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Comparing Moisture Meter Readings with Measured Equilibrium Moisture Content of Gypsum Board

ABSTRACT: Moisture meters routinely used in the field to determine the moisture content in gypsum wallboard are primarily designed and manufactured to measure the moisture content of wood. Often they are used to decide whether to replace wallboard by determining if moisture is qualitatively higher or lower than another location. Because the moisture meter is so widely used, it is necessary to establish methods to ensure their usefulness and dependability as an aid in wallboard moisture detection and remediation. A method was developed to create a series of gypsum wallboard moisture content reference standards by exposing wallboard sample sections to static moisture content levels. Gravimetric analysis revealed good accuracy and precision of the reference standards to their theoretical values. A moisture meter was then compared against these reference standards to determine the meter's accuracy and precision.

KEYWORDS: Gypsum wallboard, moisture meter, moisture content, water activity, remediation, mold.

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Introduction

Background

Regular core gypsum wallboard is the most common interior finish for residential and commercial walls and ceilings. Gypsum wallboard exposed to water or high humidity for extended time is known to support and promote mold and fungi growth [*1-3*]. The ability to accurately detect and measure the moisture content in wallboard is critical to remediate effectively. Current limitations in gypsum wallboard remediation are associated with the moisture detection instrumentation available. The hand-held instruments routinely used in the field to determine the moisture content in gypsum wallboard are primarily designed and manufactured to measure the moisture content of wood [*4-6*]. These moisture meters are often used simply to determine relative moisture content of one location to another. Water activity meters are another means of moisture detection. These meters are primarily laboratory tools for the microbial and food industry. Although water activity meters are a good measure of available moisture for microbial growth, they may be time consuming and awkward to use in the field. Whereas moisture meters typically produce moisture readings within seconds, water activity meters require several minutes per reading. Additionally, moisture meters obtain readings by direct contact with the wallboard surface, whereas water activity meters traditionally require a sample specimen placed within a sealed measurement chamber to obtain a reading.

There is no direct translation of moisture content between wood and wallboard materials due in part to their differing physical properties. Wood is a natural fibrous substance containing relatively high moisture content. Dependent upon the species, this type of structure when dried can result in a highly porous, low-density material. The primary component of gypsum wallboard core material is gypsum, or calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a naturally occurring mineral. The gypsum core is a mixture of dried, ground, and calcined gypsum, various additives, water, and trace impurities. Calcination is the evaporation of gypsum's chemically-bound water, decomposing the gypsum to form calcium sulfate hemi-hydrate ($CaSO_4 \cdot 0.5H_2O$). During the wallboard manufacturing process the gypsum is re-hydrated providing the finished wallboard with stable chemically-bound water.

Percent moisture content (% MC) is calculated on a dry-basis as the weight of water (moist material weight minus dry material weight) divided by the dry material weight multiplied by 100. Total weight is often substituted for the nomenclature moist material weight. For gypsum wallboard, the moist weight includes the weight of the material and its chemically-bound water, plus water located within the pores and interstitial spaces (free water). The dry weight does not include the water located within the pores and interstitial spaces. Since moisture content is a measure of weight and wallboard is generally denser than wood, an equal volume of water added to equal volumes of wallboard and wood will produce different % MC readings, therefore moisture content readings can be significantly higher in wood than gypsum wallboard due to density differences

Whether expressed as % MC, equilibrium relative humidity (ERH), or water activity (Aw), the amount of moisture available in the wallboard is the key factor affecting mold growth [*7*]. ERH is associated with steady state water exchange. ERH occurs when a material's water vapor pressure and temperature are equal with the ambient atmosphere. Aw, a term used widely in the microbiology field, is the available water in a material that can support mold growth versus the total water within the material. Because gypsum wallboard is a porous, hygroscopic material, it will seek to attain moisture equilibrium with the surrounding humidity. Both wood products and finished wallboard contain numerous pores and interstitial spaces. It is within these spaces that moisture penetrates and accumulates to reach equilibrium with the surrounding environment. Free water in the porous structure of the wallboard can support microbial growth under suitable environmental conditions.

% MC and ERH are related through sorption isotherms. A sorption isotherm graphically represents the relationship of a material's moisture content at equilibrium relative humidity for a specific temperature. Sorption isotherms are both material specific and temperature dependent [*8*]. Because of the complexity and dependency of the sorption process, isotherms must be experimentally determined for each material or product. Materials often differ in their absorption and desorption rates. Most building materials follow sorption curves that are non-linear in shape [*12*]. A sorption isotherm with the study data is given in the Results and Discussion section. The pharmaceutical industry has studied this relationship extensively due to its dependency on powder materials, but little data exists regarding sorption isotherms of gypsum wallboard. Data from previous gypsum wallboard studies show isotherm relationships between % MC and % relative humidity at equilibrium of 0.7% MC at 80% RH [*2*], 0.3% MC at 50% RH [*13*], 0.4-0.5% MC at 80-85% RH, and 0.7-0.8% MC at 90-95% RH [*9*]. Note the disparity between the sources referenced. Wallboard at equilibrium in an 80% RH environment is equated with moisture contents of both 0.7% and 0.4-0.5%. Additionally, 0.7% MC is associated with ERH environments of 80% RH and 90-95% RH. The usefulness of the reference data is unclear since neither methodology nor instrumentation used in obtaining the results was provided.

ERH and Aw have a direct relationship that varies slightly with temperature. In an environment of water vapor pressure and temperature equilibrium (no further moisture exchange), the Aw within a material is considered equal to % RH/100.

Objective

The research objective is to develop a method to determine the accuracy and precision of moisture meters that are primarily designed for wood products, but used on gypsum wallboard. The intent is to validate their use for remediation of water-damaged gypsum wallboard to prevent mold contamination. This initial laboratory testing will provide a baseline for the development of a standard test method for moisture meter evaluation and its practical field application. Future methods development will be modified based on the test results and data obtained.

Materials and Methods

Materials

Gypsum Wallboard─regular core gypsum wallboard was purchased from local home improvement suppliers with no preference toward manufacturer. The wallboard measured 2.4 m (8 ft) in length by 1.2 m (4 ft) in width by 1.27 cm (½ inch) thick. Gypsum wallboard has a paper covering often referred to as "cream stock" applied to the front or face and "gray stock" applied to the back. The face of gypsum wallboard is the side that faces out upon installation. The wallboard was manufactured to the following standards: ASTM C1396, Standard Specification for Gypsum Wallboard and CAN/CSA-A82.27-M Standard, Gypsum Board Building Materials and Products. The wallboard was tested as purchased: no surface coatings were applied or physical changes made to the surface structure.

