Mechanical and Physical Properties of Oriented Strand Board Exposed to High Temperature and Relative Humidity and Coupled with Near-Infrared Reflectance Modeling

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Abstract

The mechanism underlying thermal degradation of oriented strand board was tested under a humid environment. Near-infrared reflectance (NIR) spectroscopy coupled with chemometric modeling was utilized to better understand the degradation of functional groups over time. The flexural properties, internal bond (IB), water absorption, and thickness swelling were tested after exposure to various times of 0, 3, 6, and 9 weeks in a climate-controlled laboratory to 76.7°C and 60 percent relative humidity. The largest reduction in all flexural and physical properties occurred during the first 3 weeks of exposure and then leveled off thereafter, while IB decreased significantly through the 9-week period ($\alpha = 0.05$). Chemometric models built from NIR spectra revealed pertinent chemical changes in wood chemistry and resin components.

Wood-based composites are commonly used as building materials, such as oriented strand board (OSB), which is a structural panel manufactured from thin wood strands and waterproof resins bound together under heat and pressure. As an engineered composite, the main applications of OSB include structural panels in walls, roofs, floors, components of beams, underlayment in light-frame construction and packaging, etc. (Forest Products Laboratory 2010). OSB structural panels are commonly used to distribute wind and vertical loads within the structural system. The market share of OSB panels has increased significantly over the past three decades and has recently overtaken plywood in structural sales. However, a key feature of OSB, compared with plywood, is the lower dimensional stability that occurs due to the increased compaction ratio and irreversible thickness swelling (TS).

It is very important to maintain a high board strength, stiffness, and dimensional stability in most OSB applications. However, the board strength, stiffness, and dimensional stability can be substantially reduced on exposure to high relative humidity and temperature that often occur in the attic of residential houses. Wood and wood-based composites show a strong relationship between loss in strength and loss in hemicelluloses after thermal degradation (Winandy 2001). Furthermore, the mechanical properties of OSB and other wood-based composites have been reported to decrease after thermal modification, temperature and/or moisture exposure, or heat treatment (Wu and Suchsland 1997, Wu and Piao 1999, Wu and Lee 2002,

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Moya et al. 2009, Aro et al. 2014). When OSB is exposed to liquid water or high atmospheric relative humidity, the edges can swell, opening up the void space and accelerating further water absorption (WA) (Evans et al. 2013).

WA and TS in wood composites can be influenced by many factors, such as relative humidity, moisture content, and density. The TS and WA of OSB samples over time can be exacerbated when exposed to high temperatures and relative humidity, even after being sealed with paint or stain, which acts to retard the rate of absorption (Garay et al. 2009). Two face regions of OSB samples were responsible for more of the WA in the product, meaning that the high-density face layers can cause increased WA (Xu et al. 1996). More research focused on the effects of moisture change on the strength and dimensional stability of wood-based composites has been reported (Wu and Suchsland 1997). All of this research investigated the changes in stability and strength in response to different moisture levels. However, there is little reference to the mechanism of stability and strength changes at the molecular level for commercial OSB.

Near-infrared reflectance (NIR) spectroscopy is an emerging method that can be used to assess the mechanical, physical, or energy properties of the composite material as a function of changes in the molecular structure (Via et al. 2003, So et al. 2004, Via 2010). The most common mechanical property successfully modeled from NIR spectra for wood composites includes bending strength (modulus of rupture [MOR]) and stiffness (modulus of elasticity [MOE]) of small clear wood beams and flakes (Kohan et al. 2012). For solid wood, the prediction of mechanical properties could be attributed to the association between wood chemistry and strength. Via et al. (2009) found some wavelengths in the NIR region to be associated with the fundamental chemical components of wood, which have a certain relationship with the mechanical properties. For example, the most important characteristics to contribute to strength and stiffness are density and microfibril orientation. Also, the relative amount of lignin, cellulose, and hemicellulose determines cell wall density and the ability to transfer stresses between polymers within the cell wall coupled with changes in cell wall density. Although OSB is more complex than solid wood because of the chemical and macroproperties of the biomass, additives, and adhesives, NIR has still been shown to be a unique analytical tool. For example, phenol-formaldehyde–associated wavelengths could be partitioned from wood chemistry–associated wavelengths using principal component (PC) analysis and a multiple linear PC model for the prediction of OSB concentrated static load due to variation in resin loading and wood chemistry functionality (Via 2013).

Therefore, the objectives of this study were to investigate the mechanical and physical property changes of a commercial OSB treated at high temperature and humidity for up to 9 weeks in a climate-controlled laboratory, coupled with the use of NIR models to probe the chemical changes that corresponded with a reduction in bending strength, IB, WA, and TS with severity of exposure.

Materials and Methods

Materials

Two 1.22 by 2.44-m (4 by 8-ft) commercial OSB panels were purchased from a local supplier. The APA–The Engineered Wood Association panel grade was rated Sheathing and board classification was Exposure 1. The OSB nominal thickness was 11.1 mm (7/16 in.).

