The moisture buffering performance of plasters when exposed to simultaneous sinusoidal temperature and RH variations

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Abstract

Wall constructions have the capacity to contribute to the passive regulation of indoor Relative Humidity. This property, referred to as moisture buffering, is linked to the hygroscopicity of materials, which allows materials to store and release moisture from and to the surrounding air, depending on the indoor Relative Humidity levels. Laboratory testing procedures, based on a step-response method, were introduced to quantify moisture buffering. The step response method monitors the change in mass of samples, when subjected to square wave humidity variation and constant temperature. However, those protocol's prescribed testing environmental conditions may not be representative of the materials behaviour in buildings, as the surface of walls is exposed to an indoor environment that changes with respect to the temperature and humidity daily and seasonally.

This paper investigates the response of clay and gypsum plasters to quasi sinusoidal and simultaneous humidity and temperature functions. It was experimentally shown that the relative humidity influences the amount of water vapour adsorbed and desorbed by the materials, while temperature impacts the rate and the time lag response of clay and gypsum to the indoor humidity variation. The significance of the investigation is to demonstrate the joint effects of Relative Humidity and temperature on hygroscopic materials and to seek to developing a laboratory test, which can represent the real behaviour of such materials in buildings, which are exposed to sine wave-forms.

Keywords: Moisture Buffering, Sorption Capacity, Clay, Gypsum

1. Introduction

Modern buildings are designed to be highly energy efficient, in order to reduce heat losses through the enclosure. However, air tight and heavily insulated buildings can negatively influence occupant health and well-being, due to the reduced air and moisture exchange [1]. Worsening indoor air quality is linked to the reduction of ventilation in buildings, which increases the concentration of pollutants and humidity indoors. As Arundel et al. [2] showed, too high or too low levels of Relative Humidity (RH) increase risks of exposure to bacteria, viruses and mould spores, in addition to reducing people's perception and satisfaction of indoor environments [3].

Air conditioning systems aim to maintain optimal RH levels, but they are energy consuming, and their effective operation depends on users' understanding of the system correct commissioning and regular maintenance. Furthermore, noise production and costs of those appliances need to be taken into consideration [4]. An alternative solution is to passively regulate the indoor RH and to use the natural capacity of hygroscopic materials, such as clay and gypsum plasters, to store and release water vapour, reducing the extreme highs and lows of RH in the indoor environment [3, 5]. This property, referred to as

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moisture buffering, helps to moderate the indoor RH. In this way, it is possible to passively improve the indoor air quality, and has potential to reduce the operational energy consumption of any associated air conditioning system [6, 7].

As highlighted by Cascione et al. [8], several methods were developed to measure the moisture buffering capacity of materials [9, 10, 11]. The most commonly applied test is the step-response method, which is used in multiple tests protocols (NORDTEST [5], ISO 24353 [12], JIS A 1470-1 [13], DIN 1894[14]). The reasons for the success of these protocols is the simplicity and repeatably of the test. Samples of materials are exposed to a constant temperature, while RH varies cyclically from high to low humidity, following a square wave function. The outcome of the test is the relative change in mass of the material, which determines the amount of water vapour adsorbed and desorbed from and to the environment.

The NORDTEST [5], for example , requires measurements of the weight variation of specimens, when subjected to an adsorption phase for 8 h, followed by a desorption phase of 16 h, varying cyclically the RH from 75% to 33%. The ISO 24353 [12] and JIS A 1470-1 [13] also apply a square wave humdidity function, but time steps and RH are different from the NORDTEST. The International Standard [12] follows a 12/12h profile and three humidity intervals, while the Japanese Standard [13] prescribes 24/24h time steps and similar humidity intervals. The NORDTEST humidity intervals and profiles are not representative of real humidity variation in buildings, as it is assumed there is a continuous humidity generation (75%) for 8 hours, which is suddenly then switched to a low RH (33%) for 16 hours. The protocols are a simplification of the indoor humidity variation and do not give information about the behaviour of materials on the indoor environment, as they only compare the specimen's behaviour.

Step-response tests do not consider the contribution of other environmental factors, such as varying air change rate and daily outdoor temperature and RH variations. When no humidity sources or heating is present in buildings, indoor temperature and RH profiles are related to the outdoor weather, and for this reason they follow a quasi sinusoidal daily and seasonal fluctuations [15, 16]. Künzel et al. [17] also showed, there is a strong inverse correlation between RH and temperature in both indoor and outdoor environments. Consequently, performing a test, in which humidity follows square wave fluctuation and temperature is constant, may not be adequate to quantify the behaviour of hygroscopic materials in the indoors, especially in non-heated structures and historic buildings, like churches [18].

