NIR-MONITORING OF IN-SERVICE WOOD STRUCTURES

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ABSTRACT

Near infrared spectroscopy (NIRS) was used to study a set of Southern Yellow Pine boards exposed to natural weathering for different periods of exposure time. This non-destructive spectroscopic technique is a very powerful tool to predict the weathering of wood when used in combination with multivariate analysis (Principal Component Analysis, PCA, and Projection to Latent Structures, PLS). Absorbance spectra contained information about weathering behavior, and PLS models to predict exposure time were very strong, with the correlation coefficients above 0.9. These results, and the “non-destructive” nature of this technique, suggestthe potential of NIR for monitoring the condition of in-service wood structures.

Keywords: Near infrared spectroscopy, multivariate analysis, wood Weathering, Southern Yellow Pine.

INTRODUCTION

In the U.S., southern pine timber is widely used as a structural material in a variety of applications. When exposed to the elements, however, critical performance properties such as strength can he reduced very quickly. As such, the availability of instrumentation that can conveniently assess the effects of weathering on wood structures is of considerable interest. Extensive research has advanced acoustic methods for evaluating the structural integrity of in-service wood structures, and the value of this information has been demonstrated. Additional information, particularly on the characteristics of exposed surfaces, may he accessed through relatively new spectroscopic sensors. Near infrared spectroscopy (NIRS) is one such technique that is particularly sensitive to chemical composition. The principal compounds of wood are the macromolecules cellulose, hemicellulose and lignin that are able to absorb infrared light, and wood properties are derived directly from these compounds.

In its application to wood, NIR was focused initially on the chemical composition of wood and paper properties; however, research has also demonstrated potential for defining physical and mechanical properties of the material. Hoffmeyer and Pedersen (1995) showed that NIR could be used to predict wood density, and compression and bending strength of dry wood. Thygesen (1994) also showed that NIR could be used to measure the density of wood. Additionally, the use of NIR to predict the stiffness of radiata pine has been reported by Thumm and Meder (2001). Recent work by Kelley and associates showed that NIR can be used to predict the mechanical properties of southern pine using reduced spectral range, without significant loss in model quality (Kelley *et al.,* 2004).

Kelley also showed that NIR was sensitive to the extent of decay of wood exposed to different conditions (Kelley *et al.,* 2002). This result suggests that the technology may also be useful in assessing the characteristics of wood that has been exposed to the environment. When wood is exposed to weather, it is susceptible to a combination of chemical and physical factors (solar energy, moisture, pollutants,...) that cause degradation during the weathering process (Chang *et al.,* 1982, Feist and Hon, 1984, Anderson *et al.,* 1991, Horn *et al.,* 1994). Solar radiation is the most damaging component of the outdoor physical agents (Anderson *et al.,* 1991), and is responsible for the initial loss of properties reflected in the color change of wood. These processes negatively impact important performance properties, including strength, stiffness, and adhesive bonding properties (Miniutti, 1973, Feist, 1983, Williams *et al.,* 1987, 1999).

This research is part of a project to develop monitoring methods for in-service wood structures by NIR, and specifically to assess the immediate and long-term bonding characteristics of weathered wood. This information is of increasing value as technical approaches for repair, including fiber-reinforced polymers (FRPs), become viable (Lopez-hido and Xu, 2002). In this paper we describe early results on the use of NIR spectroscopy to monitor wood weathering. Our studies include (i) the analysis of the spectra, (ii) the use of PCA models to describe and distinguish the phenomenon of wood ageing, and (iii) the building of PLS models to predict wood ageing by NIR.

METHODOLOGY

Sample material

270 Southern Yellow Pine (*Pinus spp.*) boards of 122 cm x 8.6cm x 3.6 cm dimensions were exposed to natural weathering conditions in Mississippi. The boards were subject to different periods of exposure conditions: 0 (controls), 2, 9, 14, 21, 26, 35, 45, and 57 months of weathering. Each group of exposure time contained 30 individual specimens.

