In-Plane Moisture Content and Specific Gravity Evaluation of Oriented Strandboard Using a Radio Frequency Technique

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Abstract

Oriented strandboard (OSB) is a wood-based composite product with the largest market share for residential and commercial construction. Reliable in-line nondestructive evaluation devices are needed to rapidly determine OSB panel moisture content (MC) and specific gravity (SG) after hot pressing. In this report a radio frequency (RF) scanning technique was used to evaluate the MC and SG of OSB. RF scanning apparatuses were built to test OSB specimens at various MC and SG levels. Statistical models of the results were generated with the multiple linear regression method for estimating OSB MC and SG. The results indicated that the MC and SG of OSB can be estimated using RF responses in using voltage attenuation and signal phase shift.

Oriented strandboard (OSB) was developed in the second half of the 20th century as a structural panel that cost less than the panels previously available. Higher cost plywood has lost much of its previous market share to OSB (Goetzl and Ekström 2007). OSB panels are produced from oriented wood strands under high temperature and pressure with the help of adhesives (Walker 2006). Owing to the complexity of the manufacturing process, the physical and mechanical properties of OSB are influenced by many variables, such as raw materials properties, adhesive type, and process parameters. Specific gravity (SG) and moisture content (MC) play an important role in the OSB manufacturing process; they are the two critical variables that manufacturers monitor, locate, and control in order to produce a product with consistent quality (Williamson 2002).

As for all wood products, mechanical properties are significantly influenced by MC. When MC is below the fiber saturation point, normally 30 percent, wood mechanical properties increase with a decreasing MC (Gerhards 1982). Significant decreases in modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength were found in urea-formaldehyde (UF)–bonded particleboard, whereas MC increased from 10 to 15 percent (Halligan and Schniewind 1974). Watkinson and van Gosliga (1990) discovered similar results for UF-bonded particleboard, medium-density fiberboard (MDF), and hardboard. Wu and Suchsland (1997) noted a linear decrease in MOR and MOE with increased MC ranging from about 4.5 to 22 percent in phenol-formaldehyde (PF)–bonded OSB manufactured from both southern pine and aspen.

Wood product mass can be measured in terms of SG or density. Wood density is measured as weight per volume in pounds per cubic foot. The wood MC for density purposes must be specified because of its influence on the weight component of the density computation. SG is introduced to reduce confusion from variations of MC and is defined as the ovendry weight of the mass of dry wood to the equivalent volume of water (Panshin and de Zeeuw 1980).

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In addition to MC variation, density variation significantly influences OSB panel quality. Density variation within the panel plane is defined as horizontal density distribution (HDD), and the density variation across panel thickness direction is termed vertical density distribution (Suchsland 1962).

The HDD of panels immediately following hot pressing is inherited from the mat forming and hot pressing processes. Variation in mat thickness during formation will result in variance in panel HDD. When the mat is processed to a constant thickness during hot pressing, some dense areas and some low-density areas will be generated within the panel. Variance in strand thickness can also contribute to the HDD. Variation in HDD can lead to composite panels of low quality because of differential spring back rate, and thickness swelling between local areas will cause damaging stresses in panels (Suchsland 1962, 1973; Suchsland and Xu 1989, 1991). Unevenly distributed panel SG leads to strand layering and warping after manufacturing. The European EN 300 standard (2001) stipulates that composite HDD should be less than ±10 percent of the average panel density for structural OSB panel.

Wood is a natural dielectric material with complex structure and composition (Torgovnikov 1993). The influence of alternating electric fields on wood is significant, and this has led to commercial application of this concept for estimation of wood MC (Wagner 1996, Steele and Cooper 2004) and for knot and void detection in lumber (Steele and Kumar 1996) with radio frequency (RF) scanning techniques.

RF signals or radio waves refer to that portion of the electromagnetic spectrum in which electromagnetic waves can be generated by alternating current fed to an antenna. The RF electromagnetic spectrum ranges from about 3 KHz to 300 GHz. Microwaves are a subset of RF, with a higher frequency range of from 300 MHz to 3 GHz.

Torgovnikov (1993) demonstrated that wood dielectric properties, such as dielectric constant and loss tangent values, for radio frequencies range from 20 to 1,000 Hz and are strongly influenced by the wood MC and SG. These dielectric properties of wood directly influence the RF responses, such as voltage attenuation and phase shift.

