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Experimental Study of Moisture Buffering with Simultaneous Indoor RH and Temperature Variation

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Abstract
Hygroscopic materials have the potential to adsorb and release moisture from the environment; effectively buffering the humidity on an indoor environment. This study explores a method to obtain a moisture buffering value of common building materials by developing experimental methods with conditions closer to reality, as opposed to previous step response of humidity variation. Comparing a sinusoidal response with step-response profile modified from the NORD Test for simultaneous temperature and humidity variation, allowed for the variations to be ranked according to their predicted performance over time. This outcome could potentially aid designers in the practical application of hygroscopic non-structural elements where the consideration of moisture buffering can be included in their design; with a more plausible estimation of how hygroscopic materials would respond to environmental condition variations.

Keywords Indoor air quality, Sustainable construction materials, Relative humidity, Test methods

1.0 Introduction
Modern buildings are designed to be well-insulated with minimum infiltration to reduce heat loss. While indoor Relative Humidity (RH) is conventionally controlled by air-conditioning units, such systems have been shown to be inadequate to bring indoor RH to the optimal level in certain cases [1], and require additional energy consumption and associated environmental impact due to their operation. High indoor RH also requires more energy to heat up the air of low RH with the high specific heat capacity of moisture [2], further increasing energy consumption when compared to heating air in a low indoor RH environment. Occupant interaction with mechanical systems plays a vital part in energy and carbon performances of buildings, as well as regulating the indoor air quality. Simonson *et al* [3] has reported the merit of having hygroscopic materials within an enclosed space to moderate indoor humidity variation, while others later testified on the positive impact on energy efficiency [4] and occupant comfort [5]. The increasingly apparent global climate shift indicates that there is a rising need for a passive system which would be suitable across all climates.

There are a variety of methods to investigate a material's role in passive regulation of humidity levels. The NORD Test method is currently the most recognised way to appraise the moisture sorption in materials [6] and is proven to be highly reproducible

[7]. However, due to the nature of NORD Test method's test assumptions, the data-collection cycle is very limited as the moisture uptake and release pattern is restricted by the 2-step pre-set moisture load. McGregor *et al* [8] concluded that the different tests produce comparable results but only under very specific conditions, thus raising the question if such assumptions reflect real-world conditions with many other ever-changing environmental factors. Other studies have been carried out in stages, from observations of actual climate response [9][10][11] to full-scale building based on previous simulations [12]. It was validated that the heat and moisture balance model aided in predicting actual indoor temperature, RH and heating/ cooling demand.

The aim of this paper is to investigate alternative methods of quantifying a dynamic response to environmental humidity and temperature variation. The objectives include investigating the effect of temperature on moisture buffering performance, as well as a sinusoidal variation rather than the typical step-response. This understanding will help appreciate real-world conditions.

2.0 Materials and Methods

2.1 Materials

Under varying RH conditions, moisture will only penetrate into a hygroscopic material to a depth, that will vary depending on the material, but for typical plastering material is limited to approximately 10mm [16]. Therefore, this study will only consider these surface finishing materials that can interact with the environmental RH. The materials selected for this study are gypsum, a conventional building material; and clay, an earth-source material to aid further development in sustainable construction. Two materials were included in the study to observe the diversity of response to justify the feasibility of applying this testing method across different materials.

Specimen size has been established to be 150 mm × 150 mm × 20 mm thick, where specimen thickness is twice the expected moisture penetration depth [16] to allow for uncertainties. Before placing the specimens in an environmental chamber with controlled varying conditions, the back and side faces of the specimens were covered in aluminium tape to seal to ensure that the interaction with surrounding air moisture only occurs at one face (area of 150 mm × 150 mm) of the material. Specimens were first stored in an environment at 23°C and 50% RH after casting for 28 days and weighed to ensure they were at an equilibrium with the environment. After they were transferred to the environmental chamber at the same conditions for at least 96 hours (4 days) before testing in accordance with the NORD Test procedure.

2.2 Methods

The standard NORD Test procedure was used to compare the results. This method stipulates a square wave change in RH from 33% to 75%, with 16 hours at the high RH and 8 hours at the low. This method was used as a control for the further tests of temperature variation and sinusoidal wave function. To independently investigate the influence of temperature variation, the method was modified to step change the temperature between 18°C and 28°C with a constant humidity. Finally, both the variations of RH and temperature were investigated under a sinusoidal wave. The variation in methods is demonstrated in Table 1.

