Application of near infrared spectroscopy for mechanical stress grading of sawn lumber

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Introduction

Wood used for structural purposes needs to have reliable mechanical properties. Lumber sawn from a log, regardless of species and size, is highly variable in mechanical properties. A proper segregation of the sawn lumber into different grades is indispensable to cope with the range of demands of various end-uses. The increase in demand for high-performance lumber has led to greater demand for enhanced grading techniques.[1]

In a previous report, we examined the feasibility of NIR spectroscopy for on-line stress grading using the diffuse reflectance spectra from static and moving lumber conditions (Fujimoto *et al.* in press). Models predicted for wood properties, such as bending strength and modulus of elasticity, were superior in the moving condition than in a static condition. In the actual wood industry, lumber products are moved as quickly as possible along the process-lines, so the inspection of lumber quality should be done quickly. We investigated the effects of lumber conveying speed and measurement resolution of NIR spectra on the calibration performance.

Materials and methods

One hundred and two Japanese larch (*Larix kaempferi*) samples in the form of logs, with the dimensions of 30 (radial) × 100 (tangential) × 1000 (longitudinal) mm, were prepared for the mechanical tests and NIR experiments. The traits investigated in this study were the bending strength (F_b), modulus of elasticity in bending tests (E_b), dynamic modulus of elasticity (E_{fr}), and wood density (DEN).

Figure 1 shows the set-up of the NIR measurement.

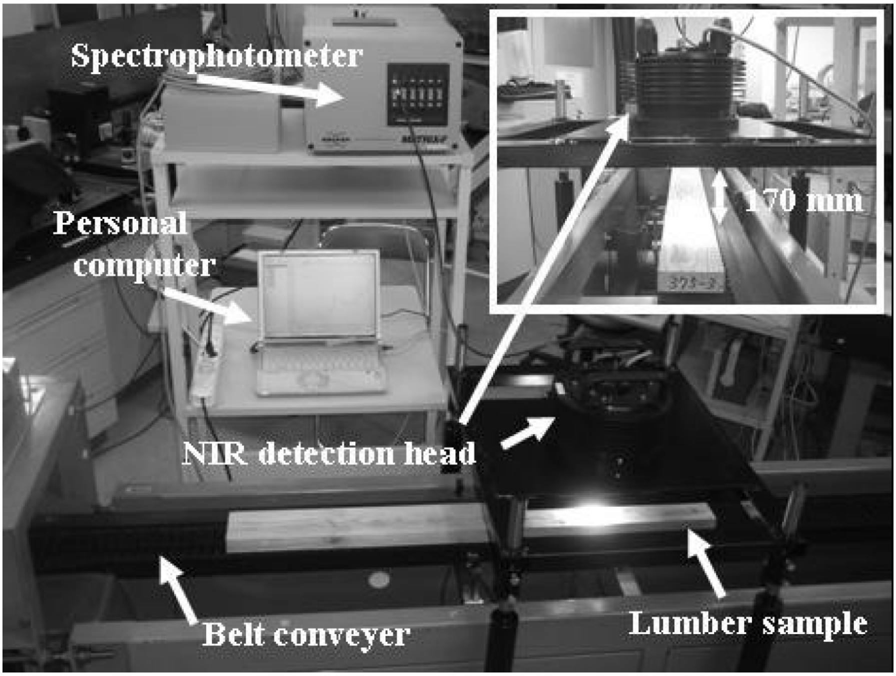

Figure 1. System outline of NIR diffuse reflectance spectra measurements.

The diffuse-reflectance spectra were acquired on a MATRIX-F spectrophotometer (Bruker Optics Co., Japan). The NIR spectra were obtained over the wavelength range 1300 nm to 2300 nm. Samples were put on the belt conveyer and the average spectra were acquired along the entire length of the sample. Spectral measurements were conducted at various conditions. In the case of TEST_1, the lumber conveying speed (LCS) was set at 10 m, 20 m and 30 m per minute, respectively. The effects of resolution on the calibrations were examined by setting the measurement resolution of spectra (MRS) at 2 nm, 4 nm and 16 nm in TEST_2. In this case, LCS was fixed at 20 m per minute.