Previous researchers have studied RF signals to estimate MC and SG of wood. Parker and Beall (1986) developed an adjacent capacitance electrode device to measure lumber MC in the range of 4 to 28 percent. Rice et al. (1992) developed a system to detect knots and voids in lumber using noncontacting adjacent electrodes. This system detected the difference in dielectric properties between clear wood, knots, and voids. Seven pairs of adjacent capacitors consistently detected knots and voids in lumber.

Sobue (2000) developed a device with adjacent capacitance electrodes to sense the moisture gradient in wood by using what he termed the electrode scanning moisture analysis (ESMA) method. ESMA determines MC at various depths through wood thickness by manipulating the distance from 11 to 55 mm between adjacent electrodes on a single wood surface. Examination of the capacitance changes developed by manipulation of the electrode distance allowed computation of wood moisture gradient at various depths through wood thickness. This method allowed measurement of MC up to 120 percent. The generated moisture gradient curve based on ESMA measurement gave a good reproduction of the original moisture gradient. Jazayeri and Ahmet (2000) described an adjacent capacitance electrode method, similar to that of Sobue, for detecting transverse moisture gradients in the range of from 7.5 to 24.1 percent in timber. A multiple-planar-electrode arrangement was used to switch the signal between pairs of electrodes at variant spacing to allow MC detection. By using the device, accurate prediction of a real moisture gradient curve has been conducted from capacitance measurement values. The studies of Sobue (2000) and Jazayeri and Ahmet (2000) both graphically showed a good match between predicted MC curves and actual MC curves; however, neither of them reported quantitative accuracy of their devices.

Steele and Kumar (1996) patented a device, the detector for heterogeneous materials (DHM), for detecting specific gravity differences in scanned lumber with the RF capacitance method using a 200-KHz alternating current (AC) signal. The DHM differs from the Parker and Beall (1986) device in that opposed parallel plate detectors rather than adjacent electrodes are used. Since the opposed parallel plate setup showed an effective determination of wood moisture and density, the setup was also used in this study to detect OSB material.

The dielectric response properties of knots, voids, and clear wood differ, and the DHM detects this difference by comparing voltage change within each piece of lumber. Recalibration for clear wood signal at any MC is performed for each piece of lumber based on a proprietary algorithm. For this reason, the bridge circuit component of the Parker and Beall (1986) device is not required. Conversion of amplified analog voltage to digital values and capture by data acquisition system is performed as for the Parker and Beall (1986) device. To date, reports on the DHM state that it has only detected knots and voids (Steele and Kumar 1996).

Wolcott and Rials (1995) used the Eumetrics System III Micro-Dielectric Analyzer by embedding miniature sensors in a formed mat to monitor the in situ cure of a particleboard panel produced with an isocyanate adhesive. They noticed the influence of MC changes to the dielectric responses during the process glue cure and the potential of the dielectric scanning method using real-time detection of adhesive cure. Wang and Winistorfer (2003) developed a technology to nondestructively monitor the bonding development of particleboard during hot pressing using a dielectric system. The conductance of the panel was monitored in real time during hot pressing. They found a significant relationship between impedance signal level and panel strength. Steele and Cooper (2004) described estimating MC and SG in their patent for the moisture and density detector (MDD). This patent claims the potential of using the MDD for determining MC and SG of composite wood products. However, the patent data provided were only for lumber, and no information was provided for a wood composite application.

None of the adjacent or opposed electrode devices for moisture or density detection reviewed above have been commercially used, with the exception of the DHM developed by Steele and Cooper (2004). This device, however, is used exclusively to detect density differences in solid wood products and identify knots and voids. A need exists for a sensing device to simultaneously measure MC and SG of wood composite products. Therefore, the objectives of this research were to (1) study MC and SG effects on RF responses in terms of voltage attenuation and signal phase shift. (2) derive regression equations to estimate SG and MC using the RF responses, and (3) develop an RF dielectric evaluation device to detect MC and SG of OSB composites.