Test Condition	Max RH	Min RH	Max temp	Min temp	Variation
Control: Square - RH	75%	33%	Constant 23°C		Steps
Square - Temperature	Constant 50% RH		28°C	18°C	Steps
Sine - RH	75%	33%	Constant 23°C		Sinusoidal
Sine - Temperature	Constant 50% RH		28°C	18°C	Sinusoidal

Table 1 - Summary of test conditions limited to ideal constants.

A sinusoidal variation curve referencing the step-variation with positive and negative RH arches has been created, where high RH is maintained for 8 hours and low RH is maintained for 16 hours (Figure 1). Being inversely proportional to RH, the temperature variation was set to start with an 8-hour negative arch instead (Figure 2). Testing profiles were limited to ideal condition taken to be 23°C and 50% RH, temperature variation inversely proportional to RH limited by lowest acceptable temperature (18°C) and maximum allowable temperature for overheating (28°C). An ACS DY100 environmental chamber was used, allowing for an accuracy of ± 0.1 K and ± 1 % for temperature and RH respectively. However, these are under static conditions and the impact under dynamic conditions needs to be considered. While efforts were made to keep air velocity within the range of 0.02-0.3m/s [18], the effect of airflow variation is not taken into account.

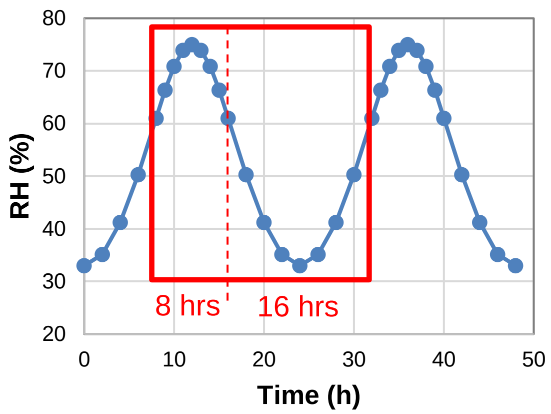

Figure 1 - Sinusoidal RH variation load profile.

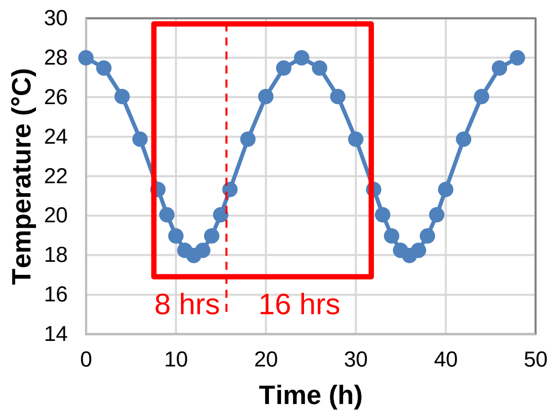

Figure 2 - Sinusoidal temperature variation load profile.

The test period is set to be 24 hours per cycle, with minute-interval data collection to study behaviour pattern of the materials under specified condition. Each test is allocated to run for two cycles to obtain feasible data, repeated for three specimens for each of the two materials.

3.0 Results

3.1 Monitoring Testing Environment

While the equipment used is programmed with temperature and humidity, this is achieved through introducing an absolute amount of water. Due to the psychometrics, changing temperature, with a constant absolute mass of water vapour, will result in a change in RH. Therefore, changing the temperature requires additional load to correct the induced change in humidity. The tendency of RH corresponding to temperature makes it complicated to maintain constant RH with temperature variation, which led to the decision to monitor actual RH and temperature within the climatic chamber despite the test profile being set. All measured temperature is lowered by a slight margin of 0.5-0.6°C, the resultant RH are relatively higher compared to programmed RH in every case and almost never able to maintain constant RH. Interestingly, the statement “RH is inversely proportional to temperature” no longer applies under low RH condition as the resultant RH appears to be fluctuating in accordance to temperature change.