Instrumentation

Delmhorst, Model BD-2100 Moisture Meter─the meter is a hand held device that determines the moisture level by measuring the electrical resistance between two contact pins inserted into the material. The two contact pins are mounted on the top of the meter and are identical in length with a fixed distance between them. The meter readings are based on the relationship between electrical resistance and moisture content within hygroscopic materials. The meter has a 0.2 to 50% moisture range with gypsum when set to scale #3, Gypsum Scale. The Delmhorst Instrument Company states a ± 20% tolerance of the reading [9]. The meter was purchased with primary certification of its electrical resistance traceable to NIST. No data was received with the instrument relating electrical resistance to moisture content, nor regarding the accuracy of the instrument readings.

Rotronic, Model HygroPalm Aw1 Water Activity Meter—the meter is a hand held device that determines the active (unbound) moisture content by measuring the humidity and temperature within a sealed volume of air containing the sample material. The water activity measurement is a measure of the ERH influenced by moisture vapor pressure and the temperature. Equilibrium is met when the humidity signal rate of change is less than 0.0001 Aw per minute and the temperature signal rate of change is less than 0.01^{o}C per minute. The small product sample probe, Model Aw-DIO, has humidity and temperature sensors positioned on its bottom face. An imbedded o-ring in the bottom face provides an airtight sensing volume with the sample specimen chamber. The HygroPalm Aw1 meter has a range of 0 to 1 Aw, with system accuracy at 23^{o}C of ± 0.015 Aw (± 1.5% RH) and ± 0.2^{o}C.

The meter has three modes of operation: Standard, AwE, and AwQuick. Standard mode is used for calibrating the humidity-temperature probe and measuring the equilibrium of the product. Typical measurement time to reach full equilibrium is 30 to 60 minutes. AwE mode performs as the standard mode but automatically ends the measurement when equilibrium is detected. AwQuick mode accelerates the measurement process, providing results within approximately five minutes. During the AwQuick measurement process, the value of the humidity signal and the stability of the temperature signal are constantly monitored. After a four minute dwell time, an algorithm projects the final equilibrium value (water activity) based on the humidity data. The measurement ends when the projected Aw value is stable. Depending on the moisture content, the final measurement is obtained within seconds to just over one minute following the dwell time. The AwQuick mode results are stated to be within ± 0.005Aw or less of the full equilibrium measurement [*10*].

During this experiment, the meter was operated in the AwQuick mode with a slight procedure modification. The sample probe's o-ring face was placed against the wallboard to form the sealed air space for humidity and temperature measurement. Normal procedure is to place a sample of the test material into the sample specimen chamber and seal in place with the probe.

Vaisala, Model HMD70Y Temperature and Humidity Transmitter─the transmitter provided continuous laboratory space monitoring of humidity and temperature throughout the experiment. The transmitter utilizes an HUMICAP 180 humidity sensor with a range of 0 to 100% RH at ± 2.0% RH accuracy and a Pt 1000 IEC 751class B temperature sensor with a range of -20 to 80 ^{o}C at ± 0.1 ^{o}C accuracy. The output signal is set at 0 to 1 volts. The temperature and humidity transmitter was used in conjunction with a Measurement Computing data acquisition board, Model PMD-1208LS with the manufacturer supplied software, InstaCal™ Version 5.44.

An electronic top-loading balance was used to obtain the mass of the wallboard specimens and moisture standards. The balance has two weighing ranges; 2100 gram and 500 gram with readability of 0.01 or 0.001 gram respectively. Repeatability is less than or equal to ± 0.001 gram. The balance has a combined uncertainty of 0.005 gram for the 500 gram range.

Method

A series of moisture content standards were generated covering the range from dry to saturation. Gravimetric weighing was performed daily to provide a benchmark for comparative analysis. Electronic measurements of moisture content were performed using the moisture meter and water activity meter. The meter readings were taken on the face side of the wallboard to mimic the typical sampling method applied in the field. Consideration was also given to simplify the research.

Six-inch square sections of gypsum wallboard were cut from one randomly selected sheet of wallboard. All specimens were dried in an oven at 75 ^{o}C for three hours to remove existing free moisture (non chemically-bound water). The drying temperature and time were selected as a reasonable compromise for this first set of experiments after a review of numerous gypsum manufacturing, testing and calcination literature. The specimens were then weighed to obtain a moisture free baseline (dry) mass and placed in a desiccator to prevent moisture uptake prior to generating the moisture content standards. Indicating silica gel was used as the drying agent in the desiccator. The desiccator was equipped with a built-in hygrometer for humidity monitoring.

The moisture content standards were generated by equilibrating wallboard specimens in relative humidity environments or by adding water directly to the specimens. The standards remained in their respective humidity environments or sealed in plastic to maintain the appropriate moisture content throughout the experiment. Moisture distribution was assumed uniform throughout the wallboard for this study. This assumption may not reflect all field conditions but was determined acceptable for this study. This determination was based in part on previous experimental observations and discussions of "real world" findings.

Four moisture content standards were prepared using saturated salt solutions in accordance with the ASTM Standard E104-85 (Re-approved 1996), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions [*11*]. The wallboard specimens were placed into the sealed humidity chambers containing saturated salt solutions. Saturated salt solutions have a unique constant relative humidity range that varies with temperature. The salt solutions chosen provided nominal RH values of 11%, 33%, 75%, and 85%. Theoretical % MC values were calculated for each RH value selected by dividing the density of water content in air by the dry air density multiplied by 100. Water content and dry air density values were based on 20 ^{o}C and 760 mmHg. The theoretical % MC values associated with the salt solutions were 0.16, 0.47, 1.08, and 1.22 respectively. Applying a linear regression through the theoretical % MC values, an equilibrium environment of 100% RH would have a % MC of 1.44.

