B6: Prediction and measurement

INDOOR DAMPNESS AND MOLD AS INDICATORS OF RESPIRATORY HEALTH RISKS, PART 6: COMPARISON OF CHAMPS SIMULATION OF THE MOISTURE CONTENT AND WATER ACTIVITY OF GYPSUM WALLBOARD TO CONTROLLED LABORATORY MEASUREMENTS

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SUMMARY

This paper describes one part of a multi-component, on-going effort at the Indoor Air Quality Section of the California Department of Public Health to develop evidence to support *quantitative*, health-protective guidelines for indoor dampness and dampness-related agents. A one-dimensional simulation was conducted using a Combined Heat, Air, Moisture, and Pollutant Simulation program (CHAMPS) to predict the moisture content (MC), percentage wood moisture equivalent (%WME), and equilibrium relative humidity (ERH) (or water activity A_w) of gypsum board under various air relative humidity levels at steady-state conditions. The simulations were then compared with controlled laboratory measurements. Results indicated that CHAMPS simulations predicted the MC, %WME, and A_w of gypsum board in the correct order of magnitude and captured well the overall trend of the experimental results. The study demonstrated the feasibility of using CHAMPS simulations to assist in the design or interpretation of moisture measurements for epidemiological studies investigating the relationship between measured moisture and health risks.

INTRODUCTION

Quantitative assessments of actual building dampness, such as measured moisture content (MC) or more recently, water activity (A_w), may provide useful information in epidemiological studies that aim to establish dose–response relationships between microbial growth, dampness, and multiple health outcomes (Mendell et al., 2011). However, different types of moisture meters have been used to take field measurements (Williamson et al., 1997; Lowenthal et al., 2002; Venn et al., 2003) and the equivalences of their responses are not well established. In addition, very limited data are available regarding the use of A_w sensors on *in situ* building materials (Aqualab, 2013). Our group is conducting laboratory experiments to compare the responses of various moisture meters and an A_w sensor and to determine how these readings correlate with the true (gravimetric) MC of gypsum wallboard (Macher et al., 2014). This paper first describes how CHAMPS, a Combined Heat, Air, Moisture and Pollutant Simulation program (Zhang and Qin, 2011), can be used to predict measured moisture content (MC) vs. relative humidity (RH) under test conditions. It then compares simulation results to experimental ones.

METHODOLOGIES

The experimental set-up and instrumentation have been described in detail elsewhere (Macher et al., 2014). Figure 1 shows a simplified schematic. We conducted a one-dimensional simulation across the board thickness using CHAMPS. Modelling a building material or assembly by CHAMPS is relatively straightforward. What the user needs to define mainly includes geometry and construction, material properties, initial conditions, boundary conditions (including climate conditions), output selections and formats, and solver settings.

