Journal of Testing and Evaluation, Vol. 40, No. 1
Paper ID JTE103895
Available online at: www.astm.org

C. R. Boardman,[1] *Samuel V. Glass,*[2] *and Charles G. Carll*[3]

Moisture Meter Calibrations for Untreated and ACQ-Treated Southern Yellow Pine Lumber and Plywood

---

ABSTRACT: This study investigates the effects of alkaline copper quaternary (ACQ) preservative treatment and of plywood glue lines on resistance-based moisture content (MC) measurements. Moisture meter readings using stainless steel screws as electrodes were acquired over a range of moisture conditions in Southern Yellow Pine (SYP) lumber and plywood. Calibration equations are presented for predicting gravimetric MC from meter readings taken in SYP lumber and SYP plywood with or without ACQ treatment. These corrections assume that the meter has been set for SYP. Correlation equations are also presented for directly relating resistance to gravimetric MC, which may be useful for automated data collection systems employed in monitoring moisture levels in buildings. The conductance of SYP lumber was raised by treatment with ACQ, particularly at higher moisture contents, but was unaffected by vacuum-pressure treatment with water. The conductance of untreated SYP plywood, measured with electrodes penetrating the glue lines, exceeded that of untreated SYP lumber. The conductance of SYP plywood was lowered by treatment with ACQ, by vacuum-pressure soaking with water, and by exposure to rain. We suggest that electrolytes in the plywood glue lines increase the conductance of untreated plywood relative to that of untreated lumber, and that the concentration of these electrolytes is lowered by the (aqueous) preservative treatment process, thereby lowering the conductance of these high-conductance pathways.

KEYWORDS: moisture meter, electrical conductance, moisture content, calibration, plywood, alkaline copper quaternary, southern yellow pine, resistance

Introduction

Moisture meters are often used to determine wood moisture content (MC), the ratio of the mass of water in wood to the mass of oven-dried wood. The commonly used conductance-type meter measures wood conductance (or more typically, its reciprocal the electrical resistance) between two or more electrodes inserted into the wood. A calibration that depends on wood species is used to calculate the MC from the measured resistance. Many wood species are well studied, and calibration curves are built into the instruments [1]. Although engineered wood products, such as plywood and oriented strand board, have been used in residential construction for a few decades, meter calibration curves for such products are not readily available.

Plywood is used extensively for floor decking, where it may be subjected to rain wetting before the building is enclosed (more specifically, before a functional roof is in place). Unlike adhered wood products fabricated from strands or flakes, plywood is suitable for pressure treating with waterborne preservatives, and pressure-treated softwood plywood (in North America, generally fabricated from Southern Yellow Pine (SYP)) is a common commercial product. Meter corrections for SYP plywood, both untreated and commercially treated with alkaline copper quaternary (ACQ), have recently been presented by Glass and Carll [2], with the corrections generally being of considerable magnitude. The relationship between moisture content and electrical resistance has also recently been reported as different for untreated SYP plywood than for SYP lumber [3] and as different for CCA (type C)-treated SYP plywood than for SYP lumber, whether untreated or treated with CCA-C [4]. All of these recent investigations were either in support of a field study [2], or as sidebars to field or case studies [3,4]. Although the three investigations concur with regard to general trends, none could be considered comprehensive. Until these three recent investigations, there was limited published work concerning the electrical conductance of plywood, all of it having been published at least three decades ago.

During the 1970s, Palka and Hejjas [5] presented a meter calibration equation for plywood derived from measurements taken in failed (broken) mechanical test specimens, with meter readings taken on the failed surfaces with short pin electrodes, and with care taken to avoid penetration of glue lines with the meter electrodes. This technique would not be feasible when making repetitive measurements in buildings, particularly when using automated data collection systems. Elevated electrical conductance in phenolic-bonded plywood has been known since the late 1940s [6], but has apparently not been widely recognized. Bell and Krueger [6] reported that moisture meter readings in phenolic-bonded Douglas-fir plywood were higher than gravimetric moisture contents when meter electrodes penetrated the glue

Manuscript received April 4, 2011; accepted for publication August 16, 2011; published online September 2011.

[1] General Engineer, Forest Products Laboratory, U.S. Forest Service, 1 Gifford Pinchot Dr., Madison, WI 53726.

[2] Research Physical Scientist, Forest Products Laboratory, U.S. Forest Service, 1 Gifford Pinchot Dr., Madison, WI 53726.

[3] Research Forest Products Technologist, Forest Products Laboratory, U.S. Forest Service, 1 Gifford Pinchot Dr., Madison, WI 53726.

lines. Observations similar to those of Bell and Krueger were not reported in the literature until recently [2–4]. The recent work of Simpson et al. [7] indicates that phenolic-bonded laminated veneer lumber (LVL) shows significantly greater conductivity than the wood from which it is fabricated, and that readings taken in LVL with a resistance moisture meter thus require substantial correction. Advice provided by meter manufacturers [8] regarding measurements taken in plywood does not address the effect of glue lines. Given the practicality of penetrating glue lines when using a moisture meter, further investigation concerning meter corrections for measurements made in SYP plywood was deemed justified.

As indicated previously, the investigation by Glass and Carll [2] yielded corrections for meter readings taken in untreated plywood and in commercial ACQ-treated plywood, with the corrections developed to support a field study. The field study [9] for which the corrections were developed involved readings taken in untreated pine boards, untreated SYP plywood, and ACQ-treated SYP plywood. As the field study did not involve readings taken in treated lumber, no attempt was made to develop meter corrections for treated lumber. Several studies [10–12] indicate that ACQ-treated pine lumber has higher conductance than untreated lumber. In light of this, the observation (by Glass and Carll [2]) that ACQ-treated plywood showed lower conductance than untreated plywood at equivalent equilibrium moisture contents appears counterintuitive. Further investigation of this observation was a key motivation for this new study.

Different commercial formulations of ACQ [13] might reasonably be expected to differ with regard to how they influence the conductance of wood and wood-based products treated with them as the formulation of CCA (type C, or oxide formulation as opposed to type A, or salt formulation) has been shown to influence conductance of treated wood [14,15]. One shortcoming of the work by Glass and Carll [2] was that the ACQ formulation in the commercially treated plywood investigated was not documented (although the retention of copper was measured and found to be in accord with the end-use for which the treated plywood was marketed). This manuscript continues the work of Glass and Carll [2], but with a focus on the effect of the plywood glue line. The new investigation included laboratory vacuum-pressure treatment of both lumber and plywood with ACQ of known formulation. It also attempted to isolate the effect of the (waterborne) treatment process from the effect of addition of treatment chemical. In addition, resistance measurements (made with a megohmmeter or a multimeter) were taken in SYP lumber and plywood and correlated to gravimetric moisture content. The resistance/MC correlations are of potential use to building researchers who wish to use automated data collection systems; such systems generally do not incorporate moisture meters.

