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ORIGINAL ARTICLE

Prediction of dry veneer stiffness using near infrared spectra from transverse section of green log

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Abstract This study examined the feasibility of near infrared spectroscopy as a novel technique for log assessment on the basis of wood property. Near infrared (NIR) spectra were obtained from the transverse section of green log and multivariate regression analysis was carried out to predict the stiffness of veneer processed from the log. The stiffness of the veneer was dynamic modulus of elasticity measured using ultrasonic method. The calibrations of veneer stiffness had moderate relationships between measured and NIR-predicted values, with regression coefficients ranging from 0.84 to 0.88. The calibration equations were applied to the test set and it was found that predictions were also well fitted, with regression coefficients ranging from 0.67 to 0.89. The results indicate that the variation of wood stiffness within the logs could be assessed using the NIR spectra from the cross-section of logs. The spectra were obtained from green condition of the log and the stiffness of veneer was measured after kiln drying. Thus, the results imply that the wood stiffness in dry condition could be predicted using the spectra collected from green logs. If the models obtained in this study put into the imaging system, the two-dimensional map of the stiffness would be visualized on the cross-section of logs. The NIR spectroscopy coupled with imaging system could compensate the weak point of the traditional methods for log assessment.

Keywords Log sorting · Veneer stiffness · Within log variation · Chemometrics · *Cryptomeria japonica*

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Introduction

The demands of veneer-based engineered wood products such as plywood, Parallam and laminated veneer lumber have increased recently, as the quality of forest resources have gradually declined. The manufacturing process of plywood involves the gluing of individual veneer sheets to form panels. Therefore, it will be of great benefit to these industries if the main raw material could be sorted on the basis of stiffness strength prior to the layup of the panels, especially for the construction purpose.

Numerous studies have demonstrated that near infrared spectroscopy (NIRS) has been successfully applied to the rapid evaluation of various wood properties [1, 2]. Moreover, it has been shown the potential of NIRS to be used on-line or at-line for the quality control of, or segregation of wood and pulp products [3–5]. For the veneer assessments, Meder et al. [6] reported that radiata pine veneer stiffness can be predicted by NIRS calibrated using mini-laminated veneer lumber test panels and veneer strips. Similar results have been reported in yellow-poplar (*Liriodendron tulipifera*) and *Pinus* spp. predicting for the density and stiffness of veneer [7, 8].

In general, many wood properties highly vary within the stem [9]. The information of the variation of wood properties is useful for the log sorting and the optimization of sawing or processing of logs. The longitudinal vibration method has been often applied to evaluate the log stiffness [10, 11]. However, the method can only evaluate the mean value of the whole log, thus it is impossible to know the variation of the stiffness within the log.

The aim of this study is to clarify the feasibility of NIRS as a novel technique for log assessment on the basis of wood property. Near infrared spectra were obtained from the transverse section of green log and multivariate regression analysis was carried out to predict the stiffness of veneer processed from the log.

Experimental

Selection of logs and veneer processing

The experimental procedure is shown in Fig. 1. Ten sample logs of sugi (*Cryptomeria japonica*) were selected from the log depository in the LVL factory of Orochi Co. Ltd. The dynamic modulus of elasticity of the green logs (E_{log}) was measured using the longitudinal vibration method [10, 11]. The weight, log length, and diameter (mean value of four-point measurements) were measured to calculate the density of green logs. E_{log} was obtained by the following formula [11]:

$$E_{\mathrm{log}} = 4f^2l^2\rho \quad (1)$$

where f (Hz) is the fundamental vibration frequency, l (m) is the length of the sample log, and ρ (kg m^{-3}) is the density of green sample log. After measuring the E_{log}, a disk, 40 mm thick, was cut from the top end of each log (Fig. 1). The disk was used for the NIR spectral measurements (described below). There was no remarkable defect in the disks, such as knot, check and black-colored heartwood. The disks were put into plastic bag and stored at dark room (not conditioned). The measurements of NIR spectra were carried out within 1 week. General descriptions of sample logs are shown in Table 1.