Four moisture content standards were prepared by directly applying demineralized (DI) water to the wallboard specimens. A density of one gram per milliliter (1 g/ml) was assumed for water. Three specimens were placed on the electronic balance face side up and the mass equivalent volume of water equal to 1, 5, and 10 percent of the specimen's dry weight was slowly poured/dripped onto each respectively. Prior to absorbing into the wallboard the water was spread across the face side of each specimen to cover as much surface area as possible. The nominal targeted % MC values were 1, 5, and 10 % MC. The calculated % MC values were equal to 0.90, 4.90, and 9.96 respectively. The standards were double sealed in plastic zip-lock bags. The fourth standard (complete saturation) was generated by initially submersing a wallboard specimen horizontally inside a container of DI water. As the water was absorbed, additional water was added to ensure the wallboard specimen remained in a saturated state through continuous contact with a thin film layer of water remaining in the container. The container's lid was kept in place to minimize evaporative water loss.

One wallboard specimen remained in the desiccator to provide a dry baseline standard. Another wallboard specimen was placed on the laboratory workbench where it remained throughout the experiment. The % MC of this ambient moisture content standard was expected to reflect the nominal laboratory % RH.The moisture content standards were allowed to equilibrate within their respective environments for three days prior to the initial weighing. The standards within sealed environments were removed only to perform measurements of mass, water activity, and percent moisture content. The time outside the sealed environment was minimized to prevent moisture loss and was less than ten minutes in duration with the exception of the ambient standard, which had no time constraint. Only one standard at a time was exposed to the laboratory environment for measurement with the exception of the ambient and saturated standards.

Each sampling day, the balance was checked with five and 100-gram reference standards to monitor its performance prior to weighing the moisture content standards. Moisture content standards were removed from their environment and placed on the balance. The saturation standard was lightly patted dry to remove the non-absorbed surface water prior to measure. Once stable, the mass was recorded and the standard was placed face side up on the laboratory bench to perform the moisture content and water activity measurements.

The moisture content measurement recorded was the average of five readings. A reading was obtained by inserting the moisture meter's contact pins into the gypsum wallboard material. The meter's contact pins were inserted steadily and firmly to the depth prescribe in the operating manual. One reading was obtained from the center of the moisture standard and the remaining four were one inch inward from each corner. The initial contact pin-holes were used repeatedly until they became loose in fit at which time a new sampling position was generated next to the existing or previous position. This was performed to provide the most reliable contact between the meter and wallboard.

The water activity meter was operated in the AwQuick mode (sample time of approximately 5 minutes). The humidity–temperature probe was placed centrally on the surface of the wallboard face and the measurement process started. Once the process was complete, the water activity measurement was recorded and the meter reset.

The experiments were conducted in a standard laboratory space lacking precise temperature and humidity control. The Vaisala transmitter continuously monitored the lab space humidity and temperature throughout the experiment series. Temperature and humidity were reasonably consistent throughout the weekdays (20 ± 0.5 ^{o}C, 50 ± 3% RH), with occasional episodic behavior observed over weekends (18 ± 3 ^{o}C, 60 ± 10% RH).

Sigma Plot 2004 for Windows, Version 9.0 was used to plot and model the data obtained in this study.

Results and Discussion

Gravimetric % MC Benchmark Standards

Gravimetric data were used to calculate the % MC of the wallboard moisture content standards. This gravimetric % MC was then used as the benchmark standard (value) for the moisture meter and water activity meter readings. To calculate the gravimetric % MC, a standard's dry weight was subtracted from its average moist (equilibrium state) weight to obtain an average water uptake weight. The moist weight is the dry weight plus the weight of the water absorbed. This water uptake weight was then divided by the standard's dry weight and multiplied by 100.

Within the first week of the experiment the desiccator (dry) standard lost an additional average water weight (mass) of 0.192g. This data suggests the wallboard specimen drying method (75 ^{o}C for 3 hours) was not sufficient in removing all of the free moisture (unbound water). A review of and modification to the drying method was deemed necessary for future research. The gravimetric % MC values obtained were corrected by normalizing for water loss of the desiccator standard. These normalized gravimetric % MC values were used in the remaining data analysis and meter reading comparisons.

The gravimetric % MC standard data are presented in Table 1. The gravimetric % MC values are given with the uncertainty of the mean. The uncertainty was derived by taking the square root of the sum of the errors squared, divided by the square root of the sample number. A factor of 2 was applied to the value derived to provide an uncertainty confidence level of 95%. The errors summed were the mass measurement errors and the balance error.

TABLE 1—Normalized gravimetric moisture content standards data.

	N~Grav[a] % MC % MC ± Unc.[b]	N~Grav % RSE [c]	Theoretical Calculated % MC	N~Grav/Theory % Error
Desiccator	0.000 ± 0.08	na	0.00	Na
11% RH Chamber	0.25 ± 0.01	5	0.16	+58
33% RH Chamber	0.47 ± 0.01	3	0.47	-2
Ambient[d]	0.67 ± 0.03	4	0.72	-6
75% RH Chamber	0.93 ± 0.02	2	1.08	-14
85% RH Chamber	1.35 ± 0.06	4	1.22	+11
1% MC	0.90 ± 0.41	45	0.96 ± 0.02 [b]	-5
5% MC	4.90 ± 0.47	10	5.07 ± 0.02	-3
10% MC	9.96 ± 0.50	5	10.17 ± 0.02	-2

Saturated	77.87 ± 6.20	8	na	Na

[a] normalized gravimetric weight
[b] uncertainty of the mean with 95% confidence level
[c] relative standard error of the mean gravimetric % MC
[d] mean ambient laboratory RH (50 ± 3%)

The high measurement deviation observed in the 1% MC gravimetric standard is reflected in its relative standard error (RSE) value of 5%. This measurement error is likely associated with the moisture sealing mechanism used and the handling of the standard. The 1% MC standard's mean moisture content value however, was shown to reasonably match its calculated % MC value. As described in the *Methods* section, the RH chamber, desiccator, and ambient standards are theoretical % MC values and the 1, 5, and 10% MC standards are calculated % MC values. No % MC value was calculated for the saturated standard. Uncertainty values were not calculated for the theoretical % MC values. The uncertainty values of the calculated % MC were based on balance error and derived as described previously.

The % error column reflects the relationship between the gravimetric % MC and the theoretical % MC. The % error values reveal good correlation between the gravimetric and theoretical % MC values with the exception of the 11% RH chamber standard. The 11% RH standard's mean moisture content was more than twice the theoretical value derived. It is unclear what lead to this discrepancy.