Specimen preparation

Three groups of specimens (flexure, internal bond [IB], and WA and TS) were randomly cut from the two OSB panels. Four treatments were 0 (as control), 3, 6, and 9 weeks. The duplicates for each treatment, dimensions, and standards referenced to test the three group specimens are shown in Table 1.

Treatment in the climate-controlled laboratory

The specimens were put in the climate chamber (Parameter Generation and Control, Inc., Black Mountain, North Carolina, USA) for treatments of 3, 6, and 9 weeks, respectively, after their weights and dimensions (thickness, width, and length) were measured and recorded. The temperature and relative humidity in the climate-controlled laboratory were set to 76.7°C ± 1°C and 60 percent relative humidity, respectively, according to ASTM D5516 (ASTM International 2003). After 3, 6, or 9 weeks, the specimens were taken out from the climate-controlled laboratory, respectively, and the weights and dimensions were measured. Before being tested, all specimens were conditioned to constant weight and moisture content in a conditioning chamber maintained at a relative humidity of 55 ± 1 percent and a temperature of 22.5°C ± 1°C. The colors of OSB samples changed after treatments (Fig. 1).

Flexural test

The flexural properties of the OSB specimens were evaluated according to ASTM D3043 Method A—Center-Point Flexure Test using a Zwick-Roell (Einsingen, Germany) load frame equipped with a 10-kN load cell (ASTM International 2011). A support span of 267 mm (10.5 in.) was used. The specimens were tested until rupture occurred in the outer surface of the composite specimens. A crosshead speed of 7.87 mm/min (0.31 in./min) was used. The four group specimens with treatments of 0, 3, 6, and 9 weeks were tested, respectively, after treated as described above. The bending MOR and MOE were calculated and compared.

IB test

The Zwick-Roell testing machine was also used to test the IB property of four group OSB specimens with treatments of 0, 3, 6, and 9 weeks. Based on ASTM D1037 (ASTM International 2012), a crosshead speed of 0.89 mm/min

Table 1.—The duplicates, dimensions, and corresponding standards of the three group specimens.[a]

	Test group		
	Flexure	IB	WA and TS
Duplicate	6	9	5
Length × width (mm)	114 × 354	50 × 50	152 × 152
ASTM standard	D3043	D1037	D1037

[a] IB = internal bond; WA = water absorption; TS = thickness swelling.

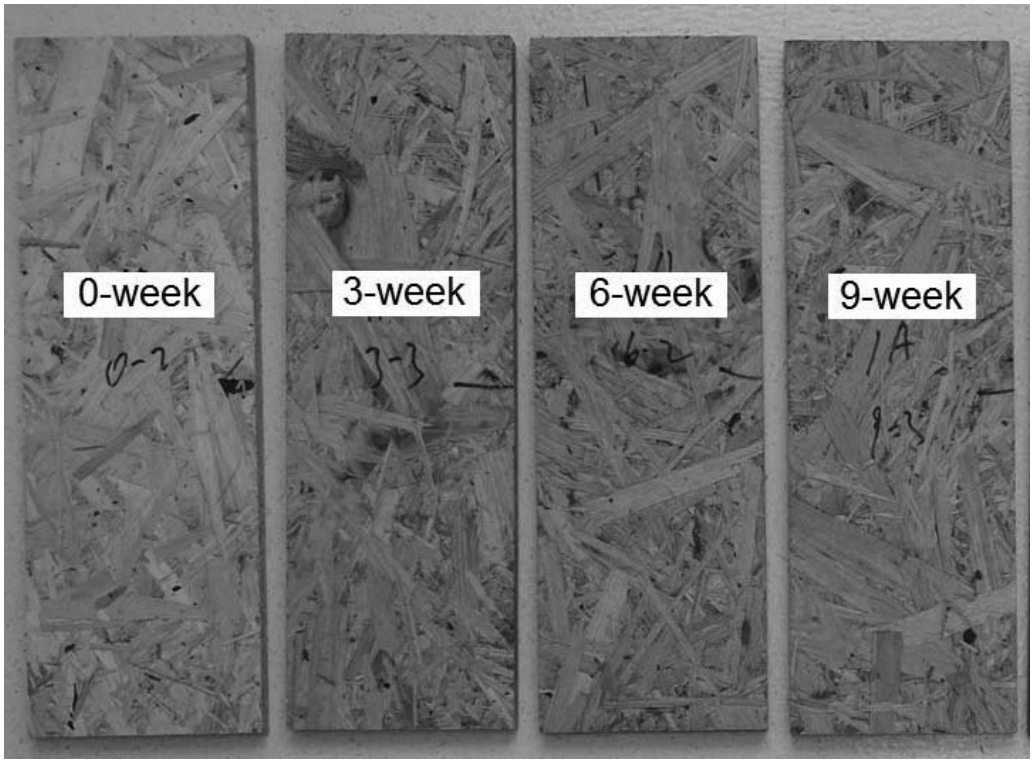

Figure 1.—Oriented strand board samples before and after different treatment times.