NIR measurements

The NIR measurements were made with a LabSpec Pro near infrared spectrophotometer (Analytical Spectral Devices, Inc.), Inc. at wavelengths between 350nm and 2500nm. A contact probe was used to collect the reflectance spectra, sampling an area of about 2 cm^2, Four spectra were collected per sample from the longitudinal surface which was directly exposed to the weathering agents.

The reflectance spectra were converted to absorbance spectra in Unscrambler® version 9.0 (CAMO, Corvallis, OR). After detection of spectral outliers, the four spectra collected on each sample were averaged to provide a single spectrum for each specimen, which was then used for further analysis. The data set was further reduced by averaging the spectra collected at 1 nm intervals, to a spectral data set at 8 nm intervals. Averaging the spectral data reduces the size of the spectral matrix and significantly reduces the time required to compute the statistical models, without decreasing the quality of the model (Kelley *et al.*, 2004). Multiplicative Scatter Correction (MSC) was applied to each exposure group separately. MSC is a transformation method used to compensate for additive and/or multiplicative effects in spectral data.

Multivariate analysis

Multivariate analysis was performed using The Unscrambler ® version 9.0 (CAMO, Corvallis, OR). The software has the capability to perform both Principal Component Analysis (PCA) and Partial Least Squares analysis (PLS). All of the NIR spectra were combined into a single data matrix (X-matrix) while the weathering exposure time constituted the response matrix (Y-matrix). The X-matrix was mean centered variance normalized prior to performing the multivariate analysis.

The models in the multivariate analysis were built with an X-matrix of 175 points (1000-2400 nm), 33 points (1400-1660 nm), 31 points (1600-1850 nm), 17 points (1865-2000nm), 25 points (2000-2200nm), 26 points (2200-2400nm) and the weathering time as the Y-matrix. The number of principal components used was 6 and 10 for PCA and PLS models, respectively, as recommended by the software. The control samples were clearly a distinct population, and were not included in the analyses.

Among aged samples, twenty samples were selected randomly from the entire set to built calibration models (CALB), and ten samples were used for an independent validation of the prediction equations (TEST). Model validation should be always demonstrated using an external test set, not included in the calibration set samples. Models were constructed using full cross-validation. Cross-validation systematically removes a single sample of the data set, constructs a models with the remaining samples, and uses that model to predict the value of the Y-variable for the extracted sample. This process continues until each individual sample has been removed from the data set and a fully cross-validated model is constructed (Martens and Naes, 1991).

RESULTS

Spectral characterization

Figure 1 shows the averaged NIR spectra of the control wood (not weathered) and the wood exposed to weather for different periods of time.

