Moisture Movement (Wicking) within Gypsum Wallboard

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ABSTRACT

Gypsum wallboard with repeated or prolonged exposure to water or excess moisture can lose its structural integrity and provide a growth medium for biological contaminants. Poorly sealed buildings, leaking or failed plumbing systems, or improperly constructed HVAC systems can all contribute to water and moisture problems. Gypsum wallboard readily absorbs moisture through direct contact with standing water and differences in water vapor pressure. Regular gypsum wallboard sample sections were hung vertically and exposed to a continuous source of standing water 1.3 cm in depth. Both water absorption (measured in percent moisture content) and vertical movement (wicking height) were monitored within the wallboard over several days. The moisture content measurements revealed a water movement pattern similar to paper chromatography. A leading edge of relative high percent moisture content (~ 20%MC) moved upward along the width of the wallboard. The immersed portion of the wallboard maintained a moisture content level ≥ 20%. Between the leading edge and immersed portion of the wallboard was an area of moderate moisture content (~ 12%MC). Water wicked to a height of 15 cm within the first three hours of testing after which the rate continued asymptotically appearing to reach a maximum height by day 16.

IMPLICATIONS

Most wallboard remediation techniques involve visual inspection and moisture content measurements to determine the extent of the water damage and the presence of or potential for mold growth. Remediation not performed within a reasonable time following discovery, may result in ineffective remediation as moisture may continue to move beyond the original detected region. Because of the wide spread used of gypsum wallboard in commercial and residential construction, understanding the moisture movement (wicking) of water in gypsum wallboard products is essential. The ability to effectively and efficiently remediate water-damaged wallboard will save money and time, and minimize waste.

INTRODUCTION

Background

Little data could be located regarding the moisture (water) movement within gypsum wallboard due to capillary action. This is especially true for ‘real-life’ scenarios where wallboard becomes damp or wet from exposure to the elements or failed plumbing systems. Regardless of cause, gypsum wallboard exposed to water or high humidity for prolong time is known to support and promote mold and fungi growth [1-3]. Bio-contaminant growth on wallboard is significantly faster due to capillary absorption of water than from excess humidity conditions [4].

Numerous guidance documents exist for the prevention, assessment, and/or remediation of gypsum wallboard regarding mold and water damage. These guidance documents are published by leading national and international health agencies and organizations, universities, private business, and the wallboard industry. Often, the details and procedures for wallboard remediation are vague and open for interpretation. Simply removing wallboard containing visible mold growth or to some specified height above existing watermarks may not be adequate. If sufficient moisture exists within the wallboard remaining post remediation, mold growth could re-occur. The key factor affecting mold growth is the amount of moisture available in the material [4]. In most materials, mold and fungal species will germinate and grow in an equilibrium relative humidity (ERH) environment of 80% and higher. Several species are known to grow within an ERH environment as low as 65% [1, 2].

Equilibrium relative humidity is a condition of steady state moisture exchange. It is reached when the water vapor pressure and temperature within the wallboard equals that of the ambient atmosphere. Gypsum wallboard contains numerous pores and interstitial spaces: a result of the manufacturing process. It is within these spaces that moisture will penetrate and accumulate to reach equilibrium with the surrounding environment. Capillary action also relies on the pores and interstitial spaces within the gypsum wallboard to wick upward.

Gypsum wallboard is a mixture of gypsum (Calcium sulfate dihydrate $CaSO_4 \cdot 2H_2O$), various additives, water, and trace impurities. The wallboard contains both chemically-bound water and “unbound” water. It is the unbound water that moves into and out of the wallboard. Percent moisture content (%MC) is a measure of the water weight within a material to its total moist weight. %MC is calculated as the weight of water (moist material weight minus dry material weight) divided by the moist material weight times 100. For gypsum wallboard, the moist weight includes the unbound water located within the pores and interstitial spaces as well as the chemically-bound water. The dry weight of gypsum wallboard includes only the chemically-bound water or as otherwise defined.

The research objective is to measure the absorption rate and vertical movement of moisture in gypsum wallboard (drywall/sheetrock/etc.) due to capillary action during continuous water exposure. Future wallboard moisture research will be modified based on the test methodology and data obtained.