The logs were processed into the veneer sheet by rotary lathe. The green weight of veneer was measured before kiln drying. The veneer was kiln-dried based on the schedule decided at the factory. After kiln drying, the density (weight and volume) and stiffness of veneer were measured. The moisture content of veneer was estimated from the weight of before and after drying. There was high variation in moisture content of veneer ranging from 40.9 to 291.0 % (mean value: 104.6 %). The density was calculated from the weight and volume of dry veneer. The volume of veneer was calculated from the length of all direction (thickness, width and length). The mean values of each direction were 3.38 mm (thickness), 1366 mm

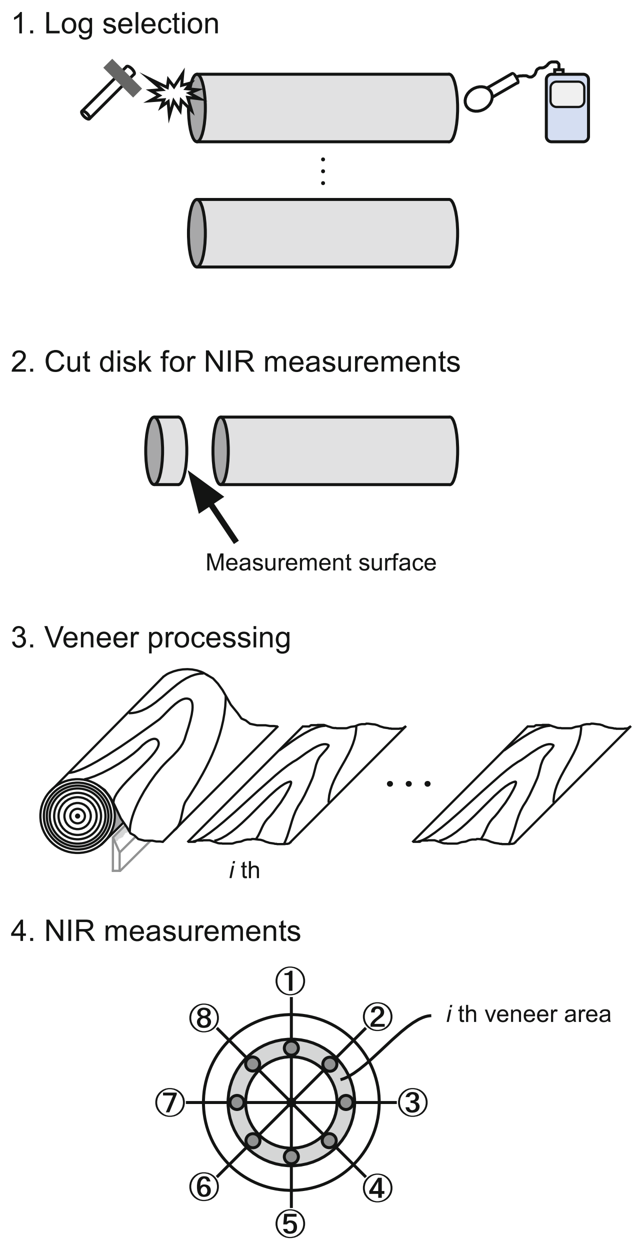

Fig. 1 Experimental procedure of prediction of veneer stiffness. Selection of sample logs carried out based the diameter and stiffness of logs. After the selection, a disk for the measurements of near infrared spectra was cut from the top end of logs. The veneer stiffness was measured using ultrasonic method after kiln drying. Near infrared spectra were acquired at eight spots in each veneer area of the disk

(width) and 1298 mm (length). The dynamic modulus of elasticity of dry veneer (E_{ven}) was measured using Ultrasonic Veneer Tester (Metriguard Inc. Pullman, WA, USA). E_{ven} was obtained by the following formula:

$$E_{\mathrm{ven}} = v^2\rho \quad (2)$$

where v (m sec^{-1}) is the propagation velocity of ultrasonic stress wave and ρ (kg m^{-3}) is the density of veneer. The moisture content of the dried veneer would be about 4–5 %

Table 1 Descriptions of sample logs

Log ID	Diameter (cm)	Density (kg m^{-3})	Stiffness (GPa)
A01	24.4	695	6.21
A02	22.8	840	7.06
A03	35.6	598	5.73
A04	25.7	791	7.46
A05	32.4	671	6.22
A06	33.1	775	7.93
A07	28.1	713	6.67
A08	41.5	589	4.82
A09	23.0	580	7.39
A10	27.1	630	6.30

The diameter, density and stiffness were measured for green logs

from our previous examinations. Four to sixteen veneers were taken from each log and total 89 veneers were used for the following analysis.

NIR measurements

The diffuse-reflectance spectra were acquired on a MATRIX-F spectrophotometer (Bruker Optics Co.) equipped with a fiber optic probe (spot diameter ≈ 3.5 mm). The NIR spectra were obtained at 8 cm^{-1} interval over the wavenumber range from 10000 to 4500 cm^{-1}. Thirty-two scans were collected and averaged into a single average spectrum. The acquisition time was approximately 15 s.