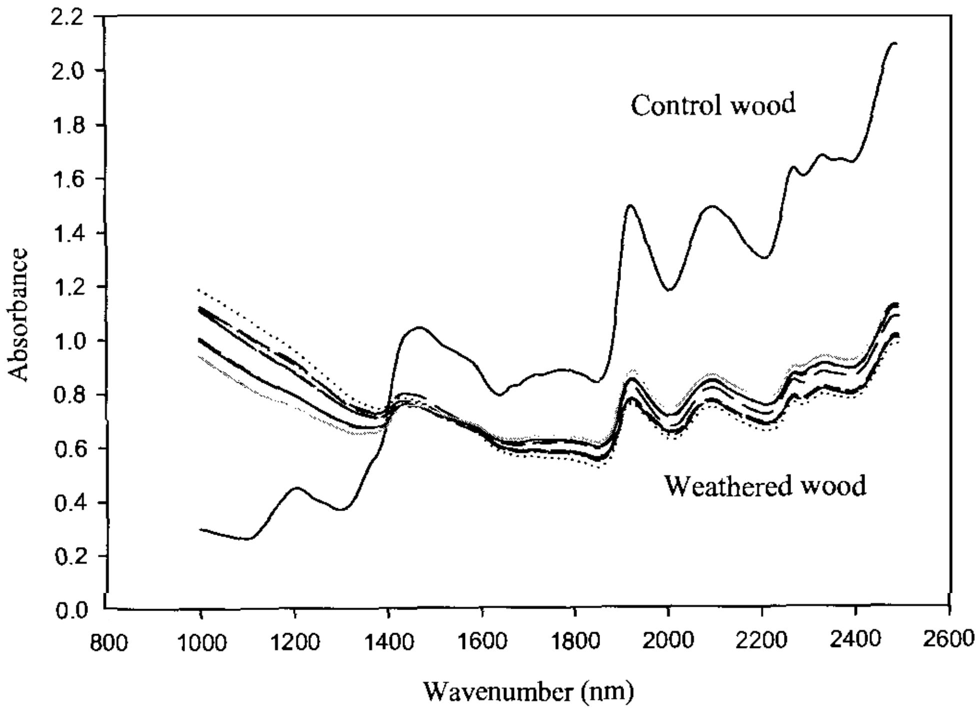

Figure 1. Effect of exposure time on infrared spectrum. Exposure months: 2 (long dash)., 9 (dotted), 14 (dash-dot-dot), 21 (short dash), 26 (dash- dot), 35 (medium dash), 45 (solid), 57 (gray).

The differences between the control and aged wood can be readily seen, both in the absorbance intensity and shape of the bands. In general for a given peak, the area under the peak of the control wood is larger than the area under the aged wood. The weathering phenomenon is accompanied by a loss of wood compounds and a change of wood color. Wood exposed to sunlight and moisture becomes yellow/brown then gray (Feist et Hon, 1984, Anderson *et al.*, 1991). The changes in wood color reveal chemical changes in wood during weathering. After only 2 months of exposure the color of the southern pine board is silver gray, and this is reflected at the lower wavelength frequencies.

Figure 1 shows that prolonged natural weathering is a phenomenon affecting all wood compounds. This degradation has a marked influence on wood surface properties (Evans *et al.*, 1996, Williams *et al.*, 1987, 1999). If the phenomenon of decay is also present, physical and mechanical proprieties of the bulk material will be affected, as decay fungi are able to cause rapid strength losses in wood associated with a loss of weight (Kelley et al., 2002).

More information about wood weathering can be extracted from the analysis of raw spectra (Figure 1). We can have an idea about the rate of the weathering process. For example, Figure 2 shows the changes of relative absorbance maxima values of three important peaks. Chemical changes due to wood exposed to weathering agents are very fast during the two first months of weathering. After two months of exposure, the changes of absorbance values are very small. The use of MVA highlights the spectral differences among weathered samples.

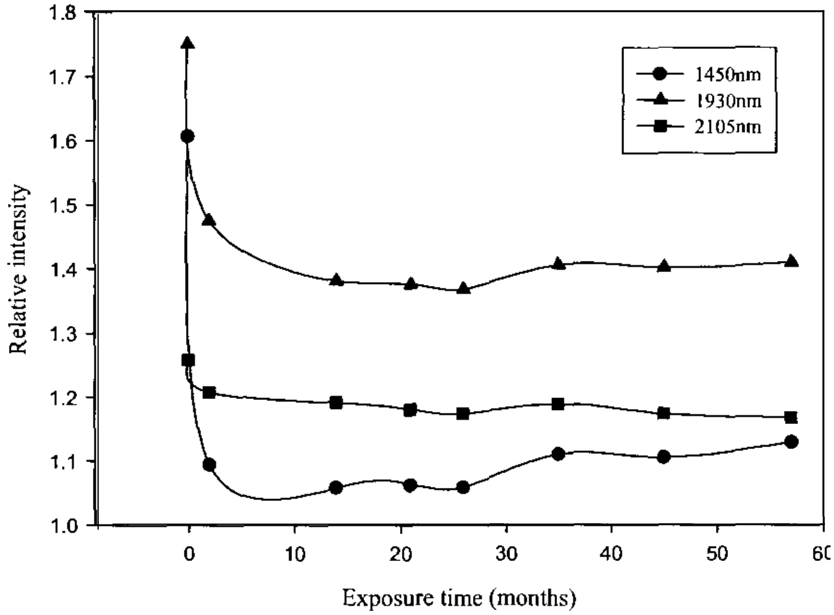

Figure 2. Changes of relative absorbance intensity of important chemical groups during weathering of Southern Yellow Pine wood.