Repeated weighing of the 1%, 5%, and 10% MC standard moist (wet) wallboard specimens revealed a slow decrease in total weight over time, but remained within 3% of their initial weight. Inadequate sealing of these standards to prevent moisture evaporation is the suspected cause. While the loss of weight within these standards gave a slightly higher uncertainty of the mean associated with its gravimetric % MC value, it did not appear to influence the usefulness of the standard as indicated by the gravimetric/theoretical % error. The saturated standard's wallboard specimen weight varied within ± 10% of its averaged weight throughout the experiment. This fluctuation in weight was attributed to inadequate experimental conditions (temperature and humidity control) and procedures such as not maintaining a consistent water level in the storage container, thus causing water absorption and desorption.

The gravimetric % MC standards were plotted against their theoretical % MC values and presented in Figure 1. The desiccator and saturation gravimetric standards were not included in the plot. A linear regression fit to the data had an R^2 value greater than 0.99, a slope coefficient estimate of approximately 1 with a p-value less than 0.001, and a standard estimate of error (SEE) of approximately 0.09. The p-value reflects the significance of the coefficient term and acts as an indication of confidence in the coefficient value. A p-value of 0.05 (95% confidence level) was used as the significance criteria limit. The SEE reflects the error associated with the residuals (the observed response minus the predicted response).

Based on the gravimetric to theoretical correlation and the regression fit parameters, seven of the ten benchmark % MC standards are considered adequate for use in evaluating the moisture meter's accuracy and precision. The 11% RH standard's poor gravimetric to theoretical correlation makes it unacceptable for use. The desiccator and saturated standard's insufficient gravimetric to theoretical correlation data render them uncertain.

Comparison of Moisture Meter Readings with the Calculated Gravimetric % MC

To determine the accuracy and precision of the moisture meter, the meter % MC readings were compared against the gravimetric standard % MC values. The moisture meter data are given in Table 2. The moisture meter readings are limited to one decimal place, but two decimal places are given for the standard deviation of the 33%, 75%, and 85% RH chamber standards and the ambient standard to remove ambiguity of a zero standard deviation value due to rounding.

TABLE 2—Moisture meter and water activity meter data.

	Gravimetric % MC	Moisture meter readings % MC ±Stdev	%RSD[b]	Water activity readings Aw ±Stdev	Theoretical Aw
Desiccator	000	BDL[a]	na	0.125 ± 0.015	0.000
11% RH Chamber	0.25	BDL	na	0.184 ± 0.008	0.113
33% RH Chamber	0.47	0.2 ± 0.03	18	0.384 ± 0.008	0.328
Ambient	0.67	0.3 ± 0.02	7	0.531 ± 0.034	0.503
75% RH Chamber	0.93	0.5 ± 0.02	4	0.733 ± 0.014	0.753
85% RH Chamber	1.35	0.6 ± 0.01	2	0.817 ± 0.010	0.843
1% MC	0.90	0.6 ± 0.2	27	0.761 ± 0.057	na
5% MC	4.90	4.7 ± 0.8	16	1.007 ± 0.004	na
10% MC	9.96	7.1 ± 0.4	5	1.003 ± 0.005	na
Saturated	77.87	26.4 ± 2.4	9	0.974 ± 0.001	na

[a] below detection limit
[b] relative standard deviation of moisture meter readings

The moisture meter's lower limit of 0.2% MC correlated to the wallboard specimen in the 33% RH Chamber which had a gravimetric % MC of 0.47. The 18% relative standard deviation (RSD) associated with this reading may reflect lower precision at the meter's lower limit. The meter's upper limit of 50% MC was not reached. The moisture meter reading for the 1% MC standard had the greatest variability (27% RSD). It is suspected this high error was due to the inadequate dispersion of the moisture throughout the wallboard specimen. The 5% MC standard had an RSD approximately half of the 1% MC standard which may reflect better moisture dispersion although not complete dispersion.

The moisture meter readings were approximately 50% of the % MC values for the Ambient, 33% RH, 75% RH, and 85% RH gravimetric standards. With the manufacturer's stated ± 20% tolerance of the reading, the meter was biased low by a minimum of nearly 30% within this range of the meter. Moisture meter readings for the 1%, 5%, and 10% MC standards were approximately 60%, 95%, and 70% of their gravimetric % MC values respectively. Due to the higher variability in meter response (%RSD) of the 1% and 5% MC standards, there is uncertainty in the response accuracy for these two standards. The water activity values provided in Table 2 are described in the following section: *Water Activity Meter Reading Analysis*.

Figure 2 shows the relationship between the moisture meter readings and the accepted gravimetric standards (final paragraph of previous section). A simple linear regression model was applied to the data plot. The linear model had a good statistical fit with an adjusted R^2 value greater than 0.98, a slope coefficient p-value less than 0.05, and low residual error (SEE).

Although the saturated % MC standard was not initially considered sufficiently validated for use, its meter response data was added to the existing data plot. The addition of this data point did not fit within the linear relationship between the existing gravimetric standards and the meter response. A non-linear (second-degree polynomial) regression model applied to this new extended data set gave slight statistical improvement over the linear fit. The model curve of the extended data set was observed to nearly overlay the linear fit of the initial data points (pre-saturation standard meter response) up to the 10% MC standard. Beyond this 10% MC data point, the non-linear model's curve became more apparent. Due to the location of the saturation standard data point along the non-linear fit it is unclear what contribution is gained in understanding the relationship between the percent moisture content and meter response for wallboard moisture content greater than 10%. Of note however, is the appearance of a relationship between the non-linear curve's maxima, the % MC and the linear regression projected forward. A seen in Figure 2, a line perpendicular to the non-linear curve's maxima intersects with the linear response curve at a value equal to the meter's maximum range (50% MC). Following the line downward it equates to a MC of ~65%. Manufacturer calibration data for the meter was not provided, but statistical analysis appears to support a piece-wise (linear or linear/non-linear combination) or full range non-linear response to moisture within gypsum wallboard.

The moisture meter used in this comparison study was chosen in part due to the manufacturers built-in Gypsum Scale. Along with the digital reading, three LEDs located on the front panel provide visual aid in the moisture level determination. Green (0% to 0.5% MC), yellow (0.5% to 1% MC), and red (>1% MC) colored lights provide guidance with regard to painting or wallpapering gypsum, as defined in the operating manual. Literature cites moisture conditions for mold growth from an ERH of 65% to 100% (Aw of 0.65 to 1.0). This study has determined that an ERH of 65% equates to a MC of approximately 0.85% for gypsum wallboard. Other literature sources give values as low as 0.7% MC for an ERH of 65%. Data are presented in the *Sorption Isotherm* Section.