Materials and Methods

Study Overview

Data from the previous investigation by Glass and Carll [2] are included in this manuscript. These measurements had been taken in untreated SYP dimensioned lumber, in untreated plywood, and in ACQ-treated plywood (purchased commercially, in which treatment had been performed by a commercial treater). The more thorough investigation described in this manuscript, hereafter termed "this study," involved laboratory treatment of SYP lumber and of SYP plywood. In each case (lumber and plywood), treatment was with ACQ-D according to an industry-recognized vacuum-pressure treating protocol. The formulation of ACQ-D incorporated solubilized copper (not "micronized"), and a carbonate (not chloride) quaternary compound. Matched specimens were also treated with water according to the same protocol. This permitted isolating the effect of the treatment process from the effect of addition of treatment chemical.

This study also included treatment of SYP lumber specimens with ammoniacal copper zinc arsenate (ACZA) to provide an additional set of data points (for another waterborne preservative). ACZA has retained EPA registration as a restricted-use wood preservative. It is used for woods (most commonly Douglas-fir) in which adequate preservative penetration is an issue. It is a preservative whose influence on conductance of wood had not, to our knowledge, been previously investigated.

This study also included outdoor exposure of SYP plywood specimens, on sleepers above a gravel-ballasted flat roof, for a seven-week period beginning in mid-April. The purpose was to expose the plywood to rain in a manner similar to what might be experienced on the floor deck of a house during construction.

Finally, this study also included direct resistance measurements, with either a megohmmeter or a multimeter, in subsets of the lumber and plywood specimens. Measurements were made over a range of moisture contents. These direct resistance measurements complement the moisture meter readings, allowing development of prediction equations for gravimetric moisture content as a function of resistance.

Specimens

Lumber—Lumber specimens in the previous investigation had been untreated. Their characteristics have been described previously [2]. All could be characterized as juvenile wood (rapidly grown wood from near the center of the tree). Forty pieces of SYP lumber, all of them composed of sapwood, were selected to provide specimens for this study. The pieces were from a variety of sources: some from nominal 2 by 4 lumber, some from nominal 1 × lumber, and some from nominal 5/4 stair tread. Growth characteristics in this sample of lumber varied; the sample included some specimens that clearly were not juvenile wood. Lumber pieces derived from nominal 2 by 4 and nominal 5/4 lumber were planed to 19 mm thickness; lumber from nominal 1 × lumber was 19 mm thick, and was not planed further. Three specimens, each 89 mm wide by 102 mm long, were cut from each lumber piece, yielding a total of 120 specimens. Specimens derived from 2 by 4 and 1 × lumber were cut sequentially from along the length of the piece ("end-matched"), whereas specimens derived from 5/4 stair tread were usually cut sequentially from across the width of the piece ("side-matched"). From each set of 40 original lumber pieces, one specimen was selected for evaluation without treatment, one for vacuum-pressure treatment with water (VPT-W), and one for vacuum-pressure treatment with ACZA. A set of evaluations, involving equilibration at a variety of conditions followed by meter readings and gravimetric measurements, were made on the untreated specimens, after which they were vacuum-pressure treated with ACQ, and again evaluated. An exact specimen match was thus obtained for the effect of ACQ treatment as compared with no treatment. Average specific gravity of the lumber specimens, based on oven-dry mass and volume at 10% MC, was 0.55 ± 0.07.

Vacuum-pressure treatment was performed according to a standard industry protocol, consisting of vacuum application at 20 kPa absolute pressure (−81 kPa gauge) for 30 min, followed by pressurization at 1034 kPa for 60 min.[4] For both ACQ and ACZA treatments, 0.63 wt. % solution was used, and target retention was 4 kg/m^3 active ingredient (as prescribed for above-ground end-uses). The nominal ACQ and ACZA active chemical retentions were 3.1 ± 0.7 and 3.7 ± 0.4 kg/m^3, respectively, measured by weight gain after treatment. As determined from copper content measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES), average ACQ retention (CuO + Quat) in the specimens was 3.3 kg/m^3, and average ACZA retention was 2.8 kg/m^3. Uniformity of chemical distribution within specimens after treatment was confirmed by visual inspection of selected samples after conditioning and evaluation.[5] Following vacuum-pressure treatment, specimens were allowed to air dry in the treatment room for a day. Groups of eight specimens were subsequently conditioned to five different equilibrium moisture contents for each of the four treatment "plans" (untreated, ACQ treated, ACZA treated, and VPT-W).

Plywood—Plywood specimens in the previous investigation had been either untreated or commercially treated with ACQ of known retention but undocumented formulation. Their characteristics have been described previously [2]. For this study, 80 additional plywood specimens were cut from the same two plywood panels used to supply untreated specimens for the previous investigation. Specimen size in this investigation, 102 mm by 102 mm, was reasonably similar, but smaller than in the previous investigation. Oven-dry specimen mass ranged from 85 to 125 g, and average specific gravity based on oven-dry mass and volume at 11% MC was 0.50 ± 0.03. Two different laboratory "treatments" were applied to the plywood specimens, both of which followed the same vacuum-pressure protocol as for the lumber ACQ treatment. One group of 40 underwent laboratory treatment with ACQ; the remaining 40 underwent VPT-W. The ACQ treatment was with the same formulation and concentration as for the lumber specimens. Uniformity of chemical distribution within plywood specimens after treatment was expected given the small specimen size and the lathe checks in veneer sheets, which enhance preservative penetration. This was confirmed by visual inspection of selected samples after conditioning and evaluation, and the limited differences in weight gain between specimens.[6] Nominal active chemical retention was 3.9 ± 0.2 kg/m^3. As determined from copper content measured by ICP-AES, average ACQ retention (CuO + Quat) in the specimens was 3.4 kg/m^3.

A third set of 36 specimens was obtained from two 102 mm wide by 2.44 m long strips that had been exposed to outdoor conditions on a rooftop for seven weeks beginning in mid-April of 2010. These strips had been cut from the same original untreated panels. During exposure, the specimens were secured to 38 mm wide wood sleepers spaced roughly 0.5 m apart. Electrogalvanized screws were used to secure the strips to the sleepers. Over the exposure period slightly over 155 mm of rain fell. Specimens measuring 102 mm by 102 mm were cut from the strips at the end of the exposure period. The average specimen moisture content at the end of rooftop exposure (which was on a rainy day) was 51 ± 4%, indicating the specimens had been wetted above fiber saturation. The electrogalvanized screws were noticeably rusty at the end of the exposure period suggesting that high moisture content conditions had been present for considerable lengths of time. Screw holes were not included in the specimens cut from the strips.