Principal Component Analysis

The goal of PCA analysis, generally, is to explore statistical differences between the spectra of samples receiving various experimental treatments (e.g., exposure time). If PCA is applied on the complete spectral data range (1000 - 2400nm), the resulting model requires only two principal components to explain 100 percent of the variance. The scores plot (Figure 3) shows 2 principal clusters: control wood and weathered wood, resolved along principal component 1. In the aged wood cluster, at least 3 “sub clusters” can be identified wood aged of 2 months (white circle), wood aged of 9, 14, 21, 26 months (black triangle up) and wood aged of 35, 45 and 57 months (white square).

Each point corresponds to a board belonging to an exposure group. The points representing the spectra of the boards allowing the same group are distant because of the natural variability of wood. However, the variability between samples of the same age is not as important as the variability arising from the two clusters, control and aged wood. The exposure time increase along PC2: the cluster of 2 months of exposure has the highest positive value of PC2, and the group of 57 months of exposure the highest negative value. The passage from samples aged less than 26 months and the older samples is characterized by an overlapping zone (Figure 3). This overlapping zone includes samples aged of 21, 26, 35 and 45 months. In this zone, for positive values of PC2, the spectra collected on the boards aged more than

26 are absent while for the negative PC2 values, the samples aged less than 21 months are absents. The boards aged of 21 or 26 months presented in the overlapping zone show sign of decay. We observe some wood deterioration and some growth of fungal fruiting bodies. The gravity of wood deterioration depends of the board. This suggests that decay is starting between 14 and 21 months of exposure and it begins more and more consistent with increasing of exposure time.

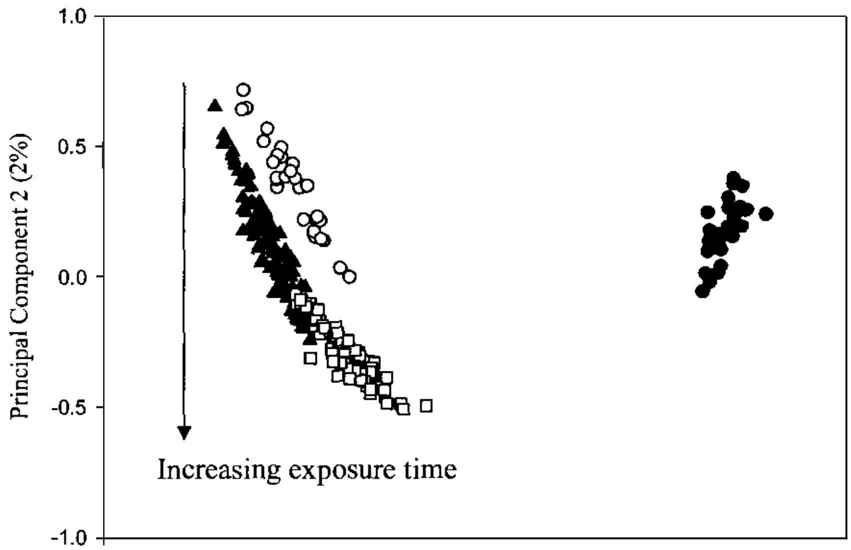

Figure 3. Principal component results from NIR spectra collected from the surface of Southern Yellow Pine boards submitted to natural weathering (the symbols correspond to the different exposure time: 0 months – control (●), 2 months (○), 9-14-21-26 months (▲), 35-45-57 months (□)

PLS models

The results in Table 1 and Figure 4 show that NIR is a powerful and non-destructive tool to predict the weathering of solid wood. We can note a very little reduction in r when the spectral range is reduced from 1000-2400nm to the other ranges. For the spectral range of 1865-2000nm, the RMSEC and the RMSEP are higher than 6 months, although the correlations between the measured age of wood and the age predicted by NIR are more than 0.9. For the high values of coefficient of correlation, maybe we can not accept the validation model if the root mean square error is to the utmost of 6 months. The changes in absorbance values of spectra after two months of exposure are little (Figure 2) and it could be a good justification to accept a RMSEP of 6 months.