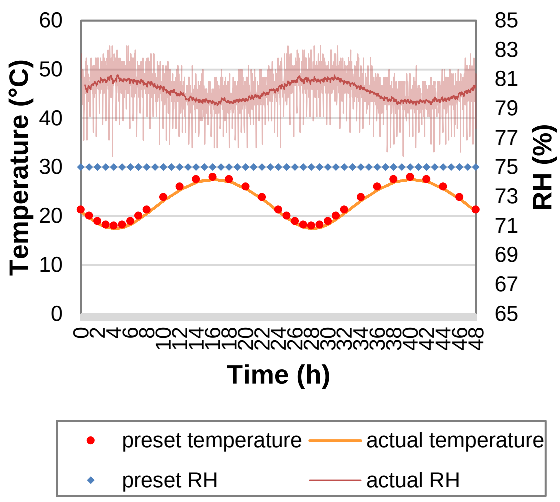

Figure 5 - Comparison of pre-set temperature sinusoidal variation profile and actual profile at high RH (75%).

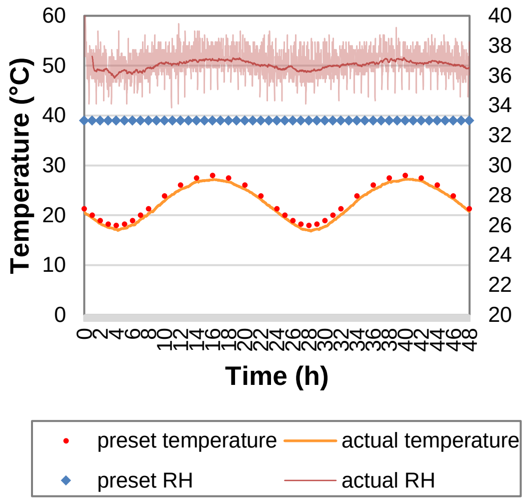

Figure 6 - Comparison of pre-set temperature sinusoidal variation profile and actual profile at low RH (33%).

3.2 Material Performance

The obtained results were analysed by the change in mass of specimens, expressed in g/m^2. The typical response of the gypsum material is presented in Figure 3 and Figure 4 respectively, and Table 2 and 3 show both gypsum and clay materials’ averaged test results.

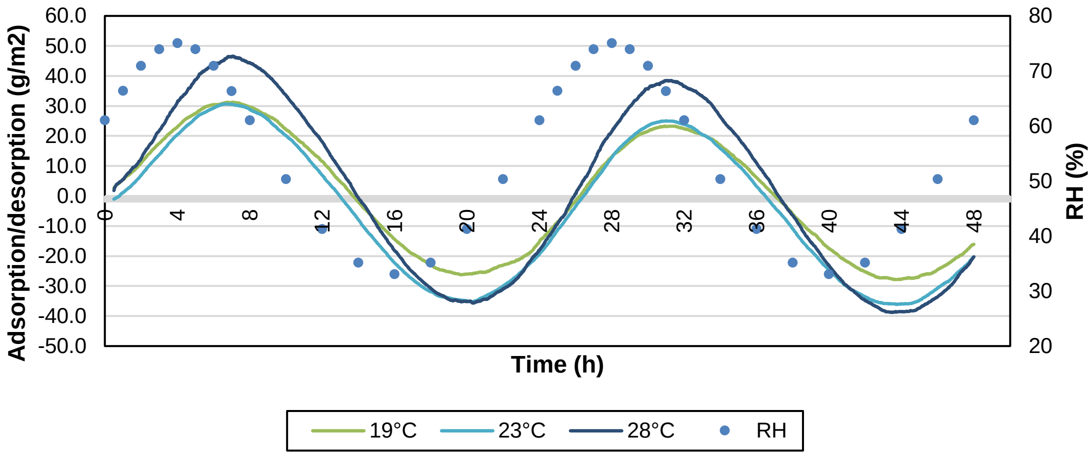

Figure 3 - Sorption of gypsum specimen against time with humidity sinusoidal variation at different constant temperatures.

Material	Temp (°C)	peak (g/m²)		offset (h)		arch period (h)	
		des.	ads.	des.	ads.	des.	ads.
Gypsum	19	28.7	21.0	4.0	3.0	13.0	10.5
	23	29.3	23.2	3.5	3.0	13.5	10.0
	28	46.7	34.5	3.8	3.0	13.3	10.8
Clay	19	22.9	14.0	4.0	2.7	13.8	9.8
	23	27.0	20.3	3.5	3.0	13.5	10.0
	28	37.1	15.2	3.3	2.5	15.0	7.8

Table 2 - Summary of averaged desorption (des.) and adsorption (ads.) test results subjected to sinusoidal RH variation.