Instrumentation

A Delmhorst, Model BD-2100 Moisture Meter was used to obtain moisture content level measurements of the wallboard under test. 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 [5]. The meter was purchased with primary certification of its electrical resistance traceable to NIST. No data were received with the instrument relating electrical resistance to moisture content, nor regarding the accuracy of the instrument readings.

Prior to use and every sample day, the moisture meter was compared against a set of moisture content standards. The standards were generated in sealed chambers using ASTM Standard E104-85 (Re-approved 1996), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions or by adding an appropriate water mass to the dry wallboard. Each standard’s %MC was calculated gravimetrically by dividing the water weight (total moist weight minus dry weight) by the total moist weight of the sample standard.

A Vaisala, Model HMD70Y Temperature and Humidity 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 – 100% RH at ± 2.0% RH accuracy and a Pt 1000 IEC 751class B temperature sensor with a range of -20 – 80^{o}C at ± 0.1^{o}C accuracy. The output signal is set at 0 – 1 V. 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.

SAMPLING METHOD

Regular core gypsum wallboard was purchased from local home improvement suppliers with no preference toward manufacturer. Multiple sheets representing two wallboard manufacturers were purchased. The wallboard sheets measured 121.92 cm (4 ft) in width by 243.84 cm (8 ft) in length by 1.37 cm (½ inch) thick. Along its length, the wallboard had a manufacturer finish paper-bound edge. This wallboard "edge" is compressed approximately ~5 cm in width along the edge. The wallboard width is manufacturer cut, exposed gypsum. The "face" and back of the wallboard are paper covered. The wallboard is manufactured to the following standards; ASTM C36, Standard Specification for Gypsum Wallboard, 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. Each wallboard sheet was assigned and marked with a unique identifier. The identifier consisted of the project acronym, the wallboard type, and an alphanumeric serial number (i.e. WMC-R-A1). The serial number indicates the manufacturer of the wallboard and each separate sheet. Each wallboard section sampled was additionally annotated with the sample test series and sample section (i.e. ...-TS1-A). The sample test series defined the physical dimensions of the wallboard sample sections and the end exposed to water. The finished paper side (face) of each wallboard sheet was marked with a 15.24 cm (6 in) square grid. Each vertical grid line was then tick marked every 2.54 cm (1 in). Each wallboard sheet was divided into two or more equally dimensioned sections dependent on the test series criteria. The wallboard was cut to size by scoring the surface with a utility knife and snapping the wallboard in two by hand along the scored line.

A freestanding metal frame was designed to hang the wallboard sample sections vertically. Several clamps allowed testing of varied sized wallboard samples simultaneously. Each test series was performed in duplicate by hanging two equally dimensioned sections in the same orientation of the same manufacture wallboard. A pan placed under the wallboard sample sections was filled with de-ionized (DI) water. The water level was maintained manually throughout the experiment to overlap the bottom 1.37 cm (½ in) of the wallboard.

During the wallboard moisture content sampling, a single reading was recorded as the measurement (data point). Moisture readings were taken prior to and immediately following water contact (immersion), then periodically throughout the remainder of test. 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 prescribed in the operating manual. 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.

During each sample measurement period, multiple data points were obtained along the wallboard test sample section grid. The measurements were taken at the intersecting lines of the grid, every 15.24 cm horizontally and 2.54 cm vertically. Measurements were not taken along the wallboard's vertical ends/edges, as oriented for sampling. The data point arrangement allowed viewing the varied moisture content across the surface plane of the wallboard as contour plots. The measurements were obtained during normal working hours. The sampling pattern was dependent upon the aspect ratio (vertical height/horizontal width) of the wallboard sample section. For aspect ratios greater than or equal to 1, measurements are taken bottom to top, left to right. Aspects ratios less than 1, measurements are taken left to right, bottom to top. Wallboard measurement locations are referenced by their position on the wallboard face. An x-y coordinate system is used with the origin located in the lower left corner of the sample section. The first reading is taken at position 15-2.5, 15.24 cm horizontal and 2.54 cm vertical from the origin, regardless of aspect ratio.