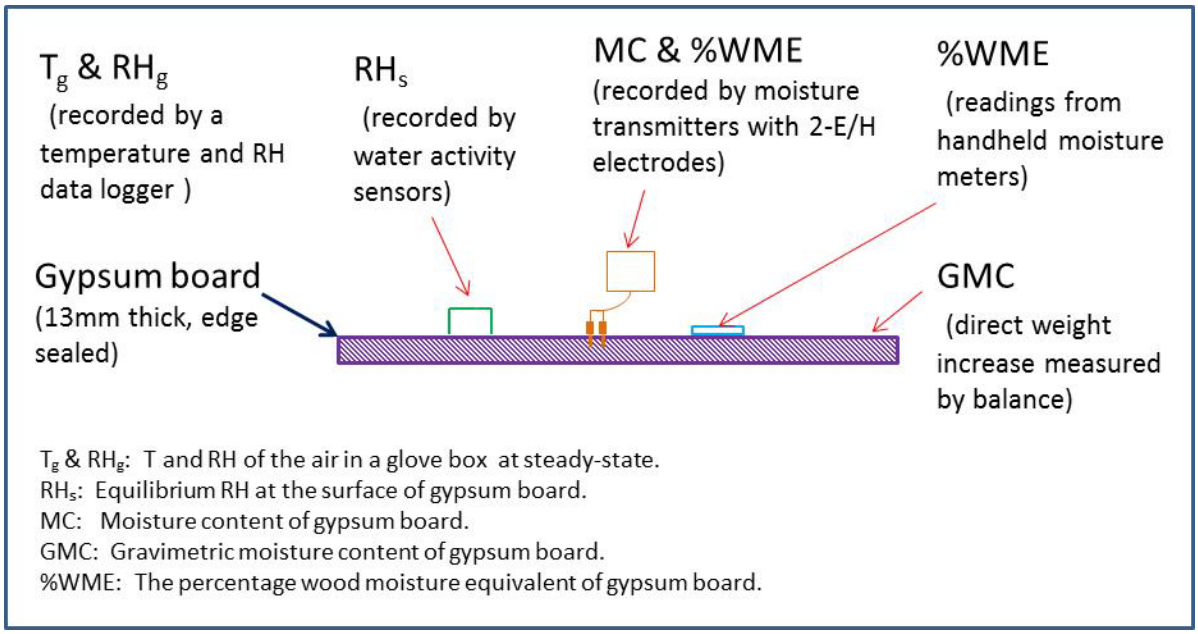

Figure 1. Simplified schematic of experimental set-up

Table 1. Basic material properties used in the simulations

	Gypsum board	Wood (Spruce)
Specific heat (J/kgK)	850	2000
Density (kg/m^3)	520	528
Open porosity (m^3/m^3)	0.65	0.70
Capillary saturation moisture content (m^3/m^3)	0.551	0.695
Thermal conductivity (W/mK)	0.20	0.13
Water vapor diffusion resistance factor (-)	10	236

Note: The density of gypsum board was determined in the laboratory from measured weight and volume; all other values were default values taken directly from the CHAMPS material database.

We conducted a grid sensitivity analysis first and determined that using a grid number of 100 was sufficient for the simulation. Table 1 summarizes the basic material properties of gypsum wallboard used in the simulation. The gypsum board density was measured gravimetrically and is within the range specified in a product datasheet from the manufacturer (Gold Bond® Brand, National Gypsum Company, Charlotte, NC). All other variables are default values taken from the CHAMPS material database, as no further information was available for the specific gypsum wallboard used in the test. For the initial conditions, we assumed that the gypsum board was initially completely dry. For the humidity boundary conditions, we used "vapour diffusion" type with a default exchange coefficient of 3×10^{-8} s/m (second/meter). For each RH condition, we conducted the simulation sufficiently long to make sure the steady-state (equilibrium) had been reached. In theory, the final MC of gypsum board under equilibrium conditions should remain the same regardless of the selection of initial conditions and exchange coefficient for vapour diffusion. We also simulated how a piece of wood of the same dimensions might perform under identical conditions using default values for spruce from the CHAMPS material database (see Table 1), and we compared this with the percentage wood moisture equivalent (%WME) of gypsum board measured by the two handheld moisture meters and the Delmhorst moisture transmitter.

RESULTS AND DISCUSSION

Figure 2 shows the predicted gravimetric MC (% kg/kg) vs. RH for gypsum board and wood (spruce) at steady-state (equilibrium) conditions at 23°C. As expected, the MC of both wood and gypsum board increased as the ERH increased, and the wood had a much higher moisture holding capacity than gypsum board. At an ERH of 60%, the MC of gypsum board was ~0.8% whereas that of wood was ~10%. At 85% ERH, the MCs were ~1.7% and ~16% for gypsum board and wood, respectively. Macher et al. (2014) experimentally verified the linear relationship between ERH measured in a glove box enclosure and the A_w measured at the surface of gypsum board. An ERH of 60%–85% corresponded to an A_w of 0.6–0.85 (unitless), a range including levels sufficient for the growth of many species of fungi and some bacteria. When ERH continued to increase to 95%–98% and above, MC fell into the over-hygroscopic range and increased very sharply, especially for gypsum board. Under these RH conditions, a relatively small increase in the MC of wood would correspond to a substantial increase in the MC of gypsum board.

Table 2 compares the measured and predicted results under the tested RH conditions. The gravimetric MC of gypsum board and the %WME measured with the handheld moisture meters and moisture transmitters are also shown in Figure 2 for comparison. The %WME of a building material is defined as the theoretical MC that a piece of wood in moisture equilibrium with the material being measured (Macher et al., 2014). In this study, we assumed that the %WME of gypsum board would be the same as the gravimetric MC of a piece of wood in equilibrium with the same environmental conditions to which the gypsum board was exposed. Results indicated that the CHAMPS simulation predicted the gravimetric MC and ERH (or A_w) of gypsum board in the correct order of magnitude and captured the overall trend of all experimental results reasonably well. As for the %WME of gypsum board, there were significant differences between readings obtained from the two types of moisture meters (pinless EP vs. two-pin PS) at high ERHs, especially at 99% ERH. Agreement with the simulation for wood was better with the PS moisture meter; however, to date only three data points are available for this and the two-pin moisture transmitter (MT). The simulation captured the trend of the EP moisture meter measurements up to ~70% ERH. The simulated %WMEs also were in the correct order of magnitude as those measured with the MT. However, the MC of

gypsum board calculated from the MT current output (only shown in Table 2) seemed to be anomalous compared with the gravimetric measurement and the simulation. This may be due to property differences between the gypsum board used by the MT manufacturer to generate the typical conversion chart and the specific gypsum board used in our tests. The agreement between simulated and measured results may be further improved if more material properties were known for the specific gypsum board used in the tests, for the specific gypsum board and wood used to calibrate the MT, as well as for the specific types of wood used to calibrate the moisture meters.