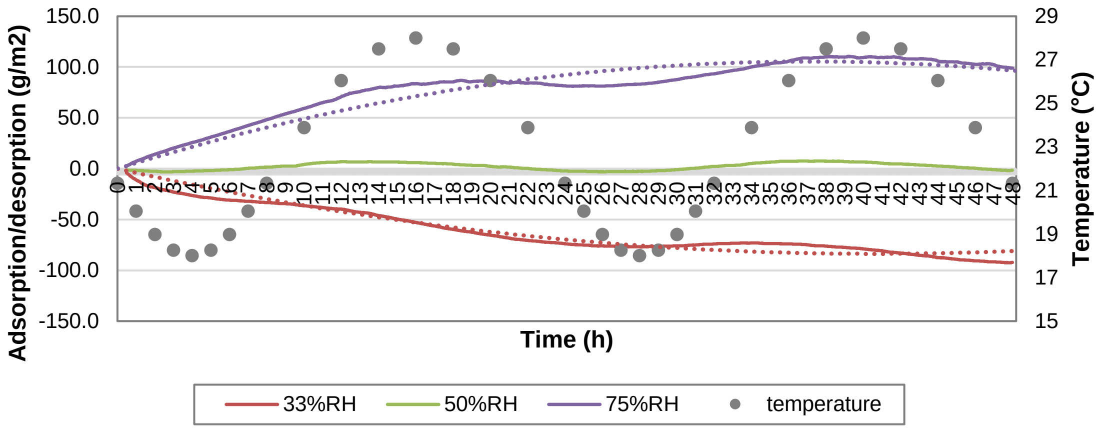

Figure 4 - Sorption of gypsum specimen against time with different constant RH, with reference balance point.

Material	RH (%)	peak (g/m²)		offset (h)		arch period (h)	
		des.	ads.	des.	ads.	des.	ads.
Gypsum	33	5.0	7.0	-4.5	-5.0	9.5	14.0
	50	5.5	6.5	-2.8	-2.0	12.0	12.3
	75	14.7	15.7	-1.3	0.2	13.7	13.7
Clay	33	3.3	5.3	-2.0	-1.3	11.8	12.3
	50	5.0	7.0	-1.5	-0.8	12.0	12.8
	75	8.3	9.7	-1.5	0.8	14.3	13.7

Table 3 - Summary of averaged desorption (des.) and adsorption (ads.) test results subjected to sinusoidal temperature variation.

Under constant temperature conditions, the sorption of clay specimens constantly peak with a delay in response to RH variation peak points, referred to in this study as response offset. Higher temperatures yielded a greater amplitude of sorption while lower temperature generated a smaller moisture uptake and release. Gypsum specimens displayed similar curves with slightly improved consistency. In contrast to the phenomena during low RH, high RH has stimulated the continuous adsorption of air moisture in the specimens. The peaks of the resultant curves are much closer to the peaks of the temperature variation profile in terms of time offset when compared to the case in low RH. Ideal RH (50%) is taken as a balance point to mirror RH response to temperature variation at high or low RH.

Both gypsum and clay samples exhibited similar behaviour when subjected under the constant RH condition. However, the materials could only fluctuate back and forth from their original state at ideal RH. At high RH, the materials displayed continual moisture uptake in stark contrast to continual moisture release at low RH. It is assumed that the significance of continual moisture uptake and release will gradually decrease as the material gets closer to achieving moisture equilibrium at the given RH.

4.0 Analysis and Discussion

4.1 Impact of Variation

The impact of variation with respect to the initial mass of the specimens is compared to the pre-conditioning values, that also represent ideal conditions, of 23°C and 50% RH. Both the materials recorded positive percentage change in sorption capacity when temperature is increased to 28°C, and negative percentage when temperature is decreased to 18°C. The desorption for clay at 28°C turned out to have a negative percentage change instead of the anticipated positive percentage change; potentially due to the variation observed in Section 3.1.