As shown in Fig. 1, the areas of each veneer in the transverse section of the log were estimated from the cross-sectional area of the veneer (thickness (3.5 mm) × width (1430 mm)). The spectra were acquired at eight spots in each veneer area of the disk and mean value of eight measurements was used for the regression analysis. The total measurement points per disk were ranging from 32 to 128, and thus the acquisition times for one disk were about 8–32 min. The spectra were measured at transverse section of disk. Because the area became larger from outer to inner position within the disks, the measurement spots were set at middle position in radial direction of each area. The disks were cut by chainsaw and the measurement surface was sawn plane and not processed by any machine (Fig. 1). After the measurements of NIR spectra, the disks were kiln-dried to calculate the moisture content. The moisture contents of the sample disks were still high ranging from 29.8 to 97.6 % (mean value: 73.1 %).

Statistical analysis

All spectral data were split randomly into the calibration and test sets, which consisted of 73 and 16 samples, respectively.

Table 2 Stiffness of veneer samples for calibration and test sets

Wood property	Calibration set (n = 73)				Test set (n = 16)			
	Mean	Min	Max	SD	Mean	Min	Max	SD
E_{ven} (GPa)	7.07	4.61	9.67	1.34	7.36	4.80	9.61	1.48

E_{ven} modulus of elasticity, *n* sample number, *SD* standard deviation

Sample set conditions are summarized in Table 2. In order to consider the effect of the spectral processing, raw, standard normal variate (SNV) and second-derivative spectra were used for the analysis. Second-derivative spectra were obtained using Savitzky–Golay algorithm with a 21-point window and second-order degree polynomial [12]. Effects of spectral range for the calibration performance were also examined comparing the two conditions (full: 10000–4500 cm^{-1}; reduced: 7500–5500 cm^{-1}).

Partial least squares (PLS) regression was used to develop all prediction models [13, 14]. The final number of factors selected for incorporation into the model was chosen to minimize the residual variance when using full cross-validation. All data analysis was performed using the Unscrambler version 9.6 (CAMO AS, Norway) software.

Results and discussion

Variation of veneer stiffness

The density and stiffness of sample logs ranged from 580 to 840 kg m^{-3} and from 4.82 to 7.93 GPa, respectively (Table 1). The stiffness of the veneer ranged from 4.61 to 9.67 GPa (Table 2). Figure 2 shows the variation of veneer

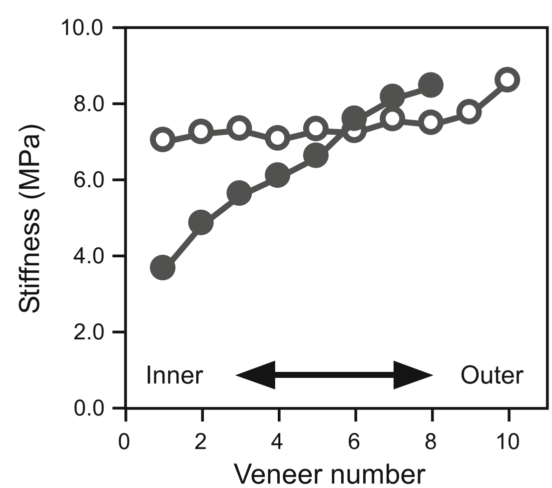

Fig. 2 Variation of veneer stiffness within the logs. *Open* and *filled circles* indicate the log ID A05 and A10, respectively. They had similar log stiffness and density. The *horizontal axis* is veneer number and the younger number means the inner position of log

stiffness within the logs. The horizontal axis is veneer number and the younger number means the inner position of log. Open and filled circles indicate the log ID A05 and A10, respectively. The two logs contained similar annual rings (33 and 31) and had also similar log stiffness (see Table 1). Although they had similar log stiffness, the variation of veneer stiffness within the logs was quite different. In general, the longitudinal vibration method has been used to evaluate the log quality. As mentioned above, however, the method can only evaluate the mean value of the whole log. It should be noted that the stiffness of the wood products processed from the log would highly vary even if the logs have similar stiffness.