Prolonged exposure of gypsum wallboard to moisture environments greater than or equal to an ERH of 100% (MC of 1.4% to 1.7% based on this study) is essentially guaranteed to support mold growth. Therefore, the more important, useful range of the moisture meter used in this study is from 0.2% to approximately 3.0% MC. This is based on the relationship of the moisture meter reading to the gravimetric measurement observed for this meter, where the meter readings in this range are approximately one half of the gravimetric values. Improper interpretation of the readings in this range could lead to further or future mold related issues.

Water Activity Meter Reading Analysis

Water activity meter readings and theoretical Aw values are provided in Table 2 for the gypsum wallboard reference standards. Meter Aw readings are given for all reference standards with their standard deviation. Theoretical Aw values are provided only for the reference standards generated by equilibrating wallboard specimens in relative humidity environments. The theoretical Aw value was considered equivalent to % RH/100 (temperature dependent).

For the salt solution environmental chambers, the theoretical Aw values were calculated using the mean % RH value obtained from ASTM Standard E104-85 at a temperature of 20^{o}C. Results of 0.113, 0.328, 0.753, and 0.843Aw were obtained for the 11%, 33%, 75%, and 85% RH salt solutions respectively. The ambient standard's Aw value of 0.503 was calculated using the weekday mean laboratory % RH. The desiccator standard's Aw value was assumed equal to zero.

The water activity meter readings were compared against the theoretical values associated with the reference standards for their respective equilibrium relative humidity environment. A least-squares linear regression was applied to the water activity data plot and is presented in Figure 3. The model had a very good fit as indicated by the R^2 value, coefficient p-values, and SEE value. The lack of 1:1 correlation between the theoretical value and meter reading may be attributed to using the meter in the quick mode or operating the meter in a modified manner. This reduction in correlation may be an acceptable trade-off for the sample time savings gained.

The baseline offset may be due to instrument bias, water vapor trapped within the sensing volume of the meter probe during readings, or the actual presence of free moisture within the wallboard. Another possibility is the detection of chemically bound water, although, based on the water activity meter's theory of operation, chemically bound water should not be detected.

The baseline offset was nearly equivalent to the Aw reading for the desiccator standard and the 11% RH theoretical value. The desiccator standard's 0.125 Aw meter reading was unexpected as the theoretical Aw was presumed equal to zero for the desiccator standard: no free moisture in the wallboard specimen. One possible explanation for the desiccator standard's non-zero Aw reading was in the desiccator's performance. An assumption was made that the desiccator, containing silica gel, would keep the wallboard specimens dry and free of unbound moisture. The desiccator's built-in hygrometer however, indicated a reading of approximately 10% RH during the study. The hygrometer was not calibrated so the desiccator's actual RH was unknown.

The water activity meter readings were also compared with the theoretical % MC values, gravimetric % MC values, and moisture meter % MC readings. Only those standards with values equal to or less than 1.4% MC were included: equivalent to the upper limit of the water activity meter. This upper limit of 1.4% MC was based on the theoretical relationship of water activity and moisture content, where a 0.7 Aw unit corresponds to approximately of one % MC unit (100% ERH ≈ 1.0Aw ≈ 1.4% MC). See *Method* section.

Due to the nearly 1:1 correlation between the theoretical % MC and the gravimetric % MC values seen in Table 1, the relationship of each with the Aw meter were essentially equivalent. The results of these two comparisons reveal a 0.6 Aw unit corresponding to approximately one unit of % MC. The difference in the theoretical and measured relationship (0.6 versus 0.7) is likely error associated with the meter's method of use. Comparison of the Aw meter and % MC meter readings revealed a nearly direct correlation with a baseline offset of approximately 0.2.

These results suggest a water activity meter could be used in place of a moisture meter if warranted. Caution must be emphasized however, due to the water activity meter's readings relative to their equivalent gravimetric moisture content and the meter's upper limit of approximately 1.4% MC (1.0 Aw). Similar precautions regarding interpretation of the moisture meter reading should be heeded with the water activity meter readings; for regular gypsum wallboard, the water activity readings represent approximately one-half of the gravimetric %

MC. Water activity readings approaching the upper limit of 1.0 Aw will provide only relative measure of available moisture to support biological growth.

Sorption Isotherm

A sorption isotherm plot of moisture uptake was generated using the gravimetric % MC standard values. The moisture meter readings obtained from this study and previous wallboard moisture studies were plotted as well. See Figure 4. The gravimetric % MC values are read on the left y-axis and the moisture meter and previous % MC readings are read on the right y-axis. With the 2:1 ratio of the y-axis scales, the relationship described previously between the gravimetric % MC values and the moisture meter % MC readings is more easily seen (*Comparison of Moisture Meter Readings with the Calculated Gravimetric % MC* Section). The non-linear shape of the data also fits the previous description given for building material isotherms.

The manufacturer's stated 20% tolerance of the reading is reflected in the error bars given with the moisture meter readings. Two of the previous wallboard moisture study data points were averaged for plotting. The 0.4-0.5% MC for 80-85% RH range was plotted as 0.45% MC at 82.5% RH and the 0.7-0.8% MC for 90-95% RH was plotted as 0.75% MC at 92.5% RH. X and y-axis error bars reflect the averaging range. The true errors associated with the previous study data points are unknown.

The data plots reveal reasonable correlation between the moisture meter readings obtained in this study and moisture content values from previously reported studies. Similarly, the previous study data values are approximately half of the gravimetric % MC measurements. This may imply the previous data was not determined gravimetrically but by some type of moisture meter.

Conclusion

The wide use of moisture meters designed for wood products in wallboard remediation may not be providing the information necessary to make sound decisions. Knowing the limitations and errors associated with any moisture meter is critical to adequately detect and measure wallboard moisture content.

The moisture meter validation method developed was simple in design, and easy to assemble and utilize. The measured gravimetric % MC of the wallboard moisture content standards had good correlation with 7 of the 10-theoretical/calculated % MC values. The ambient, 33% RH, 75% RH, 85% RH, 1% MC, 5% MC, and 10% MC standards were considered valid for use in this study: determination of the moisture meter's accuracy and precision. The three exceptions were the desiccator, 11% RH chamber, and the saturation standards. The 11% RH chamber had an error approaching 60% and the desiccator and saturation standards lacked sufficient data to calculate their % error.