(0.035 in./min) was used. The specimens were tested until rupture occurred in the inner layers of the OSB specimens.

WA and TS tests

The WA and TS specimens were tested by the method A (2 plus 22-h submersion period) described in ASTM D1037 (ASTM International 2012). Briefly, the specimens were submerged horizontally under 25 mm of distilled water maintained at a temperature of 20°C ± 1°C after the four group specimens with treatments of 0, 3, 6, and 9 weeks were conditioned. After a 2-hour submersion, the weights were measured, and the thicknesses were determined by measuring four points midway along each side 25 mm in from the edge of the specimen. Then the specimens were submerged for an additional period of 22 hours, and the above weighing and measuring procedure was repeated. The WA was calculated by weight-based and volume-based methods.

Data analysis

The data of bending MOR and MOE, IB, and WA and TS of the four group specimens with treatments of 0, 3, 6, and 9 weeks were analyzed using the SAS program (version 9.4). Analysis of variance ($\alpha = 0.05$ and/or 0.25) was used to examine differences between the four treatments. Multiple comparisons by *t* tests (least significant difference tests) were used to detect the overall significant differences of the influences of the treatments on the mechanical and physical properties of OSB samples.

NIR modeling for bending and IB tests

The PerkinElmer 400 FTIR/FT-NIR spectrometer was utilized to collect the spectra of the OSB samples after bending (scanned the panel surfaces) and IB (scanned the fractured surfaces of the broken IB samples) tests. The NIR spectrum covered a range of 10,000 to 4,000 cm^{-1} with a spectral resolution of 4 cm^{-1}. Each spectrum was collected from an average of 32 scans. Spectrum Quant+ software was used for model construction. Principal component regression (PCR) was the statistical method used to build NIR models.

Results and Discussion

Flexural properties

The MOE and MOR of the OSB specimens are summarized in Figure 2. After a 3-week treatment, the

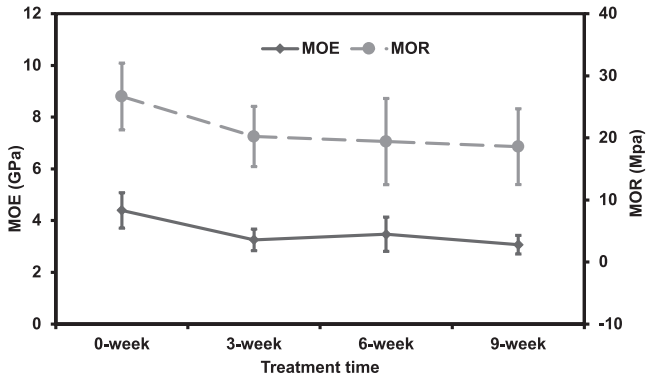

Figure 2.—Modulus of elasticity (MOE) and modulus of rupture (MOR) of oriented strand board with treatment time.

MOE and MOR decreased 26 and 24 percent, respectively. Both MOE and MOR were decreasing along with the increasing time. Tests for significance from the statistical analysis of variance (least significant difference tests) for all mechanical and physical properties are shown in Table 2. The treated samples had significantly lower mechanical properties when compared with the controls. This may be attributable to the heat and humidity exposure that degraded the wood components and decreased the bonding between the wood and adhesive (Wu and Lee 2002). Both the MOR and the MOE of the treated specimens decreased significantly after 3-week heat and humidity treatments ($P < 0.05$; Table 2). However, there were no significant differences among 3, 6, and 9 weeks for both MOR and MOE ($P > 0.05$; Table 2), indicating that the OSB mechanical properties lost were mainly during the first 3 weeks of treatment.

Internal bond

The IB of the OSB specimens did not change much (not significant, $P = 0.889$; Table 2) after a 3-week treatment, as shown in Figure 3. This may be because of the insulated effect of the OSB surface on the core, which did not see much reduction in bonding strength after 3 weeks of duration. Along with the treatment time increasing, the IB decreased 31.8 percent (not significant, $P = 0.101$ for $\alpha = 0.05$, but significant for $\alpha = 0.25$) and 44.7 percent (significant, $P = 0.031$) after 6 and 9 weeks of treatments, respectively. There were no significant differences between 3 and 6 weeks ($P = 0.130$ for $\alpha = 0.05$ but significant for $\alpha = 0.25$) and 6 and 9 weeks ($P = 0.554$), but there were some significant differences between 3 and 9 weeks ($P = 0.041$). Similar results were detected when the IB strength values of laminated panels were found to not be influenced on exposure to water for beyond 24 hours (Hiziroglu 2008). The IB decreased slower than bending strength because the heat and humidity damaged the OSB surface first and the core bonding strength (IB) later due to the fact that transference of heat and moisture in wood strands was relatively slow. The other reason that the IB may have decreased with treatment time is that the IB strength tends to decrease with increased TS (Kojima and Suzuki 2011).