Each test ended when the vertical moisture movement slowed to a non-detectable rate, when moisture measurements greater than background were obtained throughout the wallboard, or by researcher discretion. Discretionary considerations included conditions such as mold growth on the wallboard or time constraints in completing the research.

RESULTS AND DISCUSSION

The experiments were conducted in a standard laboratory space lacking precise temperature and humidity control. 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).

Five test series were performed. Test series 1 and 2 sample sections measured 60.96 cm (24 in) wide by 121.92 cm (48 in) high with the manufacturer cut, exposed gypsum end immersed in water. Test series 3 sample sections measured 15.24 cm (6 in) wide by 45.72 cm (18 in) high with a laboratory cut, exposed gypsum end immersed in water. Test series 4 sample sections measured 60.96 cm (24 in) wide by 121.92 cm (48 in) high with the manufacturer finished paper-bound edge immersed in water. Test series 5 sample sections measured 121.92 cm (48 in) wide by 60.96 cm (24 in) high with the manufacturer cut, exposed gypsum end immersed in water. Sample section descriptions are presented in Table 1.

Table 1. Test series wallboard sample description.

	Test Series 1	Test Series 2	Test Series 3	Test Series 4	Test Series 5
Width (cm)	60.96	60.96	15.24	60.96	121.92
Height (cm)	121.92	121.92	45.72	121.92	60.96
Aspect ratio	2.0	2.0	3.0	2.0	0.5
Immersed end	End[a]	End	Lab[b]	Edge[c]	End
Vertical edges	Edge/Lab	Edge/Lab	Lab/Lab	End/Lab	Edge/Edge
Manufacturer	A	B	A	B	B
Sample sections	2	2	4	2	2

[a] End is the manufacturer cut, exposed gypsum end.
[b] Lab refers to the laboratory cut, exposed gypsum end.
[c] Edge is the manufacturer finish paper-bound end.

Moisture content readings were taken of the wallboard sample sections prior to testing to determine the ambient (background) %MC. These reading were compared to an ambient standard (a portion of the same wallboard set on the laboratory bench) and the laboratory wall. The ambient moisture content of all wallboard sample sections mimicked the ambient standard and laboratory wall, measuring 0.3%MC throughout the experiment study period.

The moisture was observed to move upward across the width of the wallboard in a pattern similar to paper chromatography. The moisture content moved upward, in nearly horizontal concentration gradients, across the wallboard's width. This moisture movement pattern and the presence of moisture concentration gradients were evident in all wallboard samples tested, although the rate of upward movement and the concentrations were not equivalent. Contour plots of TS5 were generated using SigmaPlot, version 9.0, showing six elapsed time periods. Figures 1a through 1f show the moisture wicking heights attained along with the moisture gradients throughout the wallboard.

Figure 1a. Moisture height @ elapsed time = 0.033 days (~48 min)

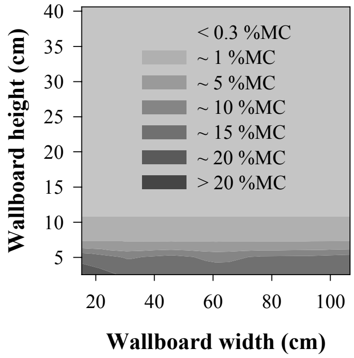


Figure 1b. Moisture height @ elapsed time = 0.124 days (~3 hours)

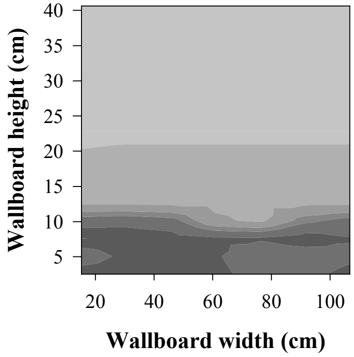


Figure 1c. Moisture height @ elapsed time = 0.240 days (~6 hours)