Materials and Methods

Experimental design

An experiment with six SG levels (0.50, 0.57, 0.59, 0.66, 0.69, and 0.74) and seven MC levels (2.5%, 3.5%, 4.5%, 6.9%, 8.5%, 10.1%, and 12%) with two replications for each of 42 combinations was performed. Therefore, a total of 84 specimens were measured individually for their RF responses in terms of voltage attenuation (Att) and signal phase shift (Phase) to derive regression equations for estimation of OSB SG and MC using the RF responses. From the two replications of each of the 42 combinations, one was randomly selected as the model-building data set, with the remaining specimen as the validation data set. OSB specimen sizes measured 5 inches wide by 5 inches deep by 0.5 inch thick. The width and depth of specimens were determined through RF field range simulation and experiment for the various RF sensor shapes and sizes (Liu 2008).

RF testing apparatus

The elements of the apparatus for transmitting the RF field through the OSB specimens are shown in Figure 1. Opposed electrodes of copper plate comprised the RF capacitor with a sending and a receiving electrode. The square sensor measured 4 inches on each side. The specimen thickness was 0.5 inch. The gap between the specimen and the sensor was 0.1 inch. The RF signal was generated with an HP 8647A signal generator and amplified by a 10-W ENI 441LA signal amplifier. The amplified signal with peak-to-peak voltage of 80 V and frequency of 250 kHz was applied to the transmitting electrode producing an electric field sensed by the receiving electrode. The AC signal used in this study was similar to the DHM (Steele and Kumar 1996), which was 28.28 V root mean square (80 V peak-to-peak) and 200 kHz. The amplified signal applied to the sending electrode was simultaneously input to one channel of Tektronix TDS714L digital storage oscilloscope as reference. The signal amplitude in volts and frequency in degrees were displayed on the oscilloscope. The signal received by the receiving electrode was input to the second channel of the oscilloscope. The phase value difference in degrees between the signal input to the sending electrode and that at the receiving electrode was measured automatically by the oscilloscope. The accuracies of the voltage and phase measurements were ± 5 and ± 7.5 percent, respectively. All connecting cables in this apparatus have the same characteristic impedance value of 50 Ω, matching the output and input impedance of all devices in this application.

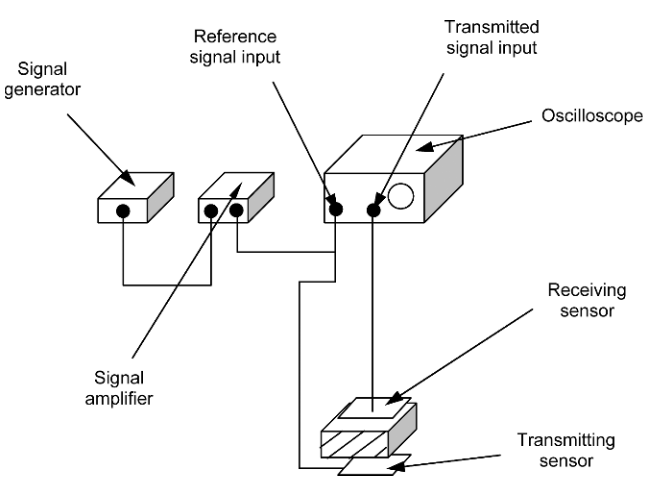


Figure 1.—Diagram of single pair sensors in the radio frequency scanning apparatus.

The phase shift in degree was expressed as the difference in degrees between the phase of the transmitted and the received signal (Eq. 1). The signal voltage attenuation in decibels was measured with the voltage logarithm of the ratio of the signal voltage on the transmitting sensor, $V_{\text{transmitting}}$, to the signal voltage on the receiving sensor, $V_{\text{receiving}}$ (Eq. 2).

$$\text{Phase shift} = \text{Phase}_{\text{transmitting}} - \text{Phase}_{\text{received}} \quad (1)$$

$$\text{Voltage attenuation} = 20 \times \log\left(\frac{V_{\text{transmitting}}}{V_{\text{receiving}}}\right) \quad (2)$$

The actual setup is shown in Figure 2. The scanning table was custom made. A piece of OSB panel (32 by 32 by 0.75 in.) was cut as the base board of the scanning table. Four adjustable legs were fitted at the four corners of the base board. Four supporting wheels were fixed on an OSB strip (22 by 2.75 by 0.5 in.) as a support wheel group. Each supporting wheel group was installed on the base board with three 5-inch threaded bolts. A total of three groups of supporting wheels were installed on the base board. Two pieces of sensor supporting strips (28 by 2.5 by 0.25 in.) were made from Plexiglas. A slot of 24 by 0.5 inches was cut in the center of each supporting strip to enable changing sensor spacing easily. The two supporting strips were installed on the base board with two 9-inch threaded bolts. Figure 3 shows a schematic cross view of the RF apparatus for better visualization. All the heights or distances between supporting wheels groups and sensor supporting strips can be easily adjusted.