During natural weathering, the quality of solar energy and the moisture content are not constant and it is difficult to define a limit of time significant to assess difference in wood absorbance. The wood ageing can be predicted by NIR using reduced spectral ranges. The r values for the CALB models were more than 0.9 in the full and in the reduced spectral ranges. More importantly, the quality of the TEST models was also very satisfactory with r-values also higher than 0.9. The RMSEP for the TEST set were 6 and 6.8 months for 2 reduced spectral ranges (1865-2000nm and 2000-2200nm). These results show that the ageing of an unknown southern pine sample could be accurately predicted from its NIR spectrum.

Table 1. Correlation coefficients and root mean square error of PLS-1 models for exposure time of the CALB and TEST sets. The RMSEC and RMSEP values are months.

	Spectral range (nm)					
Model	**1000-2400**	**1400-1660**	**1600-1850**	**1865–2000**	**2000-2200**	**2200-2400**
CALB						
r	0.97	0.96	0.97	0.93	0.95	0.95
RMSEC	4.5	4.7	4.4	6.3	5.5	5.4
PC's	5	6	5	4	6	3
TEST						
r	0.95	0.95	0.95	0.93	0.94	0.95
RMSEP	5.5	5.6	5.8	6.8	6	5.6
PC's	5	6	5	4	6	3

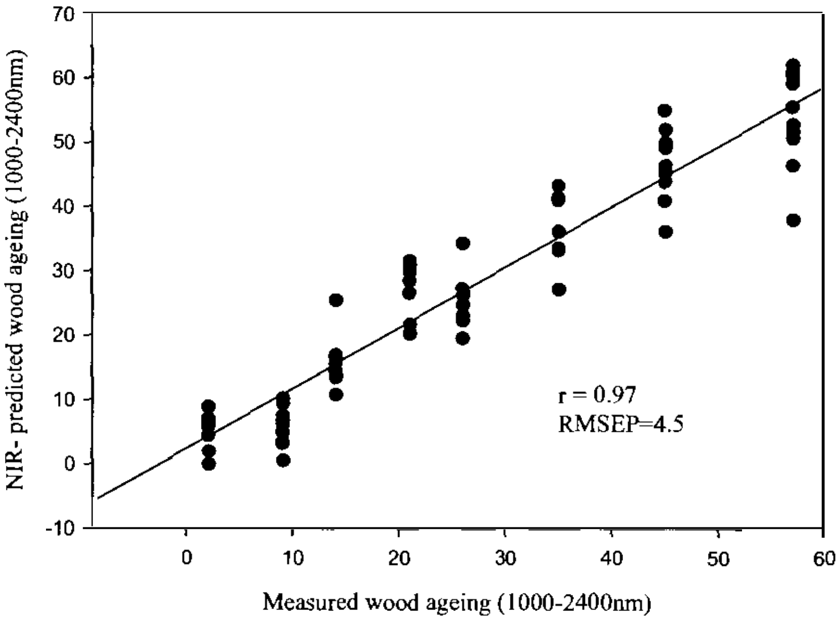

Figure 4. Relationship between the actual exposure time and the NIR-predicted exposure time.

CONCLUSIONS

Near infrared spectroscopy is particularly sensitive to changes in wood properties as a result of outdoor exposure. Multivariate statistical methods, including PCA and PLS, make it possible to extract the information of interest from the spectral data. Results from principal component analysis suggest that classification of surface quality may make it possible to identify appropriate remediation methods for in-service wood structures. Alternatively, the ability to predict weathering time and condition with a PLS approach opens additional approaches to defining relevant surface characteristics of the wood structure. Research is continuing to assess the potential of this method to define the adhesion properties of weathered wood. This would make it possible to identify appropriate treatments to optimize bonding of fiber-reinforced polymer composites, or other treatments. These results suggest that NIR spectroscopy may be an important part of what is likely to be a suite of field portable sensors for monitoring the integrity of wood structures.

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