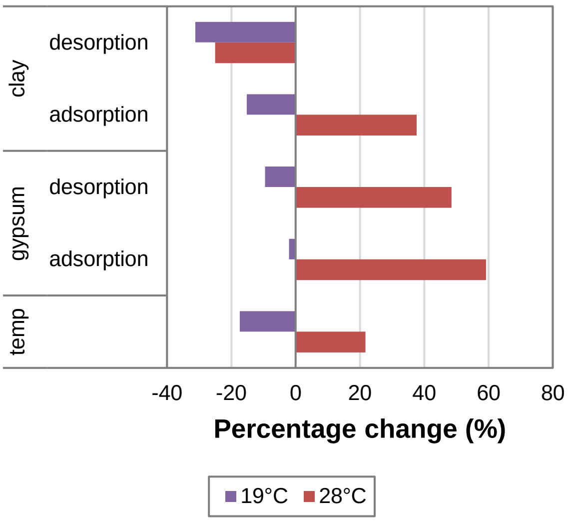

Figure 7 - Changes in gypsum and clay sorption capacity with RH sinusoidal variation at constant temperature.

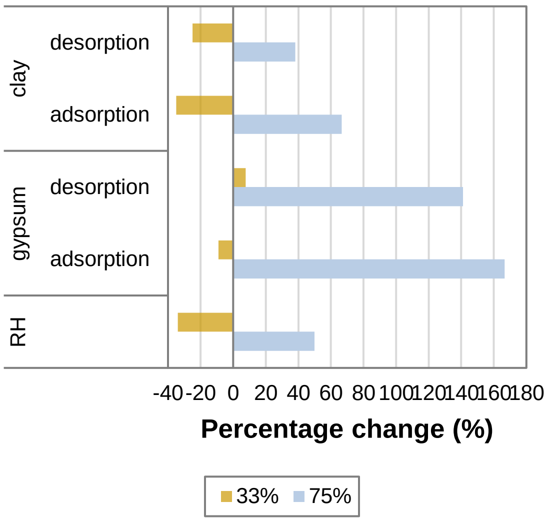

Figure 8 - Changes in gypsum and clay sorption capacity with temperature sinusoidal variation at constant RH.

With the temperature change ratio being 1:1.25 comparing 19°C to 28°C from 23°C, none of the resultant adsorption and desorption ratio are equivalent to the ratio in temperature change, where almost all cases resulted in more than twice the sorption capacity at 28°C when compared to 19°C. The case is similar for the ratio of RH change when comparing 33% RH to 75% RH from 50% RH is approximately 1:1.5. While the results obtained for clay materials posed a possible relationship between margin of change in condition and margin of resultant sorption capacity, other cases may suggest otherwise.

4.2 *Influence of Materials*

The influence of materials can be observed in Figures 9 and 10.

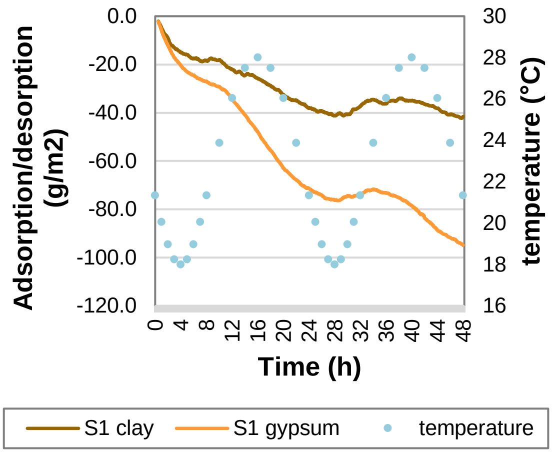

Figure 9 - Sorption of clay and gypsum samples against at 33% RH.

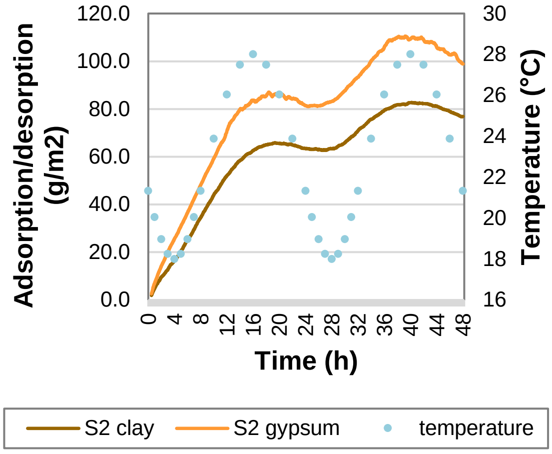

Figure 10 - Sorption of clay and gypsum samples against at 75% RH.