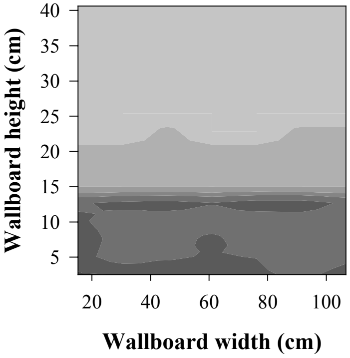


Figure 1d. Moisture height @ elapsed time = 1.042 days

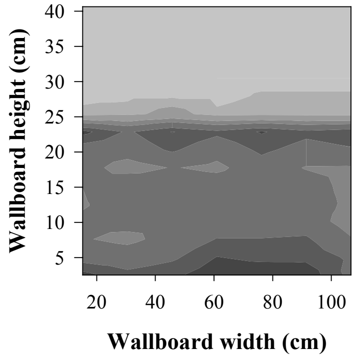


Figure 1e. Moisture height @ elapsed time = 2.048 days

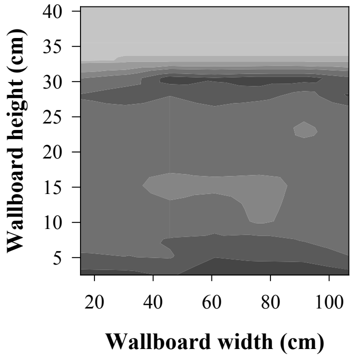
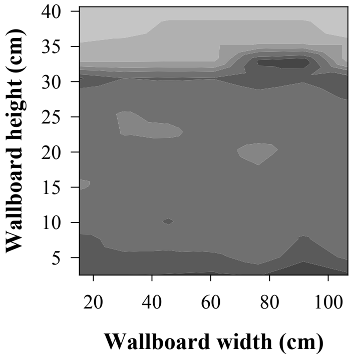


Figure 1f. Moisture height @ elapsed time = 3.063 days



Within 48 minutes of immersion (Figure 1a), discernable moisture gradients were measured along the face of the wallboard. Within the first three hours (Figure 1b), moisture readings greater than ambient moisture conditions (0.3%MC) had reached heights approaching 20 cm (8 in). After approximately six hours (Figure 1c), a leading edge formed having moisture content comparable to the immersed portion of wallboard (~20%MC). Between the leading edge and immersed end of the wallboard an area of lower moisture content (~ 10% to 15%MC) developed. On the forward side of the leading edge, moisture readings taken one increment higher (2.54 cm) were significantly lower; typically less than 1%MC.

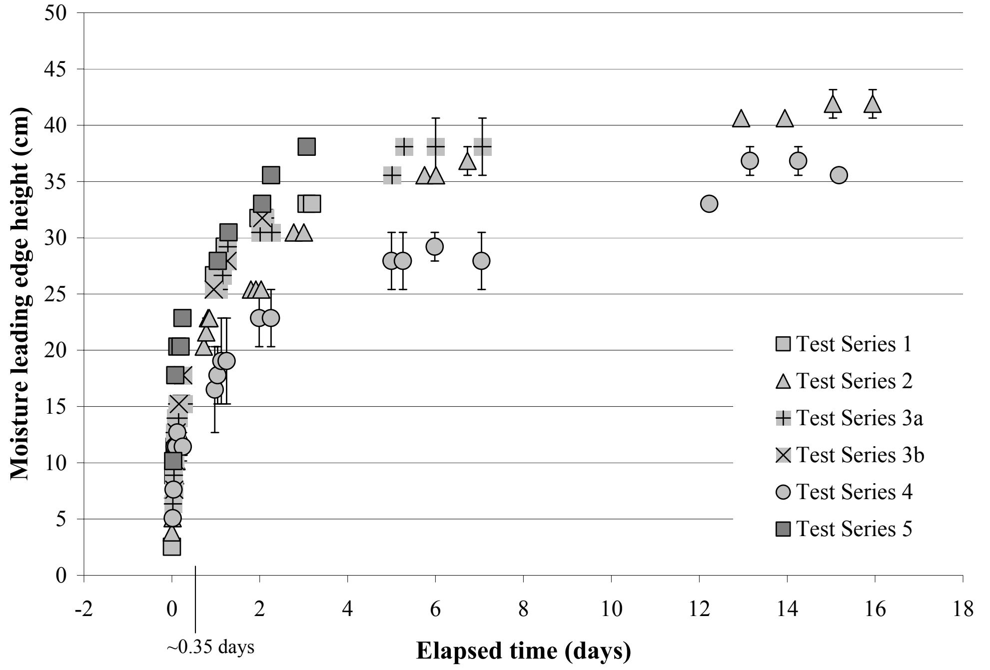
As with paper chromatography, impurities, salts, etc. within the gypsum will migrate upward with the water. It is possible that these solutes were, in part, responsible for the higher %MC measured at the leading edge. Another indicator of vertical water movement was the appearance of water-line marks on the surface of the wallboard face and back. The water-lines were reasonably horizontal across the central portion of the wallboard, but were observed to bend upward toward the outer ends of the wallboard sample sections. The outer ends of the wallboard are not shown in Figures 1a through 1f. Measurements were not taken along the outer edges of the wallboard. The water-line marks did not correlate directly to the measured water height within the gypsum. For all wallboard tested, the visible water-line reached a maximum height of approximately 10 cm (4 in) after two weeks of constant water immersion. For TS5, after an elapsed time of 1 day (Figure 1d), the water-line had reached a height of 5 cm (~2 in) whereas the moisture content leading edge was measured at a height of 28 cm (~11 in). After 2 days of continuous immersion (Figure 1e), the water-line reached a height of 8 cm (~3 in) while the moisture reached 33 cm (~13 in). No further change in the water-line movement (height) was observed with elapsed time for TS5, although moisture continued to move upward.