Issues affecting the results of the moisture content standards included moisture loss, inadequate sealing mechanisms, moisture dispersion, and laboratory temperature and humidity control. Additional moisture loss from the desiccator wallboard sample section suggested the initial drying method was inadequate and required the normalization of the remaining data. Lack of stable gravimetric mass in the direct water generated reference standards suggest an improved sealing mechanism is needed. The moisture meter readings associated with the 1% and 5% direct water generated standards indicated inadequate dispersion of the moisture throughout those standard specimens. A better means to distribute the moisture throughout the wallboard specimens is needed. Laboratory environmental conditions were reasonably stable throughout the weekdays but fluctuated over the weekends due to facility operating procedures regarding energy conservation. There is no direct link to the affect on the moisture standards resulting from the temperature and humidity variation, but it is suspected the ambient, saturation, and direct water generated standards were influenced partially as determined by the measurement standard errors.

The meter tested in this study, determined moisture content by measuring the electrical resistance between two pins inserted into the substrate. The moisture meter readings were compared against the gravimetric % MC standards produced in this study. The meter readings had good reproducibility although the meter's accuracy did not meet expectations. The % MC readings were approximately 50% of the gravimetric standard % MC values. Considering the manufacturer stated ± 20% tolerance of the reading, the moisture meter readings were still well below the gravimetric standard % MC values. Several meter response curves over the range of the instrument were considered possible from the data observed: piece-wise (linear or linear/non-linear combination) or full range non-linear response.

This study showed that the use of moisture meters might not reflect the actual moisture content within gypsum wallboard. This could be critical in the range below 1% MC, where the measured moisture content is used to determine the potential for mold growth or the application of surface treatments (i.e. paint).

The water activity meter readings were approximately 60% of the gravimetric % MC values. The results tend to support the theoretical relationship of water activity and moisture content, (0.7 units Aw to 1 unit % MC), when consideration of experimental error is applied. This error likely resulted from the sampling technique used: a combination of the sampling mode and a non-traditional sampling method. Based on the results obtained, water activity meters could be utilized to determine moisture availability for mold growth in gypsum wallboard. As with the moisture meter, caution in interpreting the actual moisture content should be considered. The water activity meter is restricted in its range of usefulness, with an upper limit of 1.0 Aw or 1.4% MC (theoretical).

The moisture isotherm plot supported the nonlinear relationship of gypsum wallboard's moisture uptake to its % RH equilibrium environment presented in previous findings. The 2:1 ratio of the gravimetric standard % MC to moisture meter reading from this study was seen more clearly in the isotherm plot. The % MC data values from previous studies mimicked those of the moisture meter readings obtained in this research, suggesting earlier data were not obtained gravimetrically.

Continued work to fine-tune the method is needed with emphasis placed on replicate sampling and the use of multiple manufacturer wallboard brands. Additionally, a field reference method is needed to support on-site moisture content measurements of gypsum wallboard using the current instrumentation designed for wood products.

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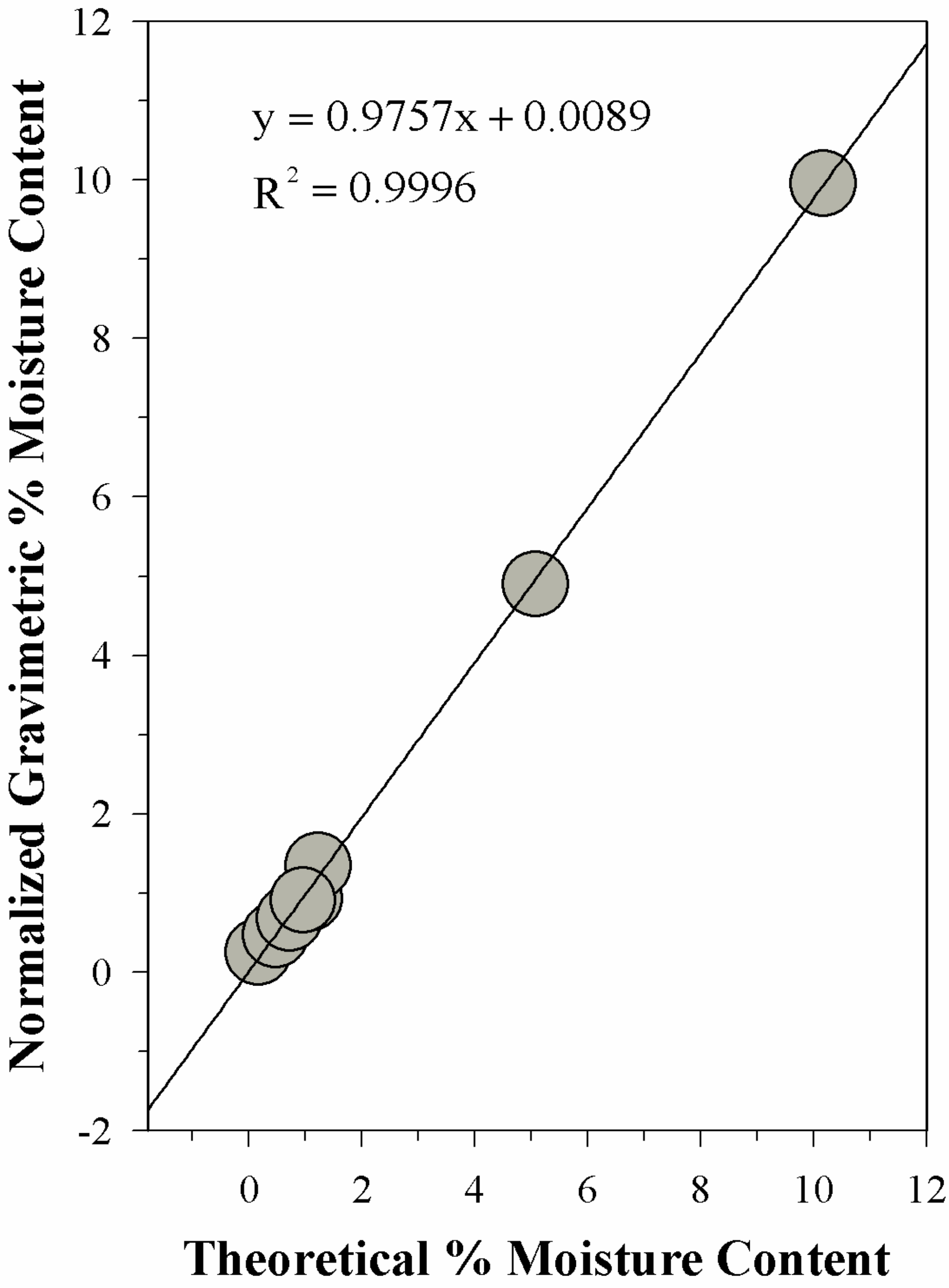
FIGURE LIST

Figure 1. Relationship of the normalized gravimetric % MC standards to their theoretical values. A simple linear regression model is fit to the data with the equation and R^2 value shown.