OSB panel fabrication

Southern yellow pine OSB strands (3.4 by 0.4 by 0.07 in.) were obtained from Norboard Mississippi Inc., Guntown, Mississippi. PF resins and wax were obtained from Georgia-Pacific Resins, Inc., Louisville, Mississippi. Two PF resin solid contents, 60 and 50 percent, were used for the core

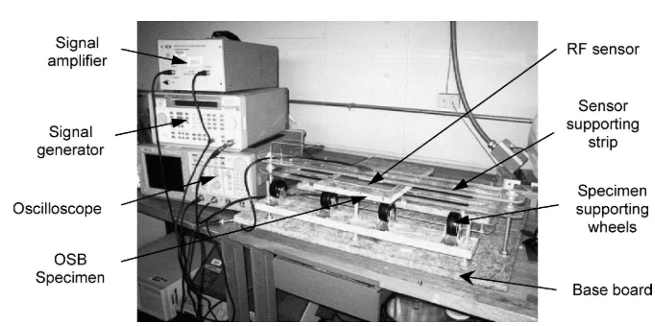


Figure 2.—The actual radio frequency scanning apparatus.

layer and surface layer, respectively. The emulsion-type solid content of the wax was 50 percent.

OSB strands were dried in a drum dryer to reach an MC below 4 percent based on the wood ovendried weight. After drying, the strands were put into a rotary blender with the rotary speed of 22 rpm. Wax and resin were injected into the blender by means of a peristaltic pump. An air-compressed spray nozzle (Spraying System Co.) sprayed the emulsion-type wax onto the strands. A spinning-disk type atomizer (Coil Model EL-2, 1,047 rad/s [10,000 rpm]) sprayed resin onto the strands following the wax application. The total blending time was approximately 15 minutes.

Core and surface layer strands were blended with wax and resin separately in terms of their different solid contents. The layer constructions of top, core, and bottom layer were 30, 40, and 30 percent of total dry furnish weight, respectively. The strands were hand formed in random orientations with a 30 by 30-inch wooden forming box.

The formed mats were then hot pressed in a Dieffenbacher hot press. The platen temperature was 210°C (410°F), and the pressing time was 4 minutes. Following hot pressing the OSB panels were air cooled to room temperature and edges were trimmed to 24 by 24 inches dimension specimen. OSB specimens were stored in a 12 percent equilibrium moisture content (EMC) conditioning room for 2 months.

Relative humidity conditioning

OSB specimens were conditioned to seven levels of MC conditions with saturated salt solutions in sealed tanks at constant temperature of 20°C according to ASTM E104-02 (ASTM International 2002), ASTM D4933-99 (ASTM International 2004), and the method reviewed by Greenspan (1977). EMC data of wood-based composite products listed in Table 1 were used as reference (Greenspan 1977, ASTM 2004). The EMC data used in this study for each specimen were obtained by the oven drying method.

The seven targeted MC levels of OSB specimens were obtained by conditioning the 84 OSB specimens in seven relative humidity conditioned chambers. Each of the 24 by 24-inch OSB panels was previously stored in the 12 percent EMC conditioning room for 2 months. Prior to storage in the smaller salt-conditioned relative humidity chambers, the 24 by 24-inch specimens were cut into three 5 by 5-inch specimens.

The conditioning chamber used in this study is shown in Figure 4. Seven commercially available 10-gallon (20 by 12 by 10.5-in.) aquarium fish tanks were obtained, and a 20 by 10.5-inch lid of 1/10-inch thickness was fitted. Dow Corning high vacuum grease was applied around the edges between the fish tank and the lid to seal the tank. A fan (3 by 3 in. square, RadioShack) was installed on the lid and inside the tank to provide good air circulation and expedite establishment of EMC in the OSB specimens. A glass baking tray (12 by 8 by 2 in.) placed in the bottom of the tank held the saturated inorganic salt solution. A plastic rack supported the OSB specimens above the salt solution and also separated the specimens to ensure good air circulation. To ensure the salt solution was oversaturated, the presence of salt crystals was monitored every 2 days during the conditioning process. Adequate amounts of inorganic salt were added when the redundant salt crystal was found dissolved.