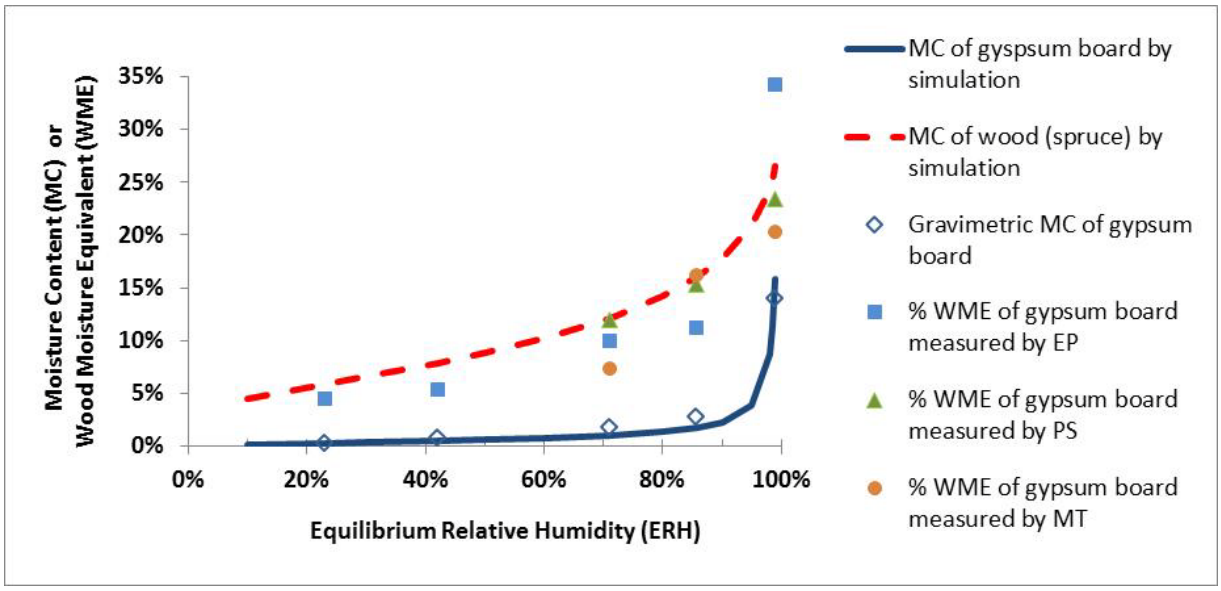

Figure 2. Comparison of predicted moisture content (MC) vs. equilibrium relative humidity (ERH), using the CHAMPS simulation (solid and dashed lines for gypsum board and wood, respectively), with the gravimetric MC of gypsum board and the %WME measured with moisture meters and moisture transmitters at five equilibrium conditions (single points); EP: Electrophysics pinless moisture meter; PS: Protimeter Surveymaster two-pin moisture meter; and MT: Delmhorst two-pin moisture transmitter.

CONCLUSIONS

This study demonstrated the feasibility of using heat, air, and moisture (HAM) simulation to predict the gravimetric moisture content, percentage wood moisture equivalent, and water activity measurements of gypsum board. Because field measurement results often involve dynamic moisture behaviour and versatile building materials, we will, in future studies, further explore how CHAMPS simulation can be used to assist in the interpretation of moisture measurements obtained from epidemiological health studies under varied environmental conditions (Mendell et al., 2014; Mendell, 2014).

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Table 2. Comparison of measured vs. simulated moisture and water activity (A_w)

Glove box RH[1]	Equilibrium relative humidity (ERH) of gypsum board		Moisture content (MC) of gypsum board (% kg/kg)			Percentage wood moisture equivalent (% WME) of gypsum board			
	Based on A_w Sensor Reading[2]	CHAMPS simulation	Gravimetric measurement	Moisture transmitter (MT)[3]	CHAMPS simulation	Moisture transmitter (MT)[3]	Moisture meter (PS)[4]	Moisture meter (EP)[5]	CHAMPS simulation[6]
23%	23%	23%	0.3	< dl[7]	0.3	< dl	< dl	4.5	5.9
42%	41%	42%	0.7	N/A[8]	0.5	N/A	< dl	5.4	7.9
71%	70%	71%	1.8	0.1	1.0	7.3	11.9	9.9	12.1
86%	82%	86%	2.8	0.7	1.8	16.2	15.3	11.3	16.1
99%	99%	99%	14	0.9	15.9	20.3	23.4	34.3	26.6

Note: (1) relative humidity (RH) in a glove box after reaching steady-state conditions. (2) water activity (A_w) sensor — Decagon Devices, Inc.; values reported in the table were A_w sensor reading (unitless) × 100%. (3) The MC and the %WME for gypsum board were calculated from the current output of the Delmhorst moisture transmitter (MT) with electrodes and pins, using a conversion chart provided by the manufacturer. (4) PS — GE Protimeter Survey master (pin mode). (5) EP — Electrophysics Model CT100. (6) Based on the simulated true MC of a piece of wood (spruce) when in equilibrium with the same environmental conditions to which the gypsum board was exposed. (7) < dl = below detection limit. (8) N/A = no data (data lost).

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