The tests indicate that gypsum out performs clay under adsorption and desorption; with respect to amount and rate. Gypsum's performance is still relatively good with the increase of temperature when subjected to low RH. Gypsum specimens seem to adsorb and desorb moisture at a faster rate, resulting in a greater sorption capacity. It is assumed that although the clay specimens may be slightly inferior in sorption capacity when compared to gypsum specimens, their excellent moisture retention capacity results in their consistent behaviour and how they respond to the change in external condition. The increasingly spread out results as temperature increases could suggest several unforeseen factors, with one of them being the decrease in performance stability in the material itself with the change of temperature.

Previous literature suggests that clay performs better than gypsum in terms of moisture buffering, which has not been observed here. Gypsum having a higher sorption instead in this study could imply that the sorption capacity in clay deteriorates over time potentially due to clay specimens having managed to get closer to moisture equilibrium through continuous moisture retention, while also continuing to adsorb and release moisture whenever there is a change in environmental condition.

4.3 *Combining Both RH and Temperature Variation*

The estimated combined effect of sinusoidal variation of RH and temperature can be estimated numerically, and presented in in Figure 11. To ensure comparability, the data obtained from tests at constant ideal conditions of 28°C and 50% RH respectively (best case scenario within ideal range) have been used to predict this resultant curve by the average of the 2 sets of data.

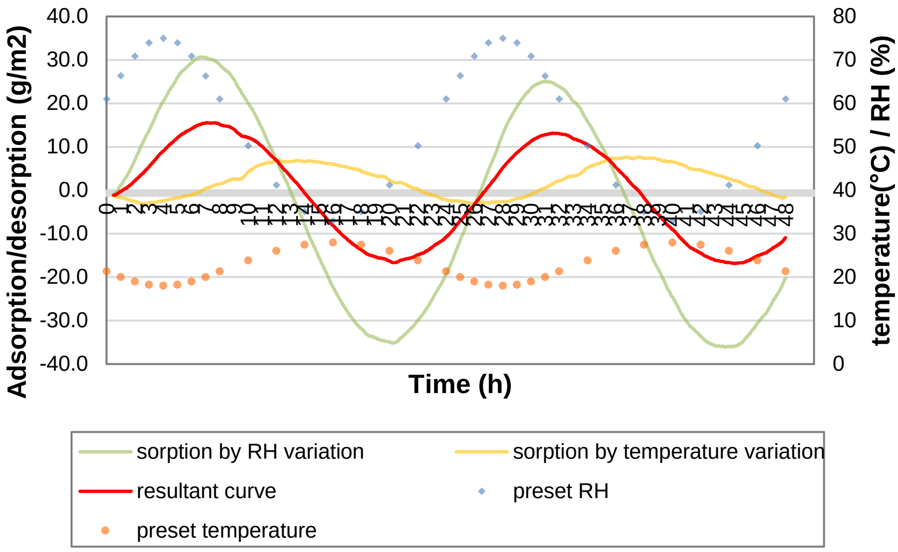

Figure 11 - Predicted curve for gypsum with combined RH and temperature variation.

The resultant curve infers that simultaneous variation of both temperature and RH will reduce the sorption capacity of the material, as well as a further delay response time indicated by response offset. A rough projection of the predicted outcome for different combinations of RH and temperature, obtained by averaging 2 sets of data each, is shown in Figure 12. The combination of the different data sets can be classified in Table 4.

Combination	Max RH	Min RH	Max temp	Min temp
Cold and Dry	33%	75%	Constant 19°C	
	Constant 33%		28°C	18°C
Cold and Humid	33%	75%	Constant 19°C	
	Constant 75%		28°C	18°C
Hot and Dry	33%	75%	Constant 28°C	
	Constant 33%		28°C	18°C
Hot and Humid	33%	75%	Constant 28°C	
	Constant 75%		28°C	18°C

Table 4 - Classification of RH and temperature profiles.