Moisture Conditioning—Specimens were equilibrated near room temperature at relative humidity levels between 32% and 85% RH. Typical values were around 35%, 50%, 65%, 75%, and 85%. Conditions were attained by use of mechanically controlled environmental rooms, environmental chambers, or saturated salt solutions. Conditions in the environmental rooms were monitored with data loggers and were found to be stable within ±1% relative humidity (RH) of the mean. Conditions in the chambers could vary up to ±5% RH, but the 10 min average was stable within ±1% RH of the mean. Saturated salt solutions (NaCl and KCl) were prepared in polypropylene containers with approximate dimensions 580 mm by 430 mm by 150 mm. Specimens were suspended above the solution in a given container, each container was placed in a room maintained at 22 ± 1°C, and the lids were sealed with aluminum foil tape. Equilibrium relative humidity values over saturated NaCl and KCl salt solutions are 75% and 85% RH, respectively [16].

Gravimetric Moisture Measurement—Gravimetric wood moisture content was calculated in the usual manner as the difference between conditioned mass and oven-dry mass, divided by oven-dry mass. At a given relative humidity, the conditioned specimen was considered stable when the difference in mass over a 24-h period was less than 0.05%, typically after approximately

---

[4] The treatment protocol, although recognized by an industry standard, involved longer periods of vacuum and of pressure application than are common for commercial ACQ treatment of wood products for above-ground applications. Further, inasmuch as the specimens were short and composed entirely of sapwood, complete treatment penetration was expected.

[5] After completion of the study, a few treated specimens were cut in half, approximately at mid-specimen thickness, for inspection. There was no visual indication of nonuniformity of treatment.

[6] After completion of this study, a 25% sample of the treated plywood specimens was selected for inspection of treatment uniformity. These specimens were cut in half at approximately mid-specimen thickness. There was no visual indication of nonuniformity of treatment. Variation in weight gain between specimens after treatment was less than 7%. Finally, in the previous study [2], where multiple pairs of screw electrodes were inserted in commercially treated plywood specimens, within specimen variation of meter readings had been limited.

2 months of conditioning. Specimens were oven-dried at 105°C after moisture meter and resistance measurements were complete. The oven-dry specimen was considered stable when mass change was less than 0.05% over a 4 h period, typically after a few days in the oven. All specimens were weighed on a top loading balance with readability of 0.001 g.

Instrumentation

Electrodes—This study was conducted in support of building research, and instrumentation was selected on the basis of several considerations. Uninsulated electrodes were chosen to detect the location of highest conductance or greatest moisture content through the thickness of the material. Additional considerations were ease of installation in the field, corrosion resistance, and reliable long-term contact with the wood over changing moisture conditions. Dai and Ahmet [17] and ASTM [18] have reported that predrilling holes and using threaded screws improves the long-term contact between the electrodes and wood.

Electrodes selected for the study were stainless steel #6 sheet metal screws 16 mm long with hexagonal washer heads. The stainless steel alloy was nonmagnetic; it was one of the 300 series stainless steel alloys with nominal composition of 18 wt. % chromium and 8 wt. % nickel. For leads to connect the screw electrodes to the moisture meter, uninsulated ring terminals were soldered to 24 AWG insulated copper wires. The screws and ring terminals were uninsulated, thus making contact with both the wood surface and wood interior (Fig. 1). The screws were driven 16 mm into the wood so that the washer heads pushed the ring terminals into the wood surface. Holes for the screw electrodes were predrilled using a 2.4 mm drill bit and a template machined from mild carbon steel, with two holes each 2.4 mm in diameter spaced 31.8 mm on center.

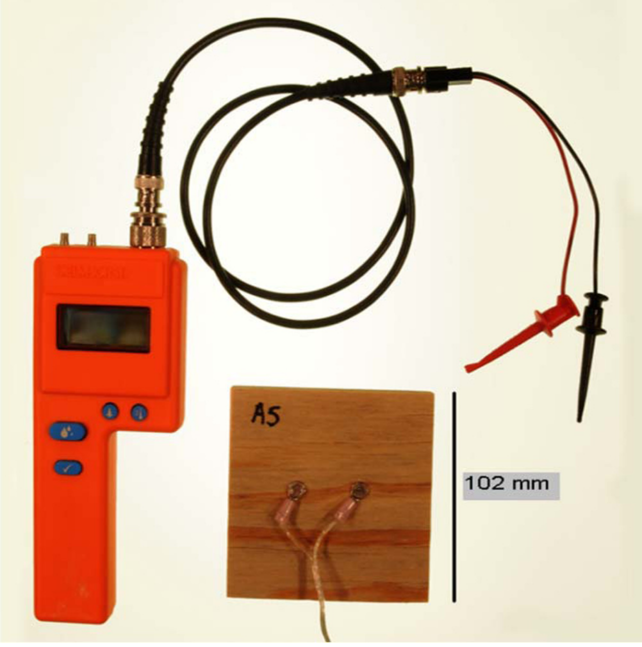

FIG. 1—*Moisture meter and specimen.*

In the previous investigation, each specimen had four pairs of electrodes so that moisture readings could be obtained in multiple locations within a specimen. Readings within individual specimens had, for the most part, been within 1% MC of each other, and the largest difference in readings within an individual specimen had been 2% MC. This within-specimen variation was evidently less than experienced by Palka and Hejjas [5] with short pin electrodes. Based on the limited within-specimen variation observed during the previous investigation, a single set of screw electrodes was placed in each specimen for this study (Fig. 1). Each hole pair was aligned parallel to the grain (in the case of lumber) or parallel to the grain of the surface ply (in the case of plywood).