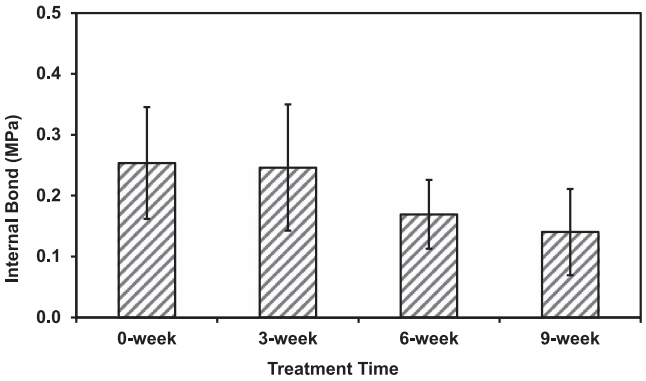

Figure 3.—Internal bond of oriented strand board with treatment time.

Water absorption and thickness swelling

Figure 4 summarizes the WA based on volume (VL) or weight (WT) and TS of the control and treated OSB samples after 2 and 24 hours more of water submersion. Generally, both WA and TS increased after high-temperature and high-humidity exposure. Compared with the untreated samples, the increases in both VL- and WT-based WA values at 3, 6, and 9 weeks were significant ($P < 0.05$; Table 2), except the 2-hour VL- and WT-based WA value between the control and 9 weeks of treatment ($P = 0.071$ and 0.207, respectively, but they were significant for $\alpha = 0.25$). All these indicated that the OSB absorbed more water after heat and high-humidity treatment. However, longer treatment time might decrease the OSB WA because heating wood changes several of its chemical and physical properties (Aro et al. 2014). The changes are caused mainly by thermodegradation of hemicelluloses because the available hydroxyl groups in hemicellulose have the most significant effect on relationship between wood and water. The heat treatment lowers water uptake, and the wood cell wall absorbs less water because of the decrease in the amount of hydroxyl groups (Inoue et al. 1993). Among the 3-, 6-, and 9-week treatments, there were no significant differences for WA values of 2 and 24 hours of soaking (Table 2), except the VL- and WT-based WA values of 2 hours between the 3- and 9-week treatments ($P = 0.005$ and 0.018, respectively).

For the TS (Fig. 4), it increased 77, 77, and 47 percent for the 2-hour soaking and 107, 115, and 116 percent for the 24-hour soaking after the 3-, 6-, and 9-week treatments, respectively ($\alpha = 0.05$; Table 2). Among the 3-, 6-, and 9-week–treated OSB samples, there were no significant

*Table 2.—*P *values from* t *tests (least significant difference test) for bending MOR and MOE, IB, WA, and TS.*[a]

	Bending			WA: volume		WA: weight		TS	
Treatment (wk)	MOE	MOR	IB	2 h	24 h	2 h	24 h	2 h	24 h
0 vs. 3	**0.0023**	**0.0462**	0.8891	**<0.0001**	**0.0006**	**0.0007**	**0.0032**	**<0.0001**	**<0.0001**
0 vs. 6	**0.0062**	**0.0180**	***0.1008***	**0.0014**	**0.0021**	**0.0118**	**0.0112**	**<0.0001**	**<0.0001**
0 vs. 9	**0.0004**	**0.0110**	**0.0309**	***0.0710***	**0.0024**	***0.2068***	**0.0139**	**0.0072**	**<0.0001**
3 vs. 6	0.6715	0.6569	***0.1299***	***0.1245***	0.5218	***0.1959***	0.5503	0.9573	0.5145
3 vs. 9	0.4372	0.5066	**0.0413**	**0.0052**	0.6515	**0.0179**	0.6129	0.0752	0.4727
6 vs. 9	***0.2355***	0.8239	0.5544	***0.1031***	0.8770	***0.1873***	0.9534	0.0836	0.9172

[a] Bold numbers mean significant at $\alpha = 0.05$, and italic bold numbers mean significant at $\alpha = 0.25$. MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond; WA = water absorption; TS = thickness swelling.