To plot wallboard moisture height as a function of elapsed time, a single representative moisture height measurement was obtained. The moisture content measurements along each horizontal grid (every 2.54 cm) were averaged across the wallboard's width. The averaged moisture content value obtained was then compared against the nominal ambient moisture content (0.3%MC). The highest horizontal grid-line with an average moisture content value greater than the ambient value was the moisture height plotted.

The representative moisture heights obtained for each test series' duplicate samples were then averaged to represent a single moisture height for plotting. A standard deviation of ±1.37 cm or less was calculated for most test series data collected. This value represents a one increment maximum difference (2.54 cm) in the measured moisture height between duplicate test samples. An exception was Test Series 4, where the maximum standard deviation reached ±3.81 cm. The standard deviation was based on two data points obtained from the duplicate sampling.

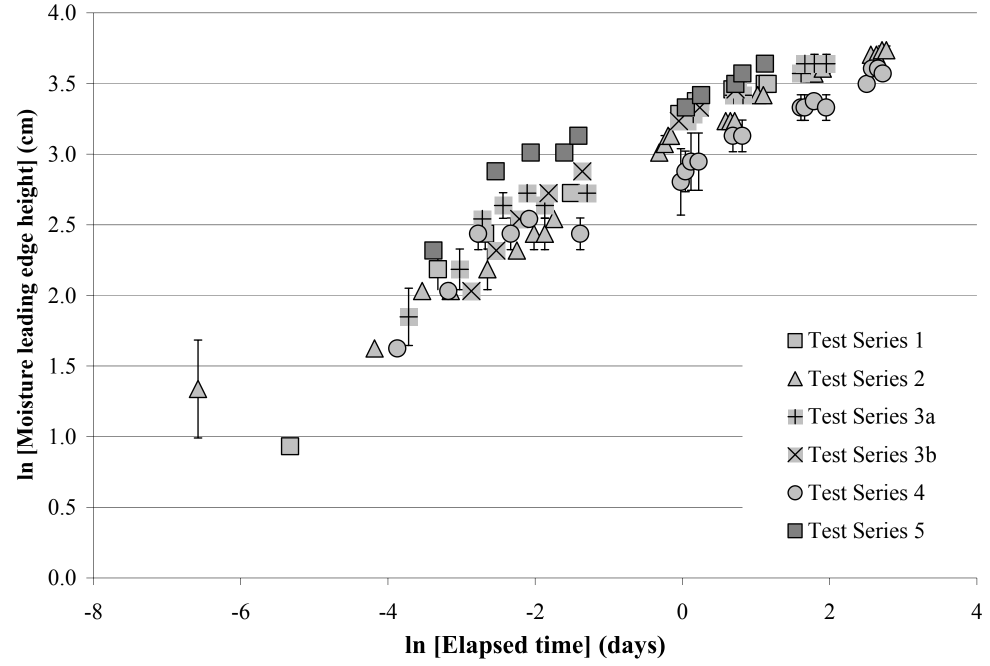
A plot of elapsed time in days versus moisture height with one standard deviation in inches is shown in Figure 2. The plotted data sets appear to follow the form of an exponential growth to maxima function. Using SigmaPlot, single and simple exponential functions of two and three parameters were applied to each data set resulting in R^2 values greater than 0.9 with parameter estimate p-values less than 0.001. These preliminary results suggest the initial assessment of curve fit was reasonable. The plots visually appear to show three differing growth rates, with TS5 greater than and TS4 less than the remaining test series; TS1, 2, and 3.