Moisture Meter—A handheld Delmhorst model J-2000 digital conductance moisture meter (Delmhorst Instrument Co., Towaco, NJ) was used to acquire moisture content readings in combination with a modified cable assembly. The modification involved connecting a minihook clip to each wire from the cable assembly such that the minihook clips could then be easily attached to lead wires (Fig. 1). The meter measures conductance and displays readings as percentage moisture content. It can be set to display moisture content readings for a number of different species; for this study the meter was set for SYP. The meter also has a setting for temperature correction. For this study, the moisture meter was referenced to a temperature of 21°C, whereas the laboratory in which readings were taken was maintained at 22°C ± 1°C. The meter's temperature correction can be set in increments of 3°C, so the difference between the actual temperature and the meter setting need not exceed 1.5°C. The potential error arising from such a temperature offset amounts to less than 0.3% MC for the moisture content range in this study [1]. Two of the environmental rooms in which specimens were conditioned were maintained at 27°C. After specimens were equilibrated in these rooms, they were sealed in polyethylene bags, transferred to the laboratory maintained at 22°C, and allowed to reach thermal equilibrium prior to moisture meter readings (the meter being referenced to 21°C as for the other groups). Moisture meter readings for these specimens were also taken in the 27°C environmental room (with the meter referenced to 27°C) prior to readings in the 22°C room (with meter referenced to 21°C). Meter readings at 22°C differed from those at 27°C by less than 0.2% MC on average, the readings at 22°C being higher on average.

The species calibration for SYP that was internal to the meter was identified (checked), by comparing a series of meter readings over a range of 9.1%–34.5% with the corresponding measured resistance values (from a configurable resistance box). Although the moisture content range was not identical to that of James [1], the meter calibration nonetheless concurred with the resistance/moisture content values that he reported for longleaf pine (*P. palustris*) or shortleaf pine (*P. echinata*), using two-pin meter electrodes spaced at 32 mm and driven to a depth of 8 mm. James' published data points are shown in Fig. 2, as are our data points for the meter calibration check. The correlation equation to approximate resistance R (Ω), given the meter reading (MC), is

$$R = 10^{\left(4.396 + 10^{(30-MC)/29.44}\right)} \qquad (1)$$

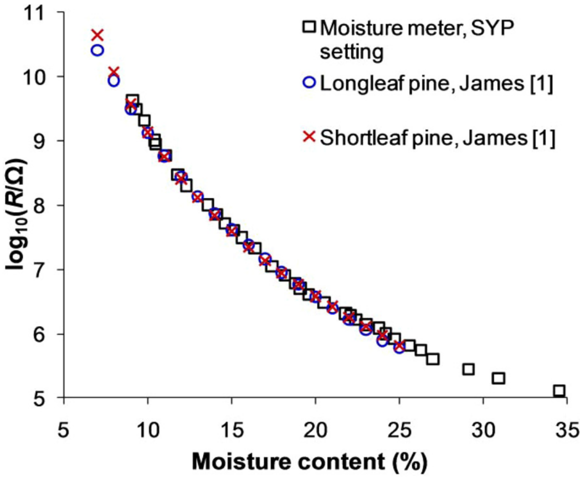

FIG. 2—*Logarithm of resistance versus moisture content for the moisture meter's internal SYP setting and for two species of the SYP group as reported by James [1].*

Resistance Measurements—Two different techniques were used for obtaining resistance measurements in specimens. In either technique, electrode configuration on specimens was the same as for measurements taken with the moisture meter—stainless steel screws with ring terminals attached to lead wires—and hence in contact with both the wood surface and wood interior (as the ring terminals were held in contact with the wood surface by the screw heads, and no portion of either the screw shank or head was insulated). One of the measurement techniques used a megohmmeter, with a 50 V test voltage applied across the specimen. Duration of voltage application to the specimen varied, and was typically on the order of 5 s. Duration was of sufficient length to provide a stable (nontransient) reading. When successive readings were taken on a given specimen (a few seconds apart), the sequential readings were similar, but increased with each sequential reading, indicating polarization within the specimen. Data collected by this method were thus limited to one reading per specimen. This technique was the first one we used. We used it on a subset of the plywood specimens, specifically on plywood treated with ACQ and plywood vacuum-pressure treated with water.

The second technique for measuring resistance involved applying 10 V to a circuit consisting of a 1 MΩ precision resistor in series with the specimen, measuring voltage across the precision resistor with a multimeter, and calculating resistance of the specimen by voltage division for the series circuit. This technique was automated to take four sequential readings (each taking $\approx$1 s), with polarity of the applied voltage being automatically reversed between sequential readings. Final resistance was calculated from the average of the four sequential readings. This technique was used on a subset of the lumber specimens, specifically on untreated lumber and on lumber treated with either ACQ or ACZA. We prefer this technique because it is capable of rapidly obtaining multiple readings that are unaffected by polarization. Although we prefer the second technique to the first, either technique yielded readings that concurred with readings taken with the moisture meter. Concurrence could be determined inasmuch as we had ascertained the internal meter calibration for SYP. Resistance measurements made using either of the techniques permitted development of prediction equations for gravimetric moisture content based on resistance at room temperature.

Results

Moisture Meter Calibrations Lumber

Lumber—Measurements in untreated lumber in the previous study had indicated that internal meter corrections for SYP are adequate and work acceptably for the electrode configuration investigated [2]. Measurements in untreated lumber in this study, which as implied previously involved a substantially larger number of specimens from a wider variety of sources, concurred with the earlier findings. In addition, we found no difference between the untreated lumber specimens and those that were VPT-W. Results for lumber from the previous investigation and this investigation are shown in Fig. 3, which plots moisture meter readings against gravimetric moisture content. The data fits for untreated SYP and for VPT-W SYP are each linear. In addition, the least-squares fit for untreated specimens is virtually identical to that for VPT-W specimens. Each fit line is only slightly above the 1:1 correspondence line, and essentially parallel with it. We expected that vacuum-pressure treatment with water would not materially influence conductance values of re-conditioned SYP lumber. The plots in Fig. 3 confirm that expectation.

In contrast, data points in Fig. 4 for ACQ-treated and for ACZA-treated lumber indicate that the treatments generally raise specimen conductance, particularly in specimens at higher moisture content levels. The data fits for treated lumber are not linear; they curve upward with increasing levels of reconditioned specimen moisture content.