NIR spectra

Figure 3 shows NIR diffuse-reflectance raw spectra (a) and that of second-derivative spectra (b and c) obtained from each veneer area in the disks. Although the figures are obtained from a single disk, similar tendency was found in any disks. The absorbance intensity at specific bands gradually increased or decreased depending on the veneer position. For instance, the absorption intensity decreased from inner to outer positions at the vicinity of 7100, 6830 and 5600 cm^{-1}. Contrary this, the absorption intensity increased from inner to outer positions at the vicinity of 5800 cm^{-1}. As discussed below, some of these bands played an important role to predict the veneer stiffness.

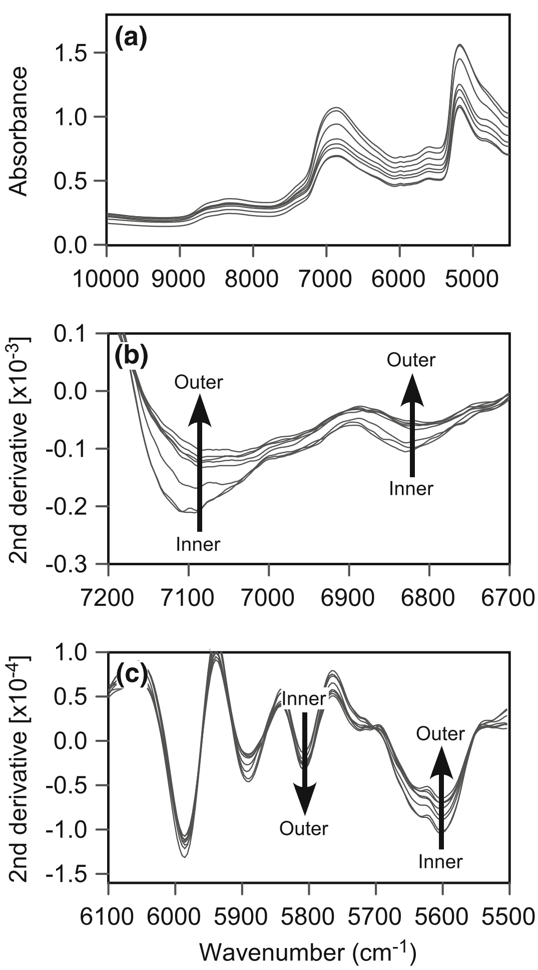

Fig. 3 **a** Original and **b**, **c** second-derivative spectra from each veneer area in the disks

Prediction of dry veneer stiffness and density

Partial least squares modeling for the prediction of veneer stiffness is shown in Table 3. The calibration had moderate relationships between measured and NIR-predicted values, with regression coefficients ranging from 0.84 to 0.88. The calibration model was successfully applied to the test set ($R = 0.67$–0.89, SEP = 0.38–0.84 GPa). The ratio of performance to deviation (RPD), calculated as the ratio of the standard deviation of the reference data to SEP, was good enough as the practical sense ranging from 1.76 to 3.93. In the calibration set, calibration performance did not show clear tendency depending on the spectral processing and range. However, the PLS models developed with reduced wavelength range showed higher prediction ability in the test set than the full wavelength range. SNV showed the best prediction ability among three treatments in the test set. This fact might be due to the elimination of scatter effect by the treatment.

Figure 4 shows the loadings for the first three PLS factors of the prediction of the veneer stiffness using the second-derivative spectra ranging from 7500 to 5500 cm^{-1}. The three factors explained the majority of the total variance (*X* matrix: 94 %; *Y* vector: 71 %). The high loadings for all three factors were found in the vicinity of 7131, 7219 and 7073 cm^{-1}. Although the band assignment is generally difficult for NIR spectra, these bands could correspond to the previous knowledge [15]. The absorption bands at 7143 and 7073 cm^{-1} are assigned to the first

Table 3 Results of PLS modeling for veneer stiffness

Treatment	Range	Calibration set			Test set		
		Factor	*r*	SECV	*r*	SEP	RPD
Raw	Full	14	0.84	0.73	0.71	0.84	1.76
	Reduced	11	0.88	0.65	0.81	0.65	2.28
SNV	Full	12	0.85	0.70	0.71	0.64	2.31
	Reduced	13	0.85	0.70	0.89	0.38	3.93
Derivative	Full	10	0.88	0.64	0.70	0.72	2.05
	Reduced	6	0.86	0.68	0.67	0.63	2.36

SNV standard normal variate, *Factor* optimum number of PLS factors, *r* regression coefficient, *SECV* standard error of cross-validation, *SEP* standard error of prediction, *RPD* ratio of performance to deviation

