSEP of 4.52, 4.84 and 4.94 corresponding to line speeds of 0, 500 and 1000 mm/s, respectively. RMSEP was slightly poorer with increasing line speed. RPD for all line speeds was over 2.5, pointing to the fact that the NIR system has an adequate ability to screen wood based on moisture. These results indicate that the NIR system with line speed of 0 to 1000 mm s^{-1} is able to measure surface moisture distribution of “wet” lam-stock up to 105% rapidly and accurately, and that NIR spectroscopy has a potential to sort green lumber before drying based on moisture content.

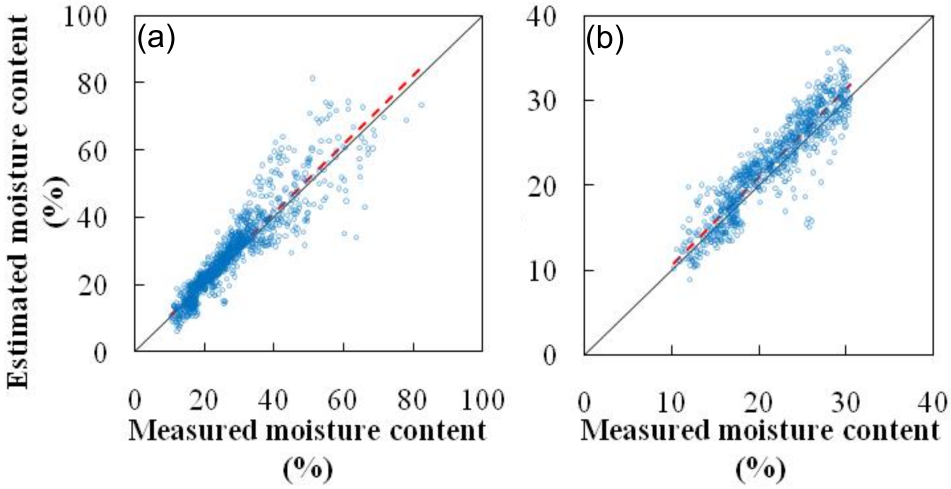

Figure 1: Measured vs. NIR estimated moisture for wide range of moisture (a) and hygroscopic range of moisture (b) with line 1000 mm/s. The dotted line is the regression - solid line R^2=1.

The results of the gravimetrically measured surface moisture content versus the estimated values determined by the calibration model for the hygroscopic range of moisture are presented in Figure 1 (b). The model resulted in R^2 of 0.85, 0.85 and 0.86, and low RMSEP of 2.12, 2.41 and 2.41 corresponding to the line speed 0, 500 and 1000 mm s^{-1}, respectively. These results suggest that the model is expected to have an average prediction error up to the RMSEP. RPD for all line speed was over 2.5, which is adequate for screening lumbers based on moisture content. The predictive ability of the NIR system was improved and could acquire spectra at ten times the line speed, compared with our past study (Watanabe *et al.* 2010).

The measured and NIR estimated surface moisture distributions are shown in Figure 2. The estimated moisture distribution with a line speed of 0, 500 and 1000 mm/s corresponds well with the measured values, indicating that the NIR system with the line speed of 1000 mm/s is able to measure surface moisture content distribution accurately and to detect surface wet-spots for post-sorting kiln dried lumber or lam-stock.

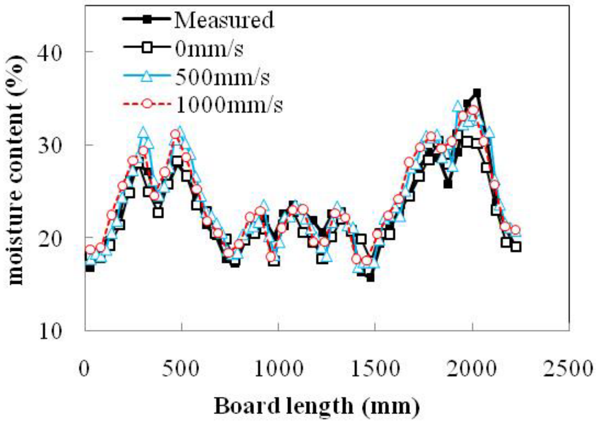

Figure 2: Representative surface moisture distributions for three speeds

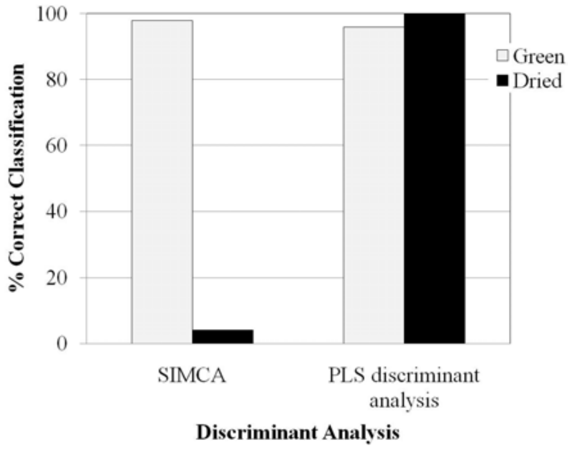

Figure 3: the Results of discriminant analysis by SIMCA and PLS discriminant analysis

3.2 Wet-pockets classification

Figure 3 shows the results of discriminant analysis by SIMCA and PLS discriminant analysis, respectively. The SIMCA model resulted in 98% separation between WW and NW in the green state, indicating that wet-pockets in the green state could be distinguished from normal wood using SIMCA model. On the other hand, the SIMCA model for dried samples showed poor predictability, and resulted in the misclassification of wet-pockets.

The discriminant PLS model showed excellent classification results: 96% for green samples, and 100% for dried samples, respectively, is indicating that wet-pockets could be distinguished from normal wood using a discriminant PLS with spectral range of 650-1150 nm in both green and dried state. Percentage correct classifications were well improved for dried samples compared with those by SIMCA. These results were similar to reported ones for classification of nutrients in alga using raman spectra (Heraud *et al.* 2006). The usefulness of reduced wavelength is analogous to the suggestion by Tsuchikawa *et al.* (2003) that the spectroscopic information about visible range plus only a short NIR range may be suitable for the classification analysis. The success in the classification of wet-pockets may be explained by the additional effect of chemical composition, along with moisture content differentials.

4 Conclusion

Partial least square (PLS) models capable of predicting surface moisture content in western hemlock were developed based on NIR spectra of conditioned small samples. Using line speed of 0, 500 and 1000 mm s^{-1}, the in-line pilot-plant NIR system combined with the developed models tested the capacity to predict surface moisture content of kiln-dried full-length lamination boards. The system showed high prediction ability. It is concluded that NIR spectroscopy has a potential to sort green lumber before drying based on moisture content, and that the NIR system with line speed of 0 to 1000 mm s^{-1} is capable of providing entire surface moisture distribution, and of detecting wet-pockets in lamina for industry applications, allowing lumber to be sorted accordingly.

Visible and near infrared NIR spectroscopy combined with discriminant analysis was used to distinguish wet-pockets from normal wood in subalpine fir samples. The results of soft independent modeling of class analogy (SIMCA) and PLS discriminant analysis were compared. The SIMCA model using the wavelength range of 650 to 1150 nm succeeded in 98% distinguishing wet-pockets from normal wood in the green state, while the model resulted in the misclassification for air-dried samples. The discriminant PLS models showed excellent correct classification results of 96% for green samples and 100% for dried samples, respectively. This indicates that wet-pockets could be distinguished using a discriminant PLS model with spectral range of 650-1150 nm.

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