Plywood—Results for plywood from both the previous investigation [2] and this study are shown in Fig. 5. The data fits for untreated plywood, VPT-W plywood, and rain exposed

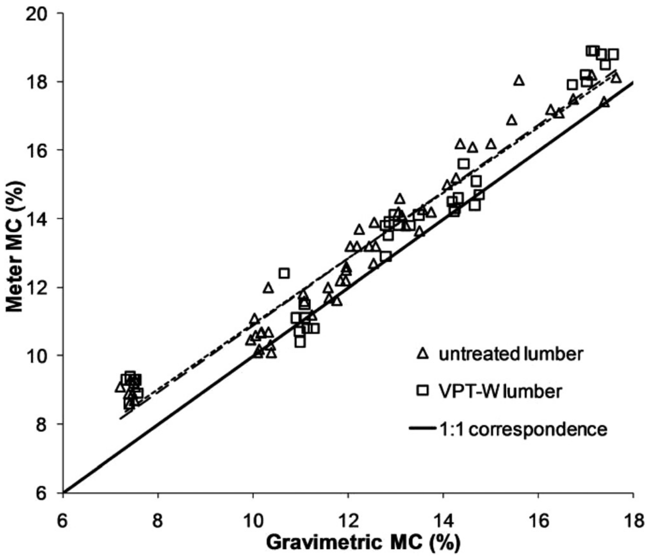

FIG. 3—*Lumber results: moisture meter reading versus gravimetric moisture content.*

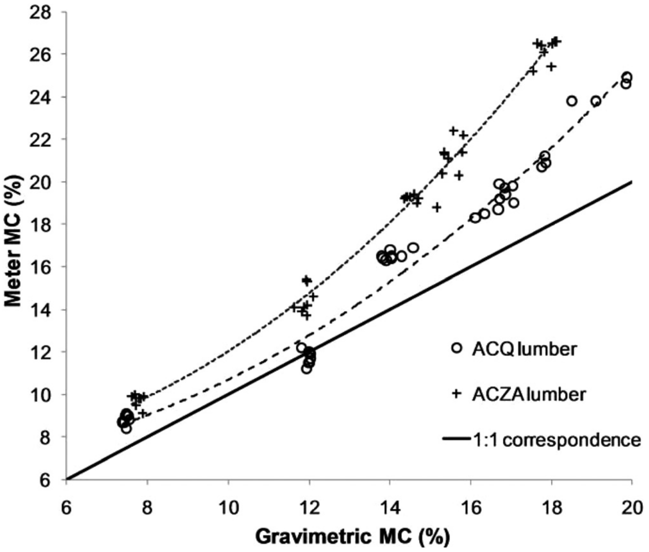

FIG. 4—*Lumber results: effect of preservative treatment.*

plywood are each linear. Least-squares fit lines for untreated plywood, VPT-W plywood, and rain-exposed plywood are shown in Fig. 5. All of these are above the 1:1 correspondence line, and have slopes greater than 1, indicating increasingly greater divergence from the correspondence line as reconditioned moisture content increases. Of the three fit lines, the one for untreated plywood is furthest from the correspondence line, and the one for rain-exposed plywood is nearest to the correspondence line. It is thus evident that water exposure of plywood results in lowered effective conductance values in reconditioned specimens.

The data points for ACQ-treated plywood (both commercially and laboratory treated) are shown in Fig. 6. Conductances of these plywoods are similar to the conductances of rain-exposed or VPT-W plywood at low and medium moisture contents, but are higher than the conductances of rain-exposed or VPT-W plywood at higher moisture contents. As was the case for treated lumber, the data trends for treated plywood are not linear; meter readings curve upward with increasing levels of reconditioned gravimetric moisture content.

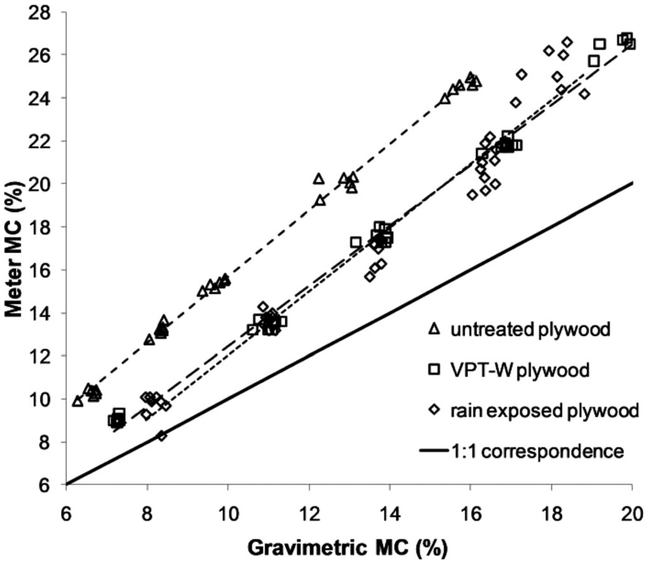

FIG. 5—*Plywood results: effect of wetting.*

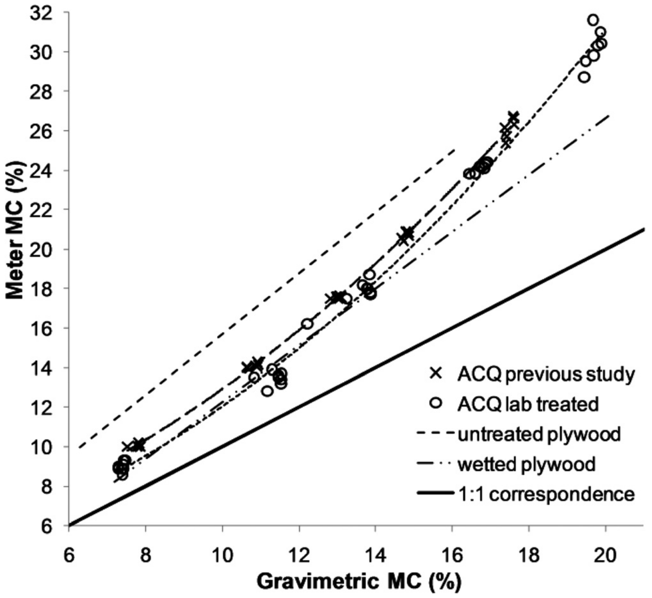

FIG. 6—*Plywood results: effect of chemical treatment.*

Meter Correction Equations—As indicated by Figs. 4–6, corrections are necessary for readings taken in plywood (whether the plywood is treated or not) and for readings taken in treated SYP lumber. Linear trends in data for untreated plywood, VPT-W plywood, and rain-exposed plywood indicate that linear correction equations are suitable for readings taken in these materials. In contrast, upward curvature in the trends for treated lumber and for treated plywood precludes use of linear correction equations. The data for treated materials can however be made linear by taking the square root of the moisture meter value. This allows use of correction equations using the following form:

$$\mathrm{MC_{grav}} = A + B \times \sqrt{\mathrm{MC_{meter}}} \tag{2}$$

Correction equations for plywood (untreated, ACQ-treated, and wetted[7]) are provided in Table I, as are correction equations for untreated, ACQ-treated, and ACZA-treated SYP lumber. The data trend for specimens of commercial ACQ-treated plywood was nearly identical to that for specimens of laboratory ACQ-treated plywood (Fig. 6).[8] A single correction equation for ACQ-treated plywood, based on pooled data from both investigations, is thus provided in Table I.