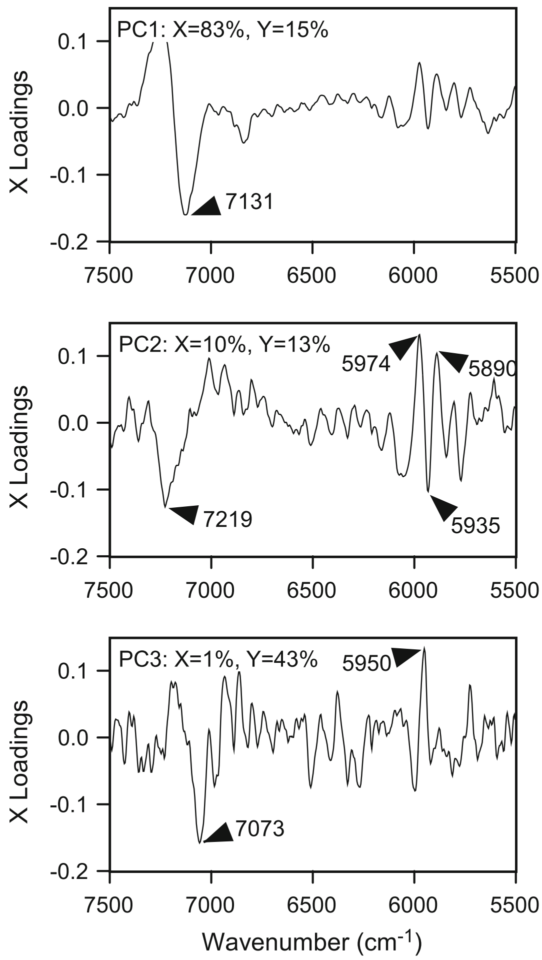

Fig. 4 Loading plots for the first three PLS factors (PC1–PC3) of the prediction of the veneer stiffness. The values how much the PLS factor can explain the deviations both of the *X* and *Y* matrices are also shown in the figure

overtone of the fundamental OH stretching vibration mode due to H_2O. Considering the possibility of peak shift resulting from second-derivative treatment, these bands might explain the variation of moisture content in the samples. There were also some notable loadings for the second and third factors at the vicinity of 5974, 5935, 5890 and 5950 cm^{-1}. The absorption bands at 5974, 5935 and 5890 cm^{-1} are assigned to the first overtone of the fundamental CH stretching vibration mode due to aromatic groups in lignin. The absorption bands at 5950 cm^{-1} are assigned to the CH first overtone due to hemicellulose. These results suggest that the variation of the matrix substance in cell wall is also important to predict the veneer stiffness.

In this study, the spectra were obtained from green condition of the disk and the stiffness of veneer was measured under dry condition. Thus, the current results imply that NIRS can predict the wood stiffness in dry condition using the spectra from wet condition. This fact is consistent with previous research [16–20]. Schimleck et al. [17, 18] reported that various characteristics (air-dry density, microfibril angle, stiffness, tracheid morphological traits) of *Pinus taeda* wood were successfully modeled using NIR spectra collected from the radial longitudinal and transverse faces when the samples were green and dry. Meglen and Kelley [19] have also shown that it is possible to determine mechanical properties of dry wood using green wood samples. Fujimoto et al. [20] noted that the specific absorption bands play an important role in prediction of wood density using the spectra collected from any moisture condition.

The current results indicate that NIRS can evaluate the spatial distribution of the wood stiffness within the logs. In general, the longitudinal vibration method has been used to evaluate the log stiffness [10, 11]. As mentioned above, however, the method can only evaluate the mean value of the whole log. Recently, the imaging techniques using wide range of electromagnetic waves including near infrared have been developed and applied to many kinds of materials as well as wood [21]. If the models obtained in this study put into the NIR imaging system, the two-dimensional map of the stiffness would be visualized on the cross-section of logs. The NIR spectroscopy coupled with imaging system can compensate the weak point of the longitudinal vibration method.

In this study, we used the disks having no remarkable defects and the moisture contents of logs were limited. Further examinations are required using wide variety of samples to build more robust prediction model.

Conclusion

This study examined the feasibility of NIRS as a novel technique for log assessment on the basis of wood property. The variation of wood stiffness within the logs could be evaluated using the NIR information from the cross-section of logs. The wood stiffness in dry conditions could be predicted using the spectra collected from green logs. This fact is important from practical point of view. Near infrared spectroscopy would be a suitable method for log segregation with the aid of the imaging techniques.

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