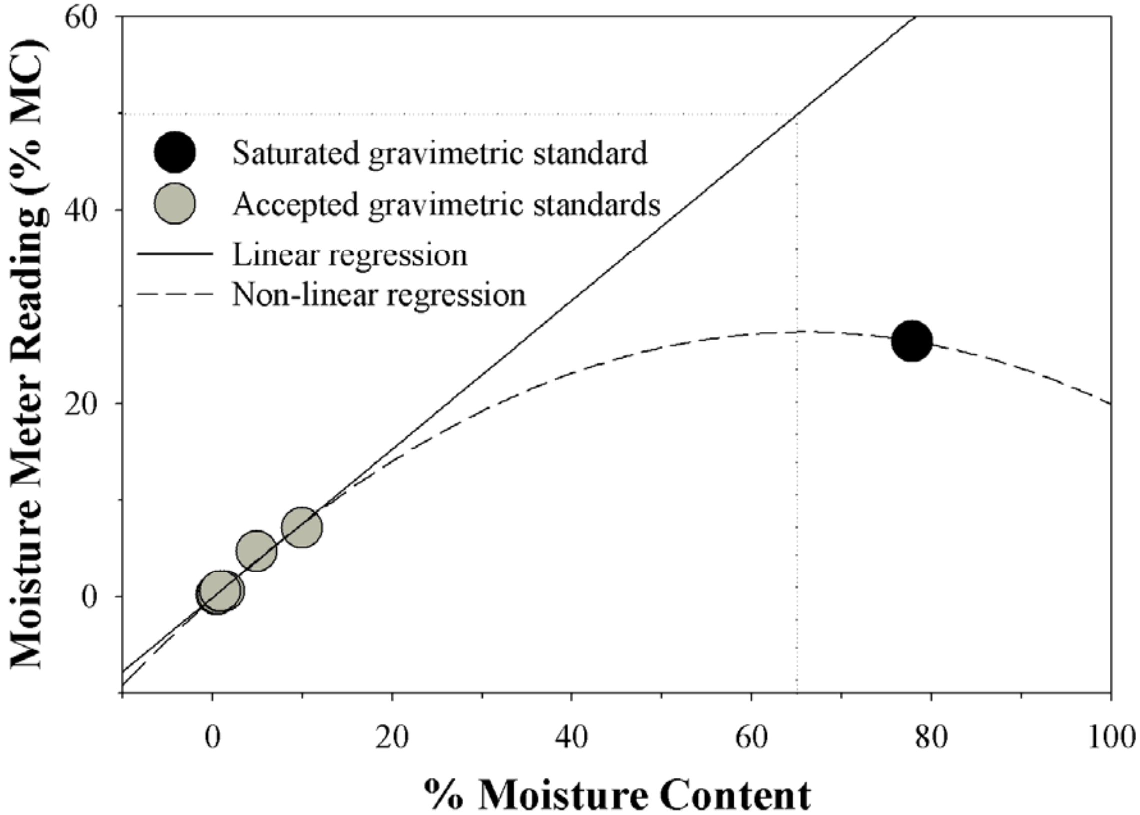
Figure 2. Relationship of the gravimetric standards (% MC) and moisture meter readings (% MC). Both linear regression and non-linear quadratic fits are shown.

Figure 3. Relationship of the water activity meter readings to their theoretical Aw value. A simple linear regression model is fit to the data with the equation and R^2 value shown.

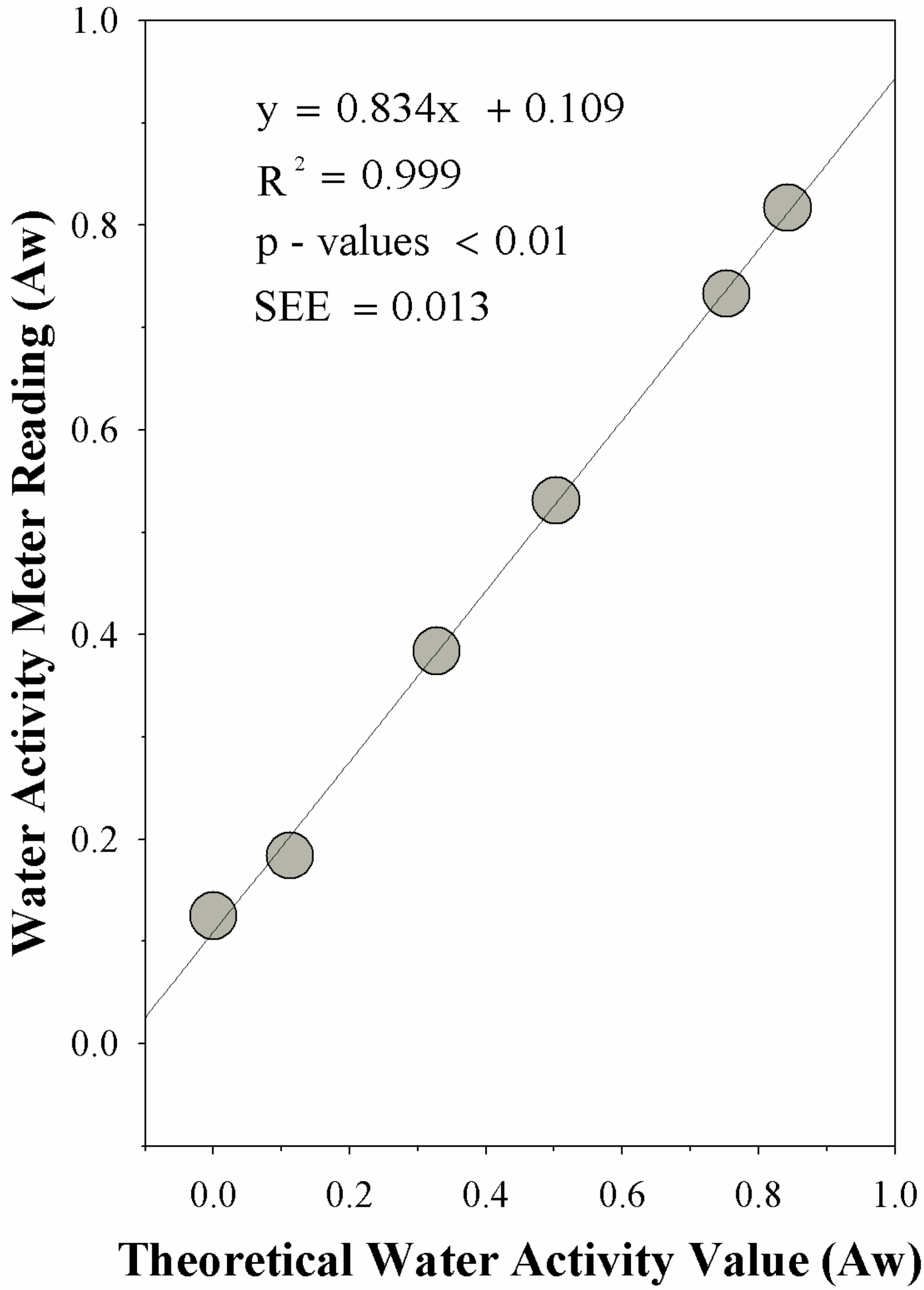
Figure 4. Sorption (moisture uptake) isotherm of gypsum wallboard composed of the gravimetric standard values, the moisture meter readings, and the previous study data. Points along each curve represent the relationship between gypsum wallboard's moisture content and the relative humidity at equilibrium at constant temperature.