All spectral data were split randomly into the calibration and validation sets, which consisted of 68 and 34 samples, respectively (Table 1).

Table 1. Summary of wood properties of lumber samples for calibration and prediction sets.

		Calibration set ($n = 68$)				Prediction set ($n = 34$)			
Wood property*		Mean	Min.	Max.	*SD*	Mean	Min.	Max.	*SD*
F_b	(MPa)	84.37	31.83	131.32	23.93	82.82	35.12	130.60	22.92
E_b	(GPa)	12.75	4.88	20.14	3.35	12.77	5.63	19.40	3.36
E_{fr}	(GPa)	13.56	5.12	21.23	3.68	13.63	5.98	21.98	3.74
DEN	(kg m^{-3})	556	382	721	67	549	412	684	61

* F_b: bending strength; E_b: modulus of elasticity in bending; E_{fr}: dynamic modulus of elasticity; *DEN*: wood density.

Second derivative spectra were obtained using the Savitzky-Golay algorithm with a 21-point window and second order degree polynomial.[2] Partial least squares (PLS) regression was used to develop all prediction models.[3] All data analysis was performed using the Unscrambler version 9.6 (CAMO AS, Norway) software.

Results and discussion

Trends of the raw and second derivative spectra were quite independent of LCS, and thus, typical absorption bands associated with the chemical components of wood were stable for each condition. This fact suggests that the intrinsic information about wood substances can be detected by NIR spectroscopy even when the sample lumbers move at high speed in a lumber production line.

Calibration models for prediction of each wood property were developed for various conditions (Table 2).

Calibration performance for all traits showed no clear tendency, in relation to LCS and MRS. The calibrations of all wood properties had relatively strong relationships between laboratory-measured

Table 2. Results of PLS modeling for each wood property in the various measurement conditions.*

Wood property	TEST_1					TEST_2				
	LCS	Factor	R_P^2	*SEP*	*RPD*	MRS	Factor	R_P^2	*SEP*	*RPD*
F_b (MPa)	10	6	0.61	13.99	1.71	2	6	0.65	13.00	1.84
	20	6	0.65	13.00	1.84	4	5	0.73	12.46	1.92
	30	5	0.64	14.11	1.70	16	6	0.72	12.32	1.94
E_b (GPa)	10	4	0.64	1.64	2.05	2	3	0.74	1.58	2.13
	20	3	0.74	1.58	2.13	4	3	0.73	1.70	1.98
	30	5	0.65	1.62	2.07	16	3	0.79	1.52	2.21
E_{fr} (GPa)	10	4	0.70	1.89	1.94	2	3	0.71	1.74	2.11
	20	3	0.71	1.74	2.11	4	3	0.71	1.75	2.11
	30	6	0.73	1.79	2.06	16	6	0.83	1.56	2.36
DEN (kg m^{-3})	10	3	0.54	37.46	1.78	2	3	0.57	32.19	2.08
	20	3	0.57	32.19	2.08	4	3	0.58	37.13	1.80
	30	5	0.61	34.91	1.91	16	3	0.63	32.08	2.08

* LCS: lumber conveying speed (unit = m min^{-1}); MRS: measurement resolution of spectra (unit = nm); R_P^2: coefficient of determination for prediction set; *SEP*: standard error of prediction; *RPD*: ratio of performance to standard deviation. In the case of TEST_1, the measurement resolution of spectra was fixed at 2 nm in all cases. In the case of TEST_2, the lumber conveying speed is 20 m per minute in all cases.