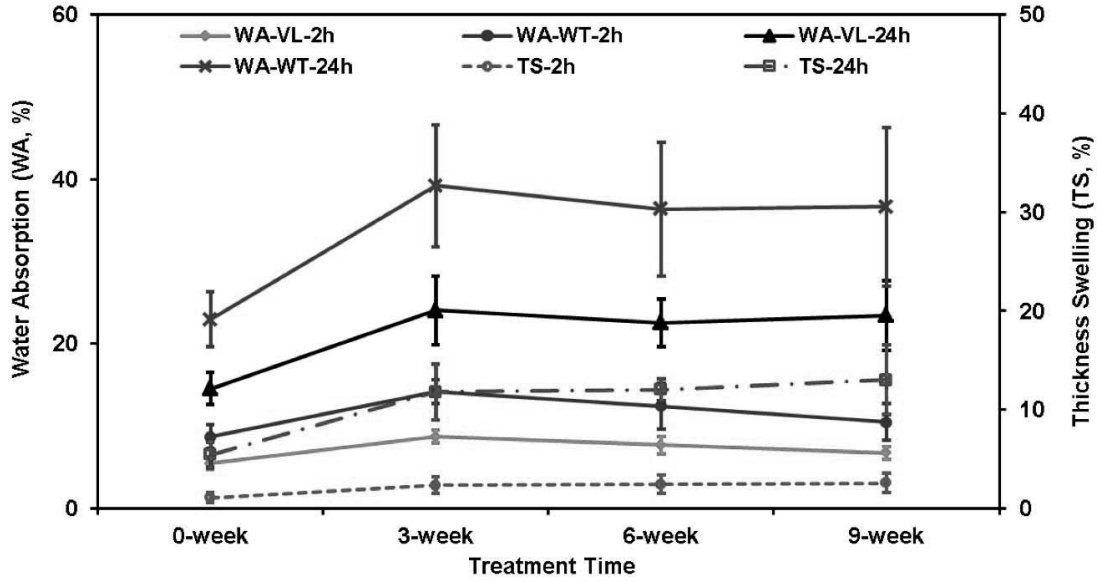

Figure 4.—Water absorption (WA) and thickness swelling (TS) of the control and treated oriented strand board samples after 2 and 24 hours of submersion. VL = volume; WT = weight.

differences for TS between the treatments (Table 2). This indicated that most of the TS happened during the first 3 weeks of treatment. A longer treatment time decreased the OSB TS of the 2-hour soaking. It is probably because heat treatment lowers water uptake and the wood cell wall absorbs less water owing to the decrease in the amount of wood hydroxyl groups of hemicellulose. As a consequence, wood swelling and shrinking are lower. Thus,

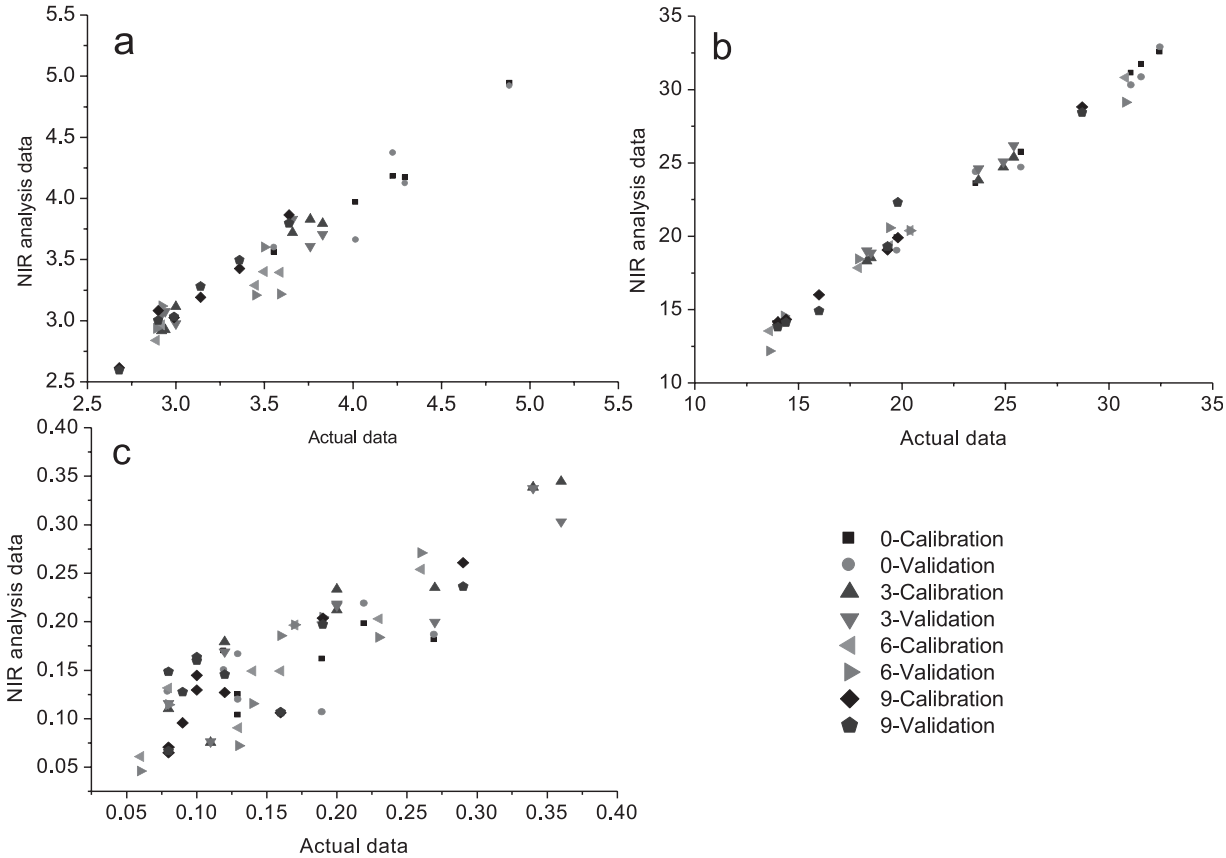

Figure 5.—Calibration and validation results of (a) modulus of elasticity, (b) modulus of rupture, and (c) internal bond of four group specimens with treatment of 0, 3, 6, and 9 weeks. NIR = near-infrared reflectance

increasing treatment time had the tendency to reduce the hygroscopicity and improve the dimensional stability of OSB (Inoue et al. 1993). The 24-hour TS changing trend was similar but much higher compared with that of 2 hours (Fig. 4). It was probably because the 24-hour soak might affect the extractive removal or any other chemical modification in the wood or resin.