---

[7] The fits for VPT-W plywood and rain-exposed plywood are similar, so pooled data from both VPT-W and rain-exposed specimens are presented in Table 1 as "wetted plywood." Note that the slopes for the correlations in Table 1 are less than one because the calibration equation predicts $\mathrm{MC_{grav}}$ (y) given $\mathrm{MC_{meter}}$ (x), whereas Figs. 3–6 switch the axes. For comparison, the intercept and slope at 95% confidence for fit to only VPT-W plywood samples were 1.1 ± 0.3, 0.71 ± 0.02; for rain-exposed plywood they were 0.9 ± 0.7, 0.75 ± 0.07.

[8] For comparison, the intercept and slope at 95% confidence for fit to only commercial ACQ-treated plywood [2] were -8.1 ± 0.3, 5.0 ± 0.1; for laboratory ACQ-treated plywood they were -6.9 ± 0.6, 4.8 ± 0.1.

TABLE 1—*Equations for predicting gravimetric moisture content (MC_{grav}) from meter readings (MC_{meter}).*

Lumber Type	Calibration Equations	Gravimetric Range (MC%)	Prediction Error (MC%)
Untreated lumber[a]	$MC_{grav} = -1.3 + 1.03\ MC_{meter}$	7–18	± 1.5
ACQ-treated lumber	$MC_{grav} = -10.1 + 6.1\sqrt{MC_{meter}}$	7–19	± 1.8
ACZA-treated lumber	$MC_{grav} = -7.7 + 5.1\sqrt{MC_{meter}}$	7–18	± 1.0
Untreated plywood	$MC_{grav} = -0.2 + 0.65\ MC_{meter}$	6–16	± 0.6
Wetted plywood[b]	$MC_{grav} = 1.2 + 0.72\ MC_{meter}$	7–20	± 1.0
ACQ-treated plywood	$MC_{grav} = -7.5 + 4.9\sqrt{MC_{meter}}$	7–20	± 0.8

[a] Calibration equation for untreated lumber is based on pooled data for untreated lumber and lumber vacuum-pressure treated with water (VPT-W).

[b] Calibration equation for wetted plywood is based on pooled data for VPT-W plywood and rain-exposed plywood.

Resistance Calibrations

Lumber—The resistance measurements follow a nonlinear curve similar to Fig. 2 when plotting the base 10 logarithm of resistance against gravimetric moisture content and of course show the same trends as in Figs. 3 and 4 when comparing the various treatments. We provide a fit of our measured data in the following form:

$$MC_{grav} = 30 - A \times \log_{10}[\log_{10}(R) - B] \qquad (3)$$

where:

R = resistance (Ω),

A and B = fit parameters.

The A and B coefficients for untreated and treated lumber at room temperature are in Table 2.

Plywood—The plywood resistance measurements are also fit to Eq 3. The A and B coefficients for untreated, ACQ-treated (both commercial and laboratory), and wetted (both VPT-W and rain-exposed) plywood at room temperature are in Table 2. Direct resistance measurements were not taken for untreated plywood; hence the resistance was calculated from the moisture meter reading using Eq 1.

Discussion

Both the previous investigation [2] and this study indicated that correction was essentially unnecessary for meter readings taken in untreated SYP lumber with the electrode configuration (employing stainless steel screws) used in these investigations. The least-squares fit of the regression line for meter reading versus gravimetric moisture content was very close to the 1:1 correspondence line and essentially parallel with it (see Fig. 3 in Glass and Carll [2] and Fig. 3 in this study). Nevertheless, regression lines in each phase were above the correspondence line, indicating that the screw electrodes, which held the ring terminals in contact with the surface, resulted in slightly higher conductance than assumed by the internal calibration of the meter. The degree to which the regression lines concur with the 1:1 correspondence line can be quantified by using a statistical method described by Berthouex and Brown [19]. The method used involves translating the error for a given meter reading into an error for predicted gravimetric moisture content, using the 95% confidence band for the regression line. Figure 7 shows the upper and lower limits of this band for the regression line based on the data for untreated lumber from this study. To determine the error in a given meter reading, we first calculated the 95% confidence interval that contained the true value of the moisture meter reading 90% of the time based on a single observation. Then using the band we translated this 95% confidence interval for the moisture meter reading into a 95% confidence interval for gravimetric moisture content; we performed this calculation for three points on the calibration line, and the 95% confidence intervals are shown as horizontal error bars in Fig. 7. These error bars overlap the line of one-to-one correspondence indicating that the calibration built into the meter is in adequate agreement with the regression line for untreated lumber (developed for the screw electrode configuration used in this investigation). Maximum prediction errors for each correction equation were individually determined by finding the largest horizontal error bar in the range of data points used to create each fit line. Prediction errors are given in the rightmost column of Table 1.

Our SYP lumber results are similar to those of a study by Blakemore et al. [10] of ACQ treated radiata and slash pine, where meter readings were found to be high (indicating greater conductance) after ACQ treatment, and where the degree of error (overestimation of moisture content) was found to increase with increasing moisture content. Similar results have also been found

TABLE 2—*Parameters for predicting gravimetric moisture content (MC_{grav}) from resistance (R) using $MC_{grav} = 30 - A \log_{10} (\log_{10} (R) - B)$.*

Lumber Type	A	B	Gravimetric Range (MC%)
Untreated lumber[a]	30.0	4.256	7–18
ACQ-treated lumber	27.5	3.607	7–19
ACZA-treated lumber	27.1	2.993	7–18
Untreated plywood	30.0	2.889	6–16
Wetted plywood[b]	30.0	3.535	7–20
ACQ-treated plywood	27.5	2.910	7–20

[a] Parameters for untreated lumber are based on pooled data for untreated lumber and lumber vacuum-pressure treated with water (VPT-W).

[b] Parameters for wetted plywood are based on pooled data for VPT-W plywood and rain-exposed plywood.