Regression models

The multiple linear regression (MLR) method was applied to analyze RF responses and derive equations to estimate MC and SG using Att and Phase. Tests for normality of the Att and Phase were performed. The model-building data set was fitted to several linear models by the least squares method, and then the best-fitted linear model was selected with the stepwise regression method (Mendenhall and Sincich 1989). The resulting models were then applied to the validation data set to test the robustness of the prediction models. Finally, the best-fitted regression models

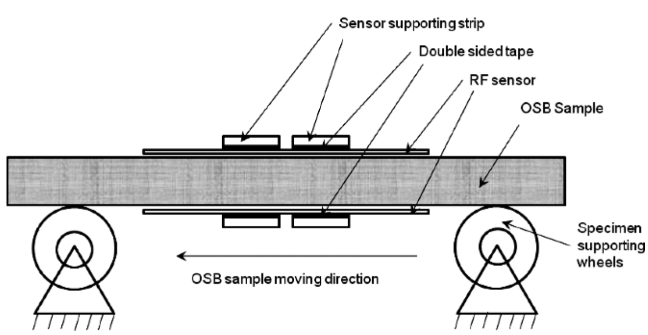


Figure 3.—Schematic cross section of radio frequency scanning apparatus.

Table 1.—EMC data for composite wood products (Greenspan 1977, ASTM International 2004).[a]

Saturated salt solution	RH (%)	EMC (%)
Zinc bromide ($ZnBr_2$)	7.94 ± 0.49	1.5–2
Lithium chloride (LiCl)	11.31 ± 0.31	2–3
Potassium acetate (CH_3COOK)	23.11 ± 0.25	2–6
Magnesium chloride ($MgCl_2$)	33.07 ± 0.18	5–7
Potassium carbonate (K_2CO_3)	43.16 ± 0.33	5–8
Magnesium nitrate ($Mg(NO_3)_2$)	54.38 ± 0.23	7–9
Sodium nitrite $NaNO_2$	75.36 ± 0.35	9–11

[a] EMC = equilibrium moisture content; RH = relative humidity.

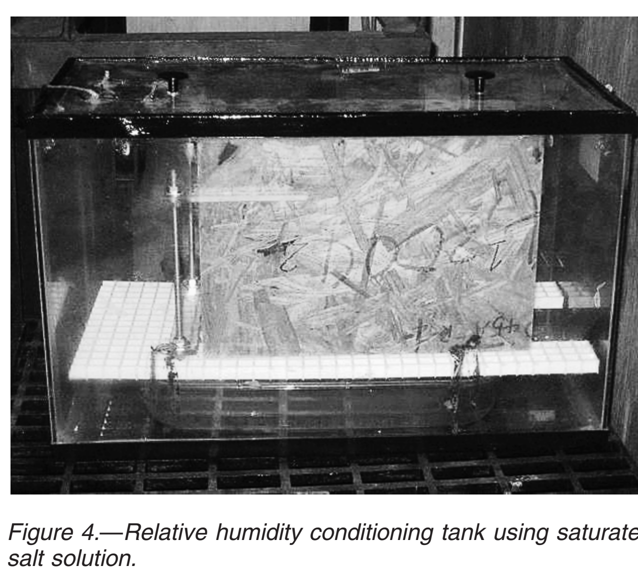


Figure 4.—Relative humidity conditioning tank using saturated salt solution.

were evaluated for estimation performance by comparing the estimated and the measured MC and SG. Statistical analyses were performed with statistical software package (SAS Institute 2006). Unless otherwise specified, all statistical analyses in this study were performed at a significance level (alpha) of 0.05.

Results and Discussion

Data normality testing

The Univariate procedure of SAS (2006) was used to conduct the data normality test on both model-building and validation data sets. The data for all 42 model-building samples and 42 validation samples were tested for normality. Results of the Shapiro-Wilk test (Kutner et al. 2005) indicated that the normality assumption for each variable, Att and Phase, were confirmed with a *P* value greater than 0.05. The normality probability plot for each of two predictors, Att and Phase, of both model-building and validation data sets was a straight line, which indicated the variable was normally distributed.