NIR modeling

NIR model was constructed using the NIR spectra coupled with the MOE/MOR data. First, NIR spectra were pretreated using multiplication scattering correction to reduce the noise; then PCR was conducted to construct the NIR model, and the wavenumber ranges were selected based on the spectra loading analysis. The final NIR model was evaluated using the ratio of performance to deviation (RPD).

There was a good relationship between the experiment results and the NIR analysis data, as shown in Figure 5. The results indicated that the MOR had a better linear correlation between calibration data and validation data than MOE and IB. To determine if a model was good for prediction or interpretation, the RPD was used. RPD is a measure of the goodness of fit and is the ratio of the standard error in prediction to the standard deviation of the samples. In this work, the RPDs of MOE and MOR were 1.53 and 1.72, which were close to the rough screening category. Generally, for NIR to be successful at screening an individual panel, the RPD should be between 1.5 and 2.5 or greater, depending on which study is referenced (Via et al. 2011). However, as Via et al. point out, this is only a model and should not be used to estimate the real strength of panels within a manufacturing process (Via 2013). The RPD values in this study were generally higher than 1.5 with the exception of IB (RPD = 0.94; Table 3). As such, NIR may be an acceptable tool for the accurate prediction of the mechanical properties of OSB panels in an attic or other high-temperature and high-humidity applications. But perhaps more important, the model can be used to understand the underlying mechanisms behind the reduction in mechanical properties.

The score plots for the first two PCs are shown in Figure 6. There was a good separation of MOE and MOR by different treatment times along PC1, which corresponded well with the above results (Fig. 2), but it became more difficult to distinguish any change in IB after 3 weeks.

As a complex material, OSB can be described as a combination of different kinds and contents of chemical substances and solid materials. Hence, the spectra reflect the energy captured (or reflected) by the chemical bonds from different wood components (cellulose, lignin, hemicellulose, and water) and their interactions. Coefficients by wavenumber for PCR for MOE, MOR, and IB when the first derivative pretreatment was processed are shown in Figure