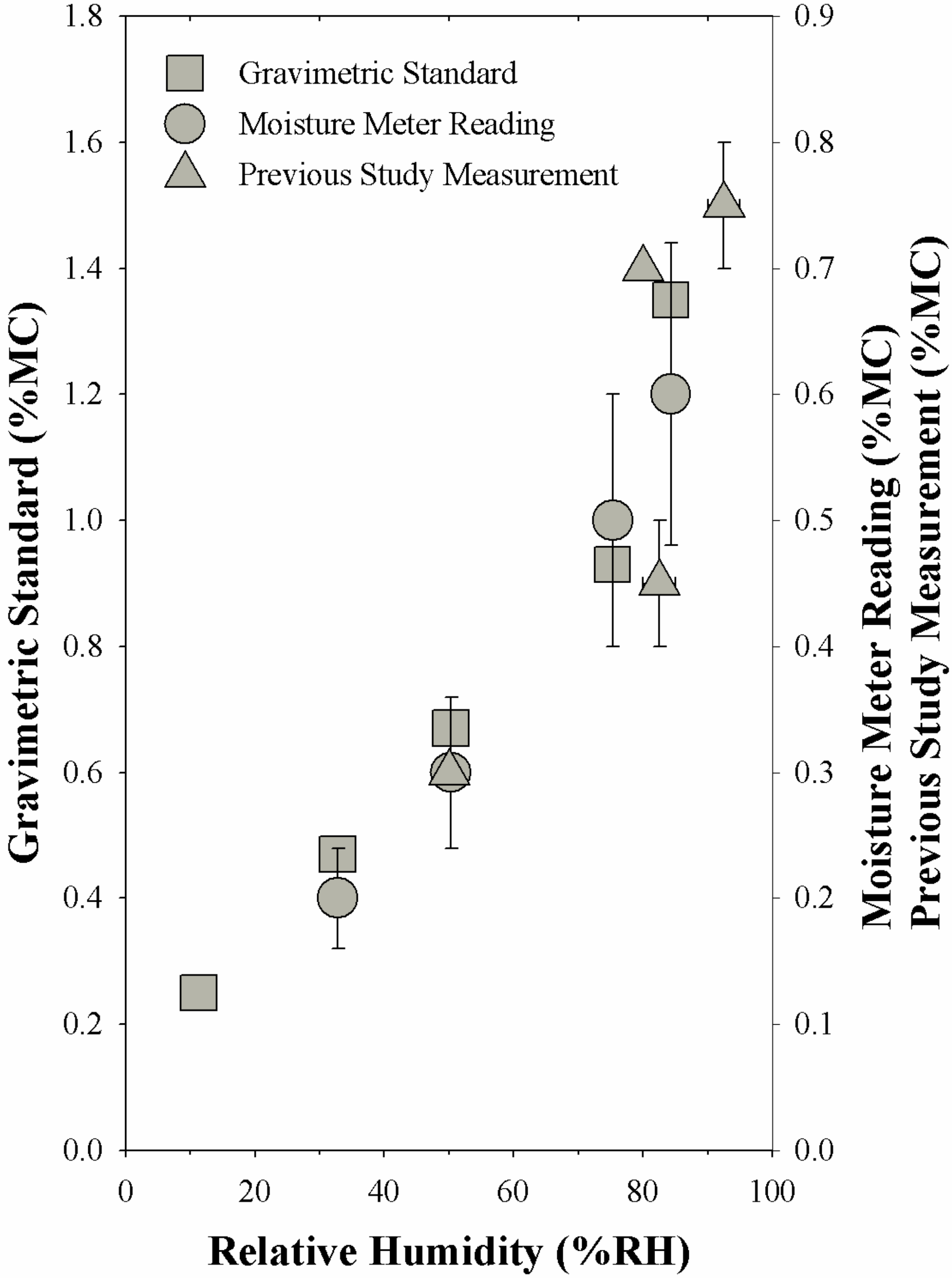


y = 0.9757x + 0.0089
R² = 0.9996
Normalized Gravimetric % Moisture Content
Theoretical % Moisture Content
-2
0
2
4
6
8
10
12



60
40
20
0
Moisture Meter Reading (% MC)
Saturated gravimetric standard
Accepted gravimetric standards
Linear regression
Non-linear regression
0
20
40
60
80
100
% Moisture Content


y = 0.834x + 0.109
R 2 = 0.999
p - values < 0.01
SEE = 0.013
1.0
0.8
0.6
0.4
0.2
0.0
Water Activity Meter Reading (Aw)
0.0
0.2
0.4
0.6
0.8
1.0
Theoretical Water Activity Value (Aw)


Gravimetric Standard
Moisture Meter Reading
Previous Study Measurement
Gravimetric Standard (%MC)
Moisture Meter Reading (%MC)
Previous Study Measurement (%MC)
Relative Humidity (%RH)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20
40
60
80
100