Model selection

Figures 5 and 6 show the scatterplots of predictor variables Phase and Att versus MC and SG of model-building specimens, respectively. Attenuation had a clear linear relationship with MC (Fig. 5a). In Figure 6a, attenuation showed clear linear relationships with SG at different MC levels, which indicated the attenuation might be a function of both SG and MC. Therefore, MC and SG are not independent variables, and while predicting SG, MC should be included in the model. There was a slightly curved relationship between phase shift and MC. However, no clear trend can be identified between phase shift and SG.

A stepwise regression method selected the optimum estimation models for MC and SG. The scatterplots of MC and SG residuals versus predicted MC and SG of the selected models (Fig. 7) indicated there was no significant nonconstancy of the error variance. Both MC residuals and SG residuals were normally distributed as well. Hence, the error terms of two models for estimating MC and SG all satisfied the normality assumption.

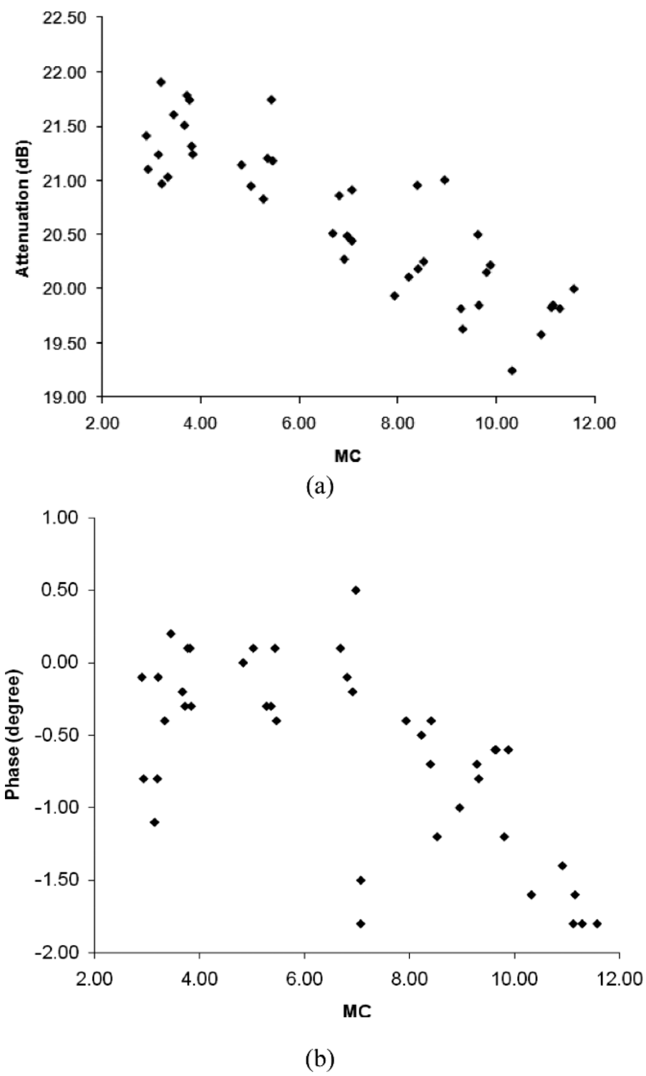


Figure 5.—Scatterplot of (a) attenuation and (b) phase against moisture content for relative humidity conditioning method specimens.