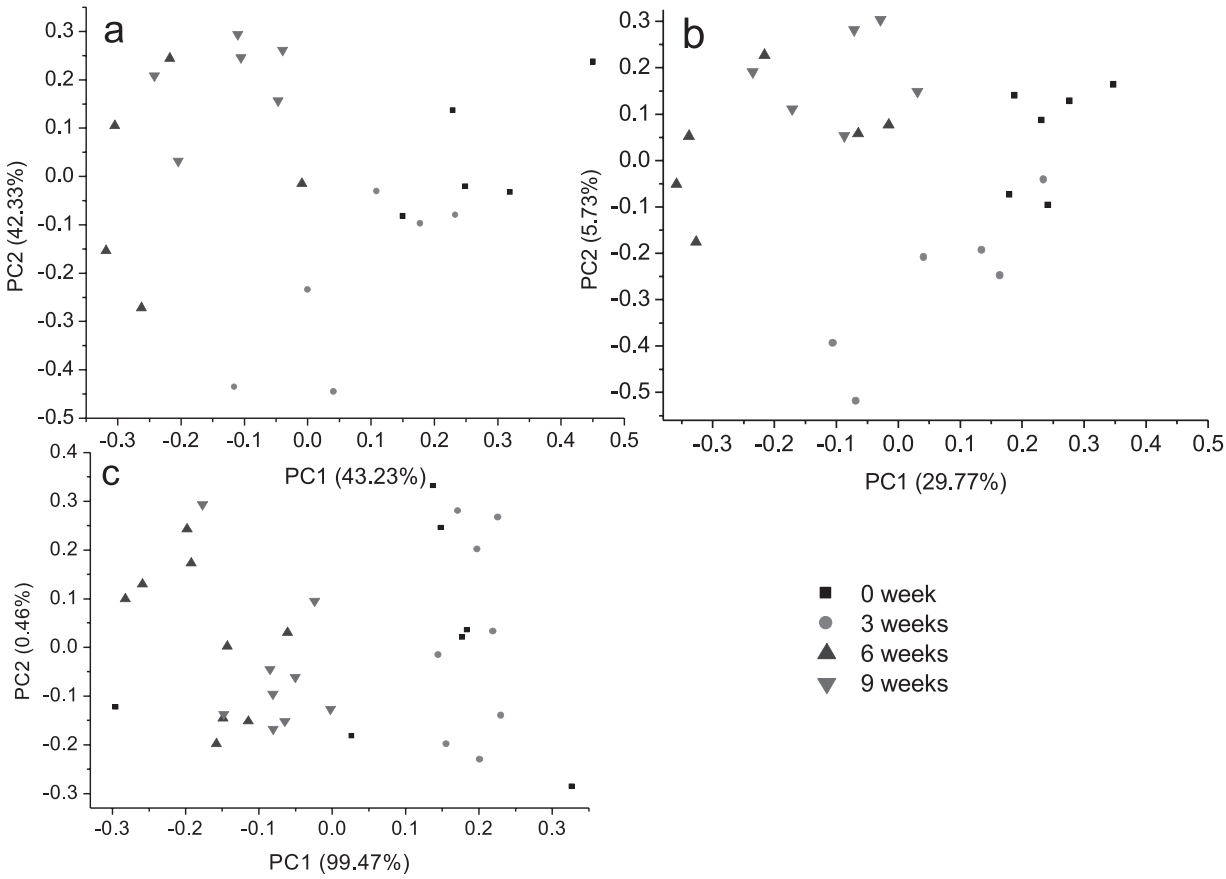

Figure 6.—Principal component (PC) 1 versus PC2 of (a) modulus of elasticity, (b) modulus of rupture, and (c) internal bond for PCs that had been pretreated with the first derivative.

Table 3.—Near-infrared reflectance–based multivariate models of MOE, MOR, and IB.[a]

Properties	Pretreatment	PCs	RMSECV	R^2	RPD
MOE	First derivative	5	0.44	90.57	1.53
MOR	First derivative	5	3.56	97.63	1.72
IB	First derivative	4	0.10	69.43	0.94

[a] PCs = principal components; RMSECV = root mean square error of cross validation; RPD = ratio of performance to deviation; MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond.

7. The assignments of the absorption bands normally associated with chemical components are summarized in Table 4. The NIR spectra collected in this study represented a great variety of interactions of the radiation along the wavenumber range and the properties of the boards. In turn, MOE, MOR, and IB properties were affected by many variables of the production process of the panels, such as the density and composition of panels, the adhesive content, the panel compression ratio, the paraffin content, and the size of the particles reflected in the slenderness index (Via et al. 2011).

Although the feasibility of the NIR spectroscopy has been shown for MOE, MOR, and IB in other investigations (Meder et al. 2002, Kelley et al. 2005), it was still unclear as to how this technique can be used to evaluate the mechanical properties after extensive humidity and temperature exposure. The regression coefficients presented in Figure 6 show that the mechanical properties (MOE, MOR, and IB) are directly linked with the chemical components within the fiber products (Hein et al. 2011).

Conclusions

The mechanical and physical properties of a commercial OSB were studied after high-temperature and high-humidity treatments in a climate-controlled laboratory with consistent temperature of 76.7°C and 60 percent relative humidity. The bending MOR and MOE decreased, while WA and TS increased significantly ($\alpha = 0.05$) after 3 weeks of treatments. The IB decreased significantly until after 9 weeks of treatment but could be significant with $\alpha = 0.25$ after 6 weeks. Also, there were no significant differences with $\alpha = 0.05$ among the 3-, 6-, and 9-week treatments for MOR, MOE, and TS. These revealed that most of the OSB property changes occurred in the first 3-week treatment. The NIR models showed that the mechanical properties (MOE, MOR, and IB) were directly linked with chemical components of the wood products. The study is useful to understand the physical