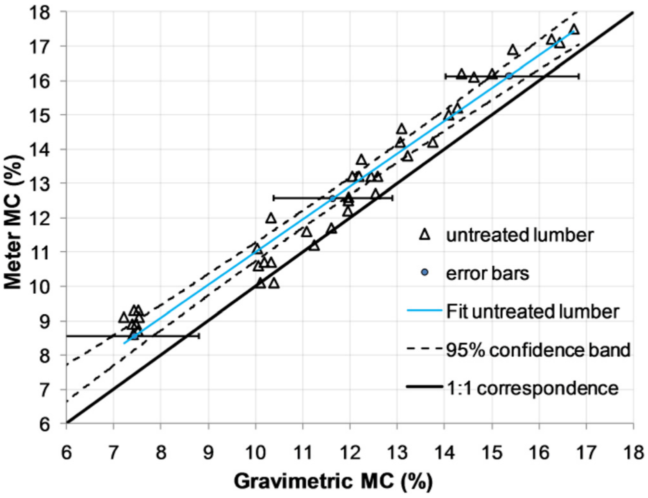

FIG. 7—*Lumber results with error bars showing overlap with line of 1:1 correspondence.*

in SYP sapwood by Smith et al. [12] and radiata pine by Kear [11]. Our data for lumber VPT-W indicates that the treatment process by itself (without treatment chemical) does not affect the conductance of lumber. In contrast, addition of the waterborne treatment chemicals, ACQ or ACZA, clearly increases conductance of the wood. These treatment chemicals contain metal ions, which evidently do not become wholly fixed (and thus immobile) within the wood. The increase in conductance is more pronounced in ACZA-treated lumber than in lumber treated with ACQ-D (at least for the formulation of ACQ-D and the chemical retentions investigated in this study). In contrast, the oxide formulation of chromated copper arsenate (CCA-C) does not result in measurable increases in wood conductance [15], presumably because the metal ions become fixed to a greater extent. ACQ- treated wood is known to have a greater amount of leachable copper and a higher degree of copper dissociation than wood treated with CCA-C [20]. These findings together lend support to some of the hypothetical explanations suggested by Zelinka and Rammer [21] for increased rates of fastener corrosion in wood treated with ACQ or ACZA as compared with that in wood treated with CCA-C.

The more pronounced increase in conductance at progressively higher wood moisture content may stem from an increase in ion mobility or from an increase in the number of dissolved ions at higher wood moisture contents. Previous measurements of ion mobility in wood by Lin [22] and by Langwig and Meyer [23] indicate that ions migrate in response to an electric field when wood moisture content is above 16%–18% MC, but that no net migration occurs at lower moisture contents. Zelinka et al. [24] suggest that a mechanism with charge carriers other than mineral ions, such as protons, may be responsible for conduction below this threshold of $\sim 16\%$ MC. An increase in ion mobility with increasing moisture content would be consistent with the percolation model of Zelinka et al. [24], which suggests that the aqueous pathways for ionic conduction in wood are more interconnected at higher moisture content. The alternative explanation, that the increased conductance at progressively higher wood moisture contents arises from an increase in the number of dissolved ions (an increase in the degree of dissociation), would be consistent with the model of Hearle [25].

We suggest that the elevated conductance of SYP plywood can be similarly interpreted. The glue lines in contemporary construction plywood (which is typically phenolic bonded) are evidently more conductive than the wood. The enhanced conductance may result from electrolytes in the glue lines; phenol-formaldehyde adhesives used in contemporary construction plywood generally contain sodium hydroxide. If the glue lines are penetrated by the electrodes used for measurement, the conductance of the plywood will exceed that of the wood from which it was fabricated. As stated previously, the high conductance of phenolic-bonded plywood has evidently been known for decades, although it apparently has not been well recognized. Our data indicate that increased conductance of SYP plywood (relative to SYP) is less pronounced at low moisture contents than at higher moisture contents. Our data further indicate that the conductance of plywood is lowered considerably if it has previously been exposed to substantial wetting (soaking or moderate term rain exposure), but that these exposures do not bring conductance down to the levels of (untreated) SYP lumber. The observed behavior is consistent with the following explanation: electrolytes in the glue lines provide high- conductance pathways, and, upon exposure of the plywood to water (including aqueous treatment processes), the concentration of electrolytes in the glue lines is lowered, thereby lowering the conductance of these high conductance pathways. At low moisture contents the conductance of ACQ-treated plywood, measured with screw electrodes, is similar to that of untreated plywood previously exposed to substantial wetting. In contrast, at high moisture contents ACQ-treated plywood has substantially higher conductance than does previously soaked untreated plywood. At higher moisture contents, the effect of the added treatment chemical evidently dominates the conductance of treated plywood.

Finally, it should be emphasized that the correlation equations presented in Tables 1 and 2 are for uninsulated screw electrodes. In general the conductance (and hence moisture content reading) is higher for screw electrodes than for more traditional insulated moisture pins that contact the wood at a particular depth. Screw electrodes allow finding the path of least resistance between the two contacts at any depth thus showing the highest moisture content in the wood. Use of insulated moisture pins should not change the general conclusions about the effects of ACQ treatment, but would complicate moisture determination in plywood as these correlations assume the glue lines are in contact with the electrodes.

Conclusions

Preservative treatment of both lumber and plywood with ACQ alters the electrical conductance of these materials when measured with screw electrodes. In the case of lumber, the conductance is increased due to the addition of ions, which can carry charge, with the effect being most pronounced at high moisture contents. In the case of plywood, when measured with electrodes that penetrated gluelines, ACQ-treatment lowers the conductance. A likely explanation for the lowered conductance is that the treatment process, which is aqueous, lowers the concentration of electrolytes in the plywood's gluelines. Conductance of southern pine plywood was found to be higher than that of southern pine lumber, indicating that the gluelines are high conductance pathways. Wetting the plywood (with or without ACQ-treatment) resulted in lowering its conductance compared to nonwetted specimens at equivalent reconditioned moisture contents.

Readings taken in SYP lumber treated with ACQ-D or in SYP plywood treated with ACQ-D will each require correction, with the corrections differing. The needed correction for readings taken in ACQ-treated plywood is influenced by both the aqueous treatment process (which reduces effective conductance in the specimen) and the counteracting influence of the treatment chemical (which increases conductance). Correction equations for treated SYP lumber and both treated and untreated SYP plywood are provided to allow accurate prediction of gravimetric moisture content based on moisture meter readings. Prediction equations for gravimetric moisture content of untreated and treated SYP lumber and plywood, each as a function of resistance, are also provided. These may be of use to building researchers who wish to monitor moisture conditions over extended time periods using data collection hardware other than a moisture meter.

Acknowledgments

This manuscript was improved by critical comments from Samuel Zelinka of the USDA Forest Products Laboratory (FPL), William Rose of the University of Illinois, and two anonymous reviewers. The writers gratefully acknowledge the help of many FPL colleagues during the course of this investigation, including Stan Lebow, Patricia Lebow, Charles Frihart, Daniel Foster, Steve Halverson, and Robert Munson.

References

[1] James, W. L., "Electric moisture meters for wood," *General Technical Report No. FPL-GTR-6*, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 1988, http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr06.pdf (Last accessed 28 March 2011).