Figure 2. Vertical moisture movement in gypsum wallboard during continuous water contact.



SAS statistical software was used to more accurately fit the data and interpret the findings. The moisture height and elapsed time data underwent natural log transformation. A plot of the transformed data with one standard deviation is shown in Figure 3. A separate-slopes general linear model was fit to the data (one slope per test series). All linear model fits of the data sets had R^2 values greater than 0.9 and parameter estimate p-values less than 0.001. A comparison of the rates of increase was performed using pair-wise tests of equality of slopes. Although the estimated slope parameters differed slightly, the analysis indicated no significant difference between the data sets.

Figure 3. Natural log transformation plot of the vertical moisture movement data.



The equality of slopes analysis results suggest the visual appearance of differing rates seen in Figure 2 is likely attributed to experimental variables and errors. Several possibilities may account for the variation observed between the test series data curves. Due to the wallboard manufacturing process and differences in raw materials, additives, and impurities, it is suspected that structural variations (porosity, density, etc.) exist throughout the gypsum wallboard. Variations in porosity or density within the gypsum material would be suspect in altering the water movement rate. It was also suspected that differences in water movement would exist between wallboard manufacturers. Test series 1 and 3 were performed with manufacturer A wallboard and test series 2, 4 and 5 were performed on manufacturer B wallboard. As mentioned previous, test series 1, 2 and 3 had similar rates of water movement. Test series 1 and 2 were identically dimensioned and oriented as tested, but differed in manufacturer. Test series 2, 4, and 5 were from the same manufacturer but varied in dimension and orientation from one another. Although the water movement rate of test series 4 and 5 appeared to differ from the other test series, no conclusion can be reached regarding this difference due to wallboard manufacturer. The dimensions and orientations of test series 4 and 5 were only tested on manufacturer B wallboard.

The method used to determine a single representative moisture height had inherent variability due to the moisture meter accuracy and the simplified concept of a horizontal moisture level movement upward in the wallboard. As mentioned previously, the meter had a manufacturer stated tolerance of ±20% of the reading. The moisture meter response was nearly linear to the gravimetric standards less than 1% MC, but the readings averaged 50% lower than the gravimetrically calculated %MC. Meter response above the 1%MC gravimetric standards followed a second degree polynomial curve with readings averaging 35% lower than the nominal 1, 10, and saturated %MC gravimetric standards. The meter reading of the nominal 5%MC gravimetric standard was nearly equivalent. Based on the meter response to the gravimetric standards, the actual moisture heights attained may have been slightly higher.

Other possibilities to consider are evaporative loss through the wallboard surface area and the exposed gypsum along the outer vertical ends. The spacing and grouping of the data points in Figure 3 are a result of the log transformation but may reveal the point that evaporative loss through the wallboard surface area affects the wicking rate. When the test series data plots were separated into two halves, greater than and less than ln[elapsed time]= -1, and linear regression applied to each half, differing estimated slope parameters were calculated. Each data plot's estimated slope decreased for the data half greater than ln[elapsed time]= -1 (approximately 8½ hours – 0.35 days). In Figure 2, this is seen as a relative change in the slope from a sharp rise to an asymptotic form at approximately 0.35 days. It is suspected that upon reaching a water mass balance relative to the surface area within the wallboard, evaporative loss of water through the surface area counters, or slows the upward wicking rate.