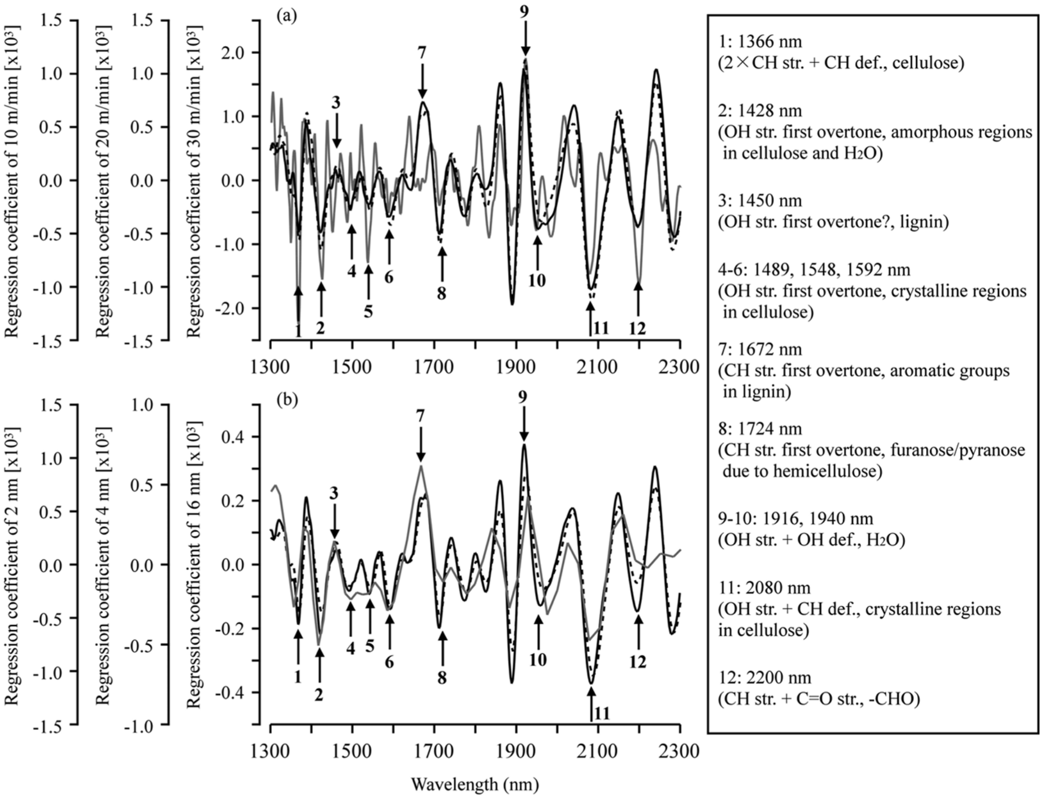

Figure 2. Regression coefficients for the PLS models predicting the modulus of elasticity (Eb). In panel (a), the solid, dashed and gray lines indicate the lumber conveying speed of 10 m, 20 m and 30 m per minute, respectively. In panel (b), the solid, dashed and gray lines indicate the measurement resolution of spectra for 2 nm, 4 nm and 16 nm, respectively.

and NIR-predicted values, and these were applied to the prediction set of 34 specimens and found that predictions of the respective wood properties were also well fitted, with coefficients of determination (r^2) ranging from 0.54 to 0.83. The SEPs showed similar values to those found in the previous reports. The ratios of performance to deviation (*RPD*)[4] was good enough in the practical sense, ranging from 1.70 to 2.36. These results imply that NIR spectroscopy can meet the demands of rapid inspection in wood products manufacture.

Since the general trends of the regression coefficients showed the same pattern for any traits, results of the E_b are shown in Figure 2.

There were no clear differences in regression coefficients for any measurement conditions. These results indicate that important explanatory variables included in the models are relatively tolerant of the measurement conditions. There were significant negative regression coefficients at the peaks related to cellulose, which is the skeletal substance of cell wall (1, 4–6 and 11). Matrix substances of cell walls, i.e., lignin and hemicellulose, showed significant regression coefficients at the peaks of 3, 7 and 8, respectively.

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