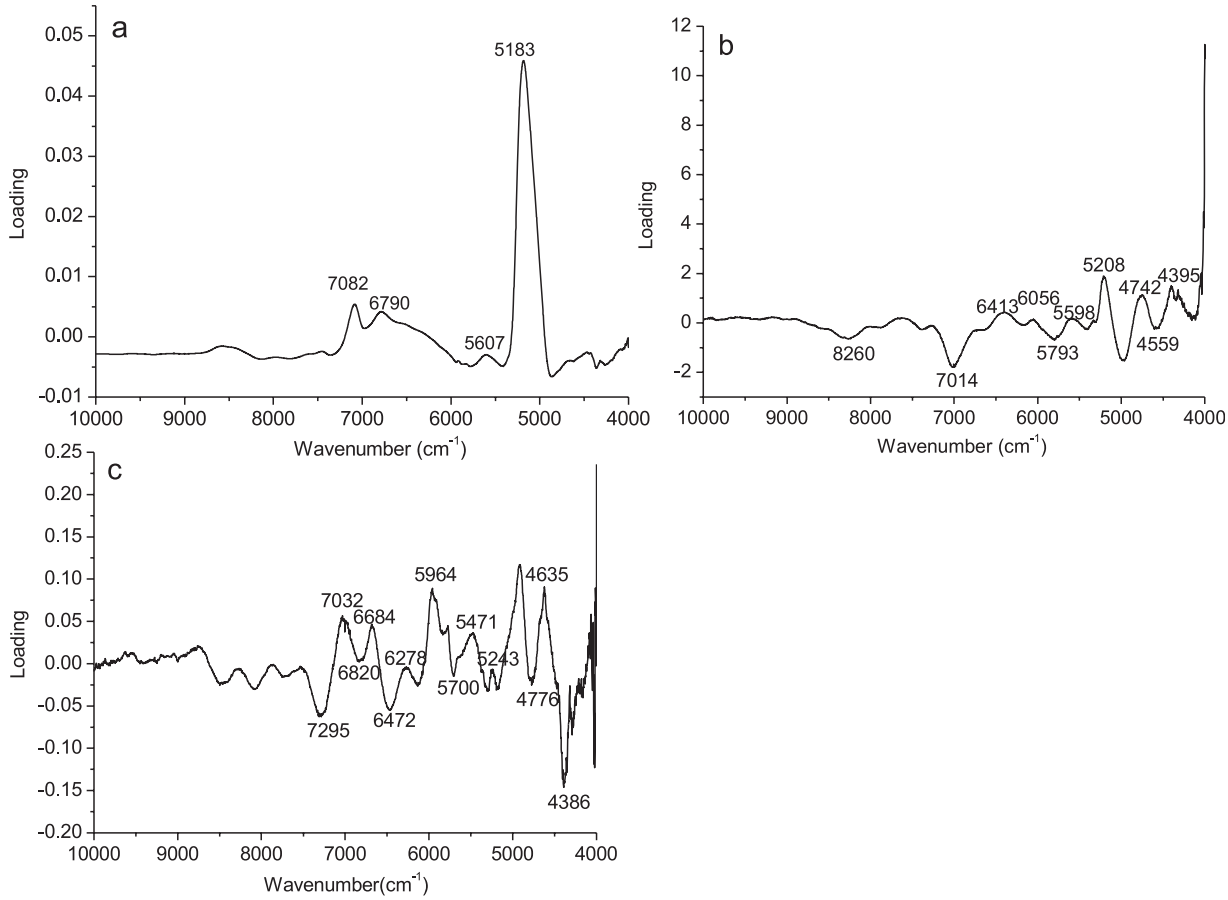

Figure 7.—Coefficients by wavenumber for principal component regression for (a) modulus of elasticity, (b) modulus of rupture, and (c) internal bond when first derivative pretreatment was processed.

Table 4.—Near-infrared reflectance absorption bands assigned to lignin, cellulose, hemicellulose, water, and resin contained in oriented strand board.[a]

Band location wavenumber (cm^{-1})			
PCR	Literature	Component	Bond vibration
		Modulus of elasticity	
7,082	7,073	Water	1st OT O-H str.
6,790	6,790	Cellulose	1st OT O-H str.
5,607	5,618	Cellulose	1st OT C-H2 str.
5,183	5,150–5,220	Water	O-H asym. str. + O-H def. of H_2O
		Modulus of rupture	
4,395	4,392	Cellulose	O-H str. + C-C str. and/or C-H str. + C-H def.
4,559	4,545	PF resin	C-H str.
4,742	4,739	Cellulose	O-H def. + O-H str.
5,208	5,220–5,150	Water	O-H asym. str. + O-H def. of H_2O
5,598	5,593	Cellulose	1st OT C-H str.
5,793	5,795	Lignin	1st OT C-H str.
6,056	6,003	Hemicellulose	1st OT C-H str.
6,413	6,460	Cellulose	1st OT O-H str.
7,014	7,003–6,993	Cellulose/H_2O	1st OT O-H str. + H_2O
8,260	8,250–8,160	Cellulose	2nd OT C-H str.
		Internal bond	
4,386	4,392	Cellulose	O-H str. + C-C str. and/or C-H str. + C-H def.
4,635	4,644	PF resin	C-H str. + def. in benzene groups
4,776	4,780–4,760	Cellulose	O-H and C-H def. + O-H str.
5,243	5,245	Hemicellulose	2nd OT C=O str.
5,471	5,464	Cellulose	O-H str. + 2nd OT C-O str.
5,700	5,776	Cellulose	1st OT C-H str.
5,964	5,963	Lignin	1st OT Car-H str.
6,278	6,281	Cellulose	1st OT O-H str.
6,472	6,472	Cellulose	1st OT O-H str.
6,684	6,700	Hemicellulose	1st OT O-H str.
6,820	6,800	Hemicellulose	1st OT O-H str.
7,032	7,057	Lignin	1st OT C-H str. + C-H bend.
7,295	7,300	Hemicellulose/all	1st OT C-H str. + C-H def.

[a] Wavenumbers assigned to the bands and regression coefficients are presented in Figure 6. PCR = principal component regression; 1st = first derivative; OT = overtone; str. = stretching vibration; asym. = antisymmetric; def. = deformation vibration; 2nd = second derivative; bend. = bending vibration.

and mechanical responses after high-temperature and high-humidity treatments.

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