The loss of moisture through the unsealed, exposed gypsum along the outer ends of the wallboard sample sections was termed the "edge effect". The smaller the aspect ratio (vertical height/horizontal width) of the wallboard sample, the lower the edge effect. The wallboard edge (finished paper-bound edge) would have a lower edge effect than the exposed gypsum ends. It was suspected that water moved faster to the unsealed, exposed gypsum ends in the wallboard sample sections measuring less than 60.96 cm wide. One indicator of this concept is the upward bend of the water-line mentioned previous.

The edge effect evaporative loss can also be described by correlating the data in Table 1 with the plots in Figures 2 and 3. TS1 and TS2 had the manufacturer cut, exposed gypsum end immersed in water with a total surface area in direct contact with the water of 36.5 in^2 (~12 in^2 of exposed gypsum and ~24 in^2 of paper covered gypsum). TS5 had the manufacturer cut, exposed gypsum end immersed with double the surface area in direct water contact (~24 in^2 of exposed gypsum and ~48 in^2 of paper covered gypsum). It is suspected this larger area replenished the water (moisture) content faster than water was drawn upward and/or evaporated from the samples in TS1 or TS2. Additionally, the TS5 sample sections had a lower edge effect. The TS5 sample sections had the manufacturer edges (finish paper-bound edges) at each vertical end. It is thought that this paper covered and pressed edge, reduced the evaporative loss through the vertical ends.

TS4 sample sections were placed with the manufacturer finish paper-bound edge immersed in water. The TS4 immersed surface area was slightly less than TS1 and TS2 due to the compressed portion of the finished edge. It was suspected this area of denser, paper covered gypsum material slowed the uptake of water, reducing the replenishment source of moisture moving upward within the wallboard. Also, TS4's higher edge effect may have slowed the movement of water upward by allowing greater loss through the unsealed ends.

Capillary action is responsible for the movement of a liquid within a substrate medium. For capillary tubes of known radius, water height is dependent on the surface tension and the weight of the column of water. At some height, the forces acting within water (adhesion, cohesive, surface tension) and interacting between the water and a medium (hydrogen bonding) would reach equilibrium with each other and gravity.

Equation 1.

$$h = \frac{2T}{\rho r g}$$

Where

h = liquid height
T = surface tension (0.0728 N/m @ 20°C, air at sea level)
r = capillary radius
ρ = density (1000 kg/m^3)
g = acceleration due to gravity (9.8066 m/s^2)

Solving Equation 1 for capillary radius r, a mean gypsum wallboard pore size can be calculated. For a height of 0.43 m (~17 in), obtained in this experiment series (Figure 2), the gypsum media would have a mean radius of 3.45×10^{-7} cm. While this mean pore radius implied by this equation is possible, it is unlikely that gypsum wallboard is uniform in its pore structure. Structural inconsistencies in gypsum provide another variable in determining the moisture wicking rate or final water height attainable.

CONCLUSION

In the uncoated regular gypsum wallboard laboratory testing, water wicked quickly upward to heights of 15 cm or more during the first several hours of continuous immersion. The wicking then decreased in rate asymptotically and after sixteen days appeared to approach a maximum height of approximately 43 cm. It is unclear what height water would wick during longer test periods.

The moisture content detected in the wallboard reached values greater than 20%MC, as measured with the moisture meter selected. Moisture content gradients formed within the wallboard after several hours, developing a leading edge with readings equivalent to the immersed portion of the wallboard sample.

Several variables appeared to complicate the determination of moisture wicking in gypsum wallboard. Among the variables considered were the manufacturing process (the finished wallboard product), the moisture height determination method, the meter accuracy, and evaporative loss from the wallboard surfaces. The wallboard's density (pore and interstitial structure) likely varies between manufacturers and possibly within each sheet itself due to the manufacturing process, raw gypsum materials, additives, and impurities. The method to determine moisture height in the wallboard samples could benefit from smaller vertical grid spacing and/or a different method or technique of detection. A change in the detection technique or moisture meter would require additional testing to ensure reliable data collection. A sampling test method to determine the influence of moisture within the paper versus the gypsum would prove beneficial. Other experimental variables to consider are the moisture loss through the uncoated paper surfaces and unsealed ends.

Continued study of gypsum wallboard moisture wicking is needed to better understand the variable interactions and to determine the effects of surface finishes and material composition.

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