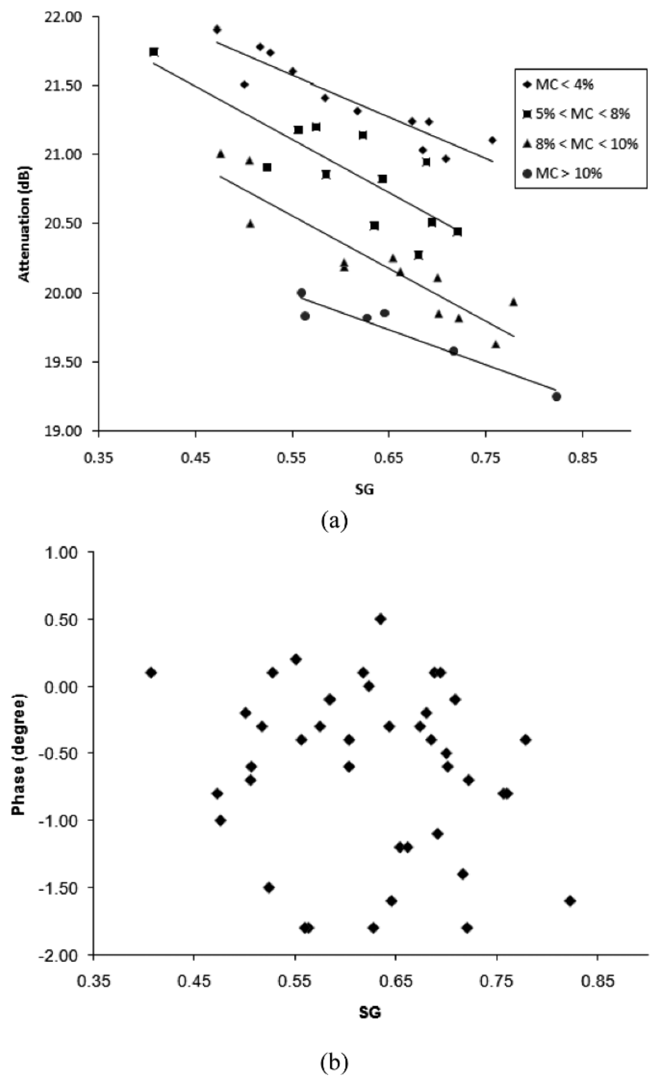


Figure 6.—Scatterplot of (a) attenuation and (b) phase against specific gravity for relative humidity conditioning method specimens.

Model validation

The 42 validation samples' data sets were used to validate the previously generated regression models based on the model-building data set. The predicted residual sums of squares, the sum of squares, and the coefficient of determination (R^2) values from the models of both model-building and validation data sets were compared, and the differences are relatively small (Kutner et al. 2005). This indicated that the models generated from the model-building data set had the ability to estimate MC and SG with the validation data set. The mean squared prediction error (MSPR) was close to the mean square error (MSE) for both MC and SG prediction. The closeness of MSPR and MSE indicated the high predictive accuracy of fitted regression models for both MC and SG estimation.

Final regression model

After the models have been validated, it is appropriate to use the data sets of all samples for generating the final regression models (Kutner et al. 2005).

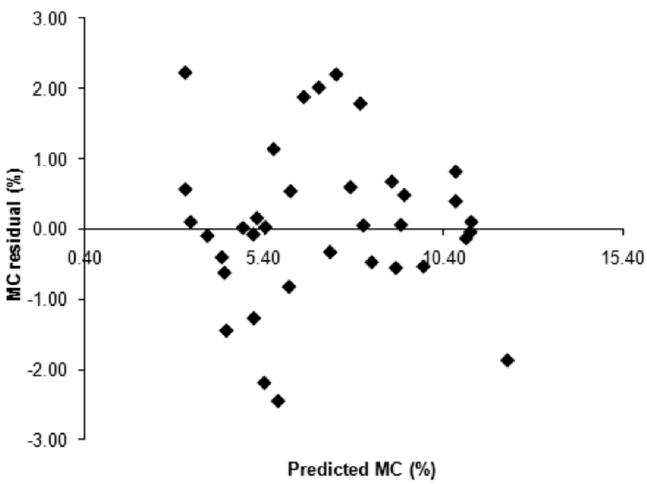
$$\begin{aligned}\mathrm{MC} = &-11403 + 1665.637\mathrm{Att} - 80.843\mathrm{Att}^2 \\ &+1.305\mathrm{Att}^3 + 0.571\mathrm{Phase}^2 \qquad (\text{Model1})\end{aligned}$$

$$\begin{aligned}\mathrm{SG} = &\ 6.0375 - 0.2505\mathrm{Att} - 0.0071\mathrm{MC}^2 \\ &+0.00032\mathrm{MC}^3 \qquad (\text{Model2})\end{aligned}$$