[2] Glass, S. V., and Carll, C. G., "Moisture meter calibration for untreated and ACQ-treated southern yellow pine plywood," *Research Note No. FPL-RN-0312*, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2009, http://www.fpl.fs.fed.us/documnts/fplrn/fpl_rn312.pdf (Last accessed 28 March 2011).

[3] Drumheller, S. C., and Carll, C. G., "Effect of Cladding Systems on Moisture Performance of Wood-Framed Walls in a Mixed-Humid Climate," *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference*, Clearwater Beach, FL, Dec 5–9, 2010, http://www.fpl.fs.fed.us/documnts/pdf2010/fpl_2010_drumheller001.pdf (Last accessed 28 March 2011).

[4] Carll, C. G., Boardman, C. R., and Olson, C. L., "Case Study: Performance of a House Built on a Treated Wood Foundation System in a Cold Climate," *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference*, Clearwater Beach, FL, Dec 5–9, 2010, http://www.fpl.fs.fed.us/documnts/pdf2010/fpl_2010_carll002.pdf (Last accessed 28 March 2011).

[5] Palka, L. C., and Hejjas, J., "Calibration of moisture-meter readings for Douglas-fir plywood," *For. Prod. J.*, Vol. 26(12), 1976, pp. 47–48.

[6] Bell, E. R., and Krueger, N. T., "Effect of plywood glue lines on the accuracy of moisture-meter indications," *Proceedings of the National Annual Meeting of the Forest Products Research Society*, Grand Rapids, MI, May 2–4, 1949, Forest Products Research Society, Madison, WI, Vol. 3, pp. 85–91.

[7] Simpson, I., Riley, S., and Ball, R., "Moisture Meter Correction Figures for J-Frame LVL Framing," New Zealand Forest Research Institute (Scion), Rotorua, New Zealand, 2009, http://www.jnl.co.nz/Shared/Documents/Moisture%20Meter%20Correction%20Figures.pdf (Last accessed 28 March 2011).

[8] "Using a Moisture Meter for Flooring Applications FAQ, Question 10: Does the Glue Used in Plywood Affect Meter Accuracy?" http://www.delmhorst.com/popups/floor_faq.html#q10 (Last accessed 28 March 2011).

[9] Glass, S. V., Carll, C. G., Curole, J. P., and Voitier, M. D., "Moisture Performance of Insulated, Raised, Wood-Frame Floors: A Study of Twelve Houses in Southern Louisiana," *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference*, Clearwater Beach, FL, Dec 5–9, 2010, http://www.fpl.fs.fed.us/documnts/pdf2010/fpl_2010_glass002.pdf (Last accessed 28 March 2011).

[10] Blakemore, P., Morrow A., and Ngo, D., "Moisture Meter Corrections for ACQ Treated Pine," *Project No. PN07.2045*, Forest & Wood Products Australia Limited, Melbourne, Australia, 2008.

[11] Kear, G., "The Influence of Timber Treatment Preservative Systems on the Performance of Commercial Moisture Meters," *BRANZ Study Report No. 161*, BRANZ Ltd., Judgeford, New Zealand, 2006, http://www.branz.co.nz/cms_show_download.php?id=41186d854cef8e53621bc4470b8d3322e58f6306 (Last accessed 28 March 2011).

[12] Smith, W. B., Yeo, H. M., Stark, C., Morey, B., Tascioglu, C., Schneider, P., Herdman, D., Freeman, M.,"Use of Moisture Meters with Treated Wood," *Proceedings of the 38th Annual Meeting of the International Research Group on Wood Protection*, *2007*, *Document No. IRG/WP 07-40382*, Stockholm, Sweden, IRG Secretariat.

[13] Lebow, S. T., "Wood Preservation," *Wood Handbook*, *General Technical Report No. FPL-GTR-190*, Forest Service, Forest Products Laboratory, U.S. Dept. of Agriculture, Madison, WI, 2010, Chapter 15, http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_15.pdf (Last accessed 28 March 2011).

[14] James, W. L., "Effects of Wood Preservatives on Electric Moisture-Meter Readings," *Research Note No. FPL-0106*, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 1980, http://www.fpl.fs.fed.us/documnts/fplrn/fplrn106.pdf (Last accessed 28 March 2011).

[15] Richards, M. J., "Effect of CCA-C Wood Preservative on Moisture Content Readings by the Electronic Resistance-Type Moisture Meter," *For. Prod. J.*, Vol. 40(2), 1990, pp. 29–33.

[16] Greenspan, L., "Humidity Fixed Points of Binary Saturated Aqueous Solutions," *J. Res. Natl. Bur. Stand., Sect. A*, Vol. 81A(1), 1977, pp. 89–96.

[17] Dai, G., and Ahmet, K., “Long-Term Monitoring of Timber Moisture Content Below the Fiber Saturation Point Using Wood Resistance Sensors,” *For. Prod. J.*, Vol. 51(5), 2001, pp. 52–58.

[18] ASTM D4444-08, “Standard Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters,” *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2008.

[19] Berthouex, P. M., and Brown, L.C., *Calibration, Statistics for Environmental Engineers*, 2nd ed., Lewis Publishers (CRC Press) Boca Raton, FL, 2002, Chap. 36, pp. 319–325.

[20] Waldron, L., Cooper, P.A., and Ung, T.Y., “Prediction of Long-Term Leaching Potential of Preservative-Treated Wood by Diffusion Modeling,” *Holzforschung*, Vol. 59, 2005, pp. 581–588.

[21] Zelinka, S. L., and Rammer, D. R., “Review of Test Methods Used to Determine the Corrosion Rate of Metals in Contact with Treated Wood,” *General Technical Report No. FPL-GTR-156*, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2005, http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr156.pdf (Last accessed 29 March 2011).

[22] Lin, R. T., “A Study of Electrical Conduction in Wood,” Ph.D. Dissertation, State Univ. of New York College of Forestry at Syracuse, 1965.

[23] Langwig, J. E., and Meyer, J. A., “Ion Migration in Wood Verified by Neutron Activation Analysis,” *Wood Sci.*, Vol. 6(1), 1973, pp. 39–50.

[24] Zelinka, S. L., Glass, S. V., and Stone, D. S., “A Percolation Model for Electrical Conduction in Wood with Implications for Wood-Water Relations,” *Wood Fiber Sci.*, Vol. 40(4), 2008, pp. 544–552, http://www.fpl.fs.fed.us/documnts/pdf2008/fpl_2008_zelinka002.pdf (Last accessed 29 March 2011).

[25] Hearle J. W. S., “The Electrical Resistance of Textile Materials: IV. Theory,” *J. Textile Inst.*, Vol. 44(7), 1953, pp. T177–T198.