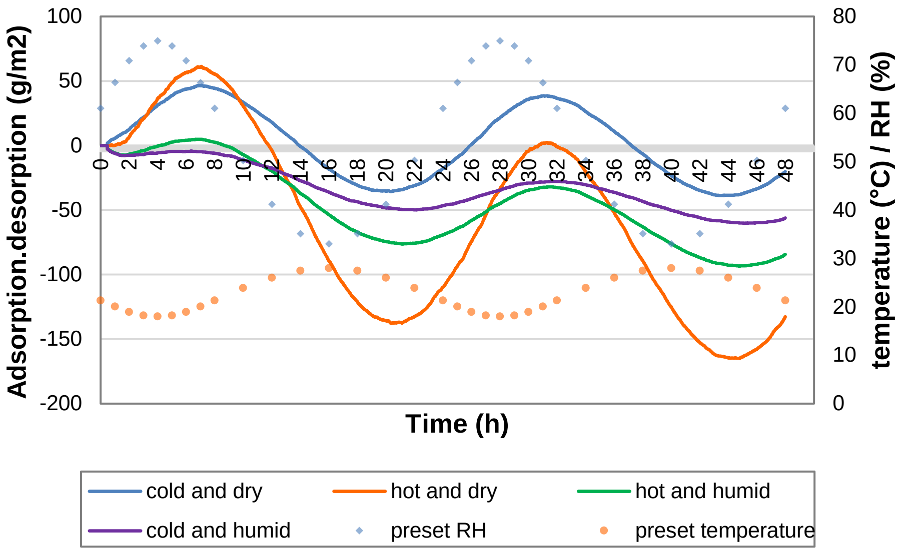

Figure 12 - Predicted curves for gypsum under combinations of different conditions.

Removing ideal condition altogether, the combination of hot and dry condition appears to make full use of the material's sorption capacity while cold and humid condition results in a sorption fluctuation of the least vertical amplitude. The material's performance appears to be fairly consistent when subjected under cold and dry condition, and the inclination for continual moisture desorption in hot and humid condition is less than the hot and dry condition's resultant curve. Hot and humid condition would produce a better material performance when compared to cold and humid condition, but also has the tendency to release moisture continuously. This would imply it is best to avoid dependence of hygroscopic materials' moisture buffering ability when designing a closed space under cold and humid conditions. The combination of cold and dry condition rated relatively well in terms of sorption capacity and response time while being able to maintain performance.

4.4 Sorption Balance Point

This study has adopted a testing profile of 8-16 hour cycle for both time distribution and temperature/ RH variation amplitude distribution. Observing that the test result outcome does not correspond to the profile setting, there could be a possibility where the profile setting itself is not appropriate for a fair comparison to achieve the case of similar adsorption and desorption within 8-16 hours profile distribution. A change of test profiles in accordance to the function and suitability of each building design, the resultant adsorption might turn out to be equal or at least close to desorption and could therefore better justify the moisture buffering performance of materials. The preconditioning environment for both materials are the same with the humidity being controlled at 50% RH and the temperature set to be 23°C. The reason for preconditioning is to ensure that the materials are in equilibrium state before the commencement of testing. Yet, both materials exhibited variable performance during the second cycle of testing, which indicates an additional time effect.

4.5 Moisture Offset

The resultant peak point could also be another form of sorption balance point, where instantaneous adsorption is equal to desorption. The results obtained in this study shows that the peak points are almost never in sync with the programmed setting, causing an offset in response time. This is a comparable phenomenon to thermal lag. The moisture offset is likely due to the non-literarily of sorption connects typically observed through isothermal steady state sorption. The different combination of high and low temperature corresponding to the given humidity affects the instantaneous adsorption and desorption rate of the material, which governs the shape of the resultant sorption graph.

5.0 Conclusion

This study has experimentally demonstrated the impacts of RH and temperature variation on various hygroscopic materials' ability to passively regulate the indoor environmental RH. A change from a step cure to a sinusoidal curve has resulted in additional properties that are not typically considered included rate of adsorption and a moisture offset or lag. This paper has presented numerical results when these variations are combined. The combination of two variations would result in the occurrence of reduced sorption capacity and a delay in response time, irrespective of how high the moisture buffering performance of the material is. The passive system of moisture buffering has a great potential to be applied across all climates with proper adjustments and thorough considerations. This paper has questioned the long-term performance of moisture buffering material which is key for consistent performance over a prolonged period of time with minimal maintenance, and preferably sustainably sourced.