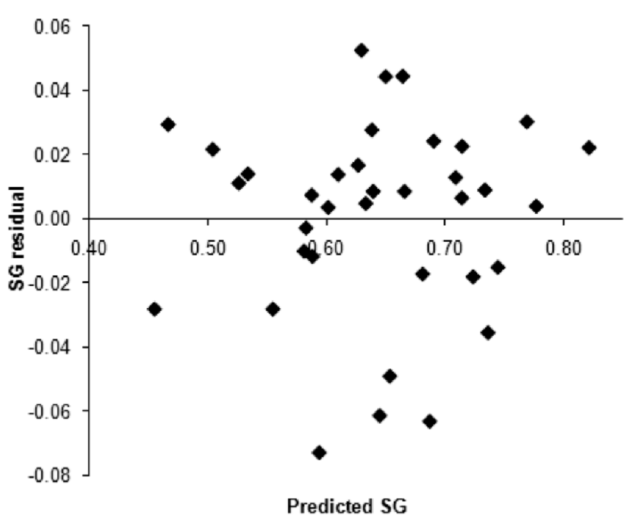
where

MC = moisture content (%),
SG = specific gravity,
Att = voltage attenuation (dB), and
Phase = phase shift (degrees).

The R^2 values for Model 1 (MC) and Model 2 (SG) are 0.87 and 0.89. The scatterplots of observed and predicted MC and SG values are shown in Figure 8. The regression lines for the MC and the SG regression model are close to a straight line, which indicates the MC and the SG models are appropriate

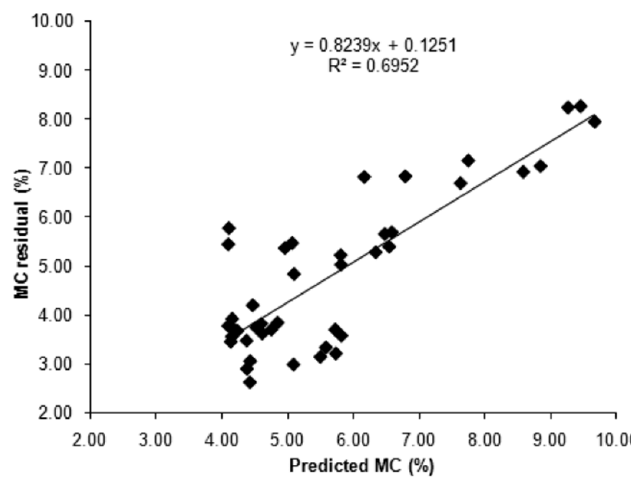


(a)

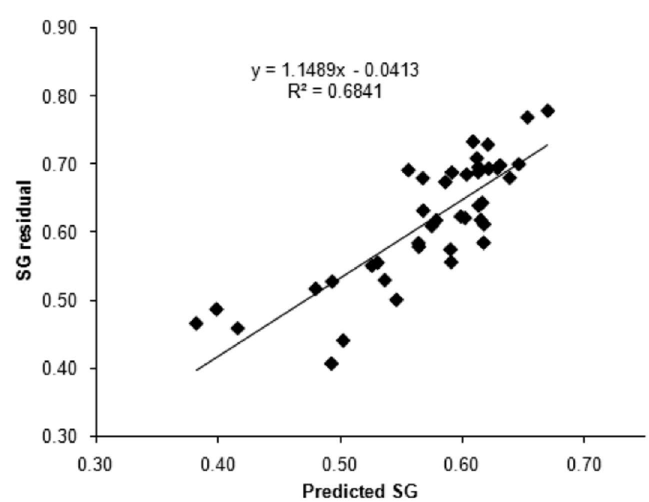


(b)

Figure 7.—(a) Moisture content and (b) specific gravity residual versus predicted values of regression equation generation data for relative humidity conditioning specimens.



(a)



(b)

Figure 8.—(a) Observed moisture content (MC) against predicted MC and (b) observed specific gravity (SG) against predicted SG for relative humidity conditioning method specimens.

for predicting the MC and the SG values. The models also suggest that the MC needs to be first estimated based on Att and Phase, and then the SG can be predicted by Att and MC.

Conclusions

The radio frequency (RF) scanning method was evaluated experimentally as a potential nondestructive evaluation tool to measure the MC and SG of OSB panel products. The MLR method was used to derive regression models including significant RF signal responses, attenuation, and phase shift to estimate MC and SG of OSB.

The following conclusions can be made from this study. (1) MC and SG estimation models derived from RF scanning data using the procedure conducted in this study can be used to estimate MC and SG of OSB composites simultaneously. (2) The RF scanning method is an effective technique to nondestructively evaluate the OSB MC and SG. Further research along these lines should eventually lead to the development of a multiple sensor RF scanning device, which could be used as an in-line real-time MC and SG detector for the OSB industry.

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