As the environmental condition is almost never constant in the real world, studying the pattern of how materials may respond under variable conditions would be impactful to aid designers in their choices of indoor surface materials. The expected impacts could include passive pre-tempering of outdoor air supply, the design of low-energy airtight building and other applications requiring close environmental control. The material choices could result in a significant contribution to the moisture balance of the indoor environment and become part of the humidity control system.

6.0 References

(1) Wolkoff P (2018). *Indoor air humidity, air quality, and health – An overview*. International Journal of Hygiene and Environmental Health. Vol. 221, Issue 3: 376-390

(2) Woloszyn M, Shen J, Mordelet A and Brau J (2005). *Numerical simulations of energy performance of a ventilation system controlled by relative humidity*. ASHRAE Transactions 115.

(3) Simonson C, Salonvaara M, and Ojanen T (2001). *Improving Indoor Climate and Comfort with Wooden Structures*. VTT Publ. 431. Technical Research Centre of Finland.

(4) Osanyintola O and Simonson C (2006). *Moisture buffering capacity of hygroscopic building materials: experimental facilities and energy impact*. Energy and Buildings 38 (10) 1270–1282.

(5) Woloszyn M, Kalamees T, Abadie M (2009). *The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering*

capacity of materials on indoor climate and energy efficiency of buildings. Building and Environment 44 (3): 515-524.

(6) Rode C, Peuhkuri R, Hansen K, Time B, Svennberg K, Arfvidsson J, and Ojanen T (2005). *Moisture Buffering of Building Materials*. Department of Civil Engineering, Technical University of Denmark. Report R-126.

(7) Roels S, Carmeliet J, Hens H, Adan O, Brocken H, Černý R, Pavlik Z, Hall C, Kumaran K, Pel L, Plagge R (2004). *Interlaboratory Comparison of Hygric Properties of Porous Building Materials*. Journal of Building Physics 27: 307-325.

(8) McGregor F, Heath A, Fodde E, and Shea A. (2014a). *Conditions affecting the moisture buffering measurement performed on compressed earth blocks*. Building and Environment 75: 11–18.

(9) Goto Y, Ghazi Wakili K, Ostermeyer Y, Frank T, Ando N, Wallbaum H (2011). *Preliminary investigation of a vapor-open envelope tailored for subtropical climate*. Building and Environment 46 (3): 719-728.

(10) Goto Y, Ghazi Wakili K, Ostermeyer Y, Frank T, Ando N, Wallbaum H (2012). *Heat and moisture balance simulations of a building with vaporopen envelope system for subtropical regions*. Building simulation 5(4): 301-314.

(11) Yoshino H, Mitamura T, and Hasegawa K (2009). *Moisture buffering and effect of ventilation rate and volume rate of hygrothermal materials in a single room under steady state exterior conditions.* Building and Environment 44 (7): 1418-1425.

(12) Goto Y, Ostermeyer Y, Ghazi Wakili K, Frangi A, Ando N, and Wallbaum H. (2014). *Sustainable wooden envelope for subtropical regions - The realization and validation in Japan*. Conference paper. WCTE 2014 - World Conference on Timber Engineering, Proceedings.

(13) Cerolini S, D’Orazio M, Di Perna C, and Stazi A (2009). Moisture buffering capacity of highly absorbing materials. Energy and Buildings 41: 164–168

(14) Svennberg K, Lengsfeld K, Harderup LE, Holm A (2007). *Previous experimental studies and field measurements on moisture buffering by indoor surface materials*. Journal of Building Physics 30 (3): 261e74.

(15) Vololonirina O and Perrin B (2016). *Inquiries into the measurement of vapour permeability of permeable materials*. Construction Materials 102: 338-348.

(16) Maskell D, Thomson A, Walker P, Lemke M (2018). *Determination of optimal plaster thickness for moisture buffering of indoor air*. Building and Environment 130: 143–150

(17) Woods J, Winkler J, and Christensen D (2013). *Evaluation of the effective moisture penetration depth model for estimating moisture buffering in buildings*. Technical Report NREL / TP-5500-57441

(18) Vololonirina O and Perrin B (2016). *Inquiries into the measurement of vapour permeability of permeable materials*. Construction Materials 102: 338-348.