A new approach to measure moisture buffering in laboratory scale testing has been developed in this study. The new protocol is based on the NORDTEST set-up, where the change in mass of the clay and gypsum plasters, due to humidity fluctuation from 75% to 33%, were monitored. Unlike the NORDTEST, the RH follows a sinusoidal variation functions and temperature is not constant. The materials were exposed alternatively to sinusoidal RH variation and constant temperature, and then to sinusoidal temperature and constant RH, in order to quantify and isolate the impact of the temperature and RH on the moisture buffering capacity of the plasters. The tests were also repeated at different constant temperature and RH. The method was then developed by simultaneously varying temperature and RH. To ensure the simultaneous variation of temperature and RH do not activate different water transport mechanisms in the materials, the change in mass curves, obtained through the tests at constant temperature and RH, were compared to the measured behaviour of the samples at simultaneous temperature and RH variations.

This study aimed to show the complexity of the response of porous materials to sinusoidal and simultaneous humidity and temperature functions, which highlighted the importance to improve moisture buffering understating and testing practises. The initial objective was to analyse the materials' response to humidity sinusoidal variations at different temperatures. This was followed by an analysis of the effect of temperature dynamic variations with fixed RH on the sorption capacity. Results were compared to the sorption curves obtain with square wave humidity fluctuation. Finally, the joint effect of dynamic temperature and the obtained RH variations were analysed, to quantify the impact that environmental factors have on hygroscopic materials.

2. Materials and Methods

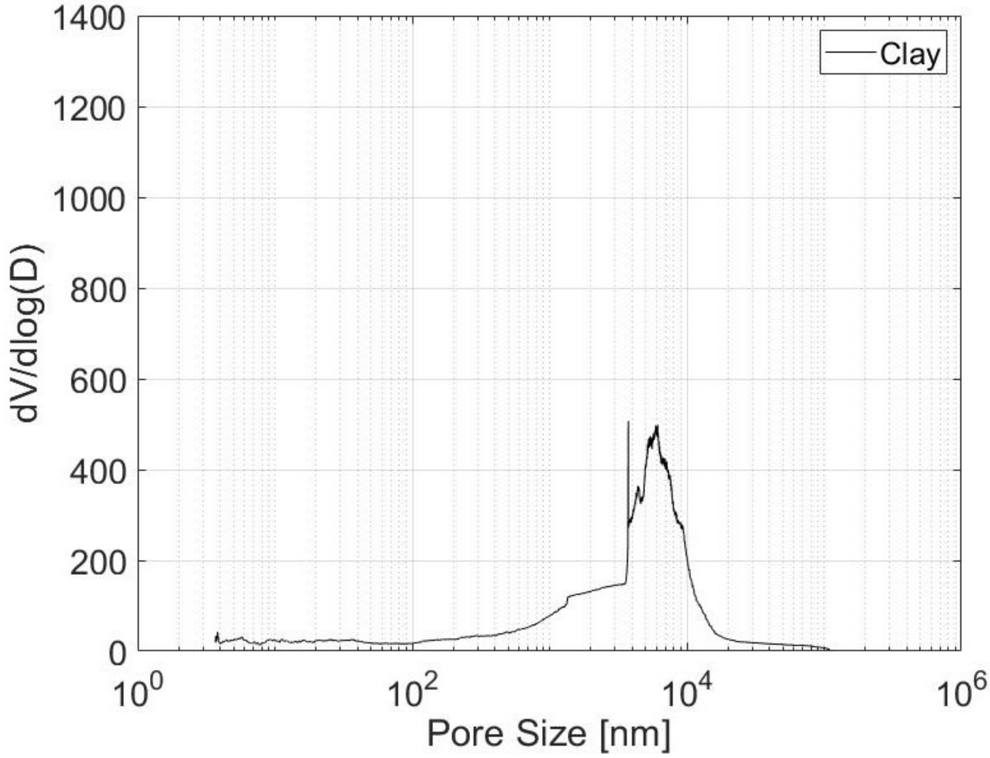
2.1. Materials

Undercoat gypsum and clay plasters were analysed in this study, due to the good moisture buffering capacity of clay and the wide use of gypsum for interior surfaces. The air-dry clay base coat had a dry density of 1258 kg/m^3, and is composed of 69% sand, 25% silt and 5% natural clay [c1]by mass [19]. Gypsum had a dry density of 856 kg/m^3. Specimens were prepared according to manufacturer guidelines. Three specimens for each plaster were cast in 150 mm x 150 mm x 20 mm phenolic-faced plywood moulds. Specimens were air cured for 28 days in a controlled room environment at 20°C and 60% RH prior to testing. The dry density ρ_{dry}, water vapour resistance factor $\mu(-)$, porosity $\Phi(\%)$, total pore volume $V_p(mm^3/g)$, total pore surface area $S_p(mm^2/g)$ and average pore diameter $D_p(nm)$ are presented in Table 1. The density were measured as ratio of specimens weight, after drying at 105°C, and the measured volume of the specimen. Water vapour resistance factor was measured and calculated following the dry cup method in the ISO 12572 (2016) [20], while the other properties were measured by the by the Mercury Intrusion Porosimetry (MIP) (Pascal 140/440). The pore distribution of the two plasters can be seen in Fig. 1. Clay presented mainly macro-pores, which have an average diameter of around 125 nm. Gypsum also had macro-pores of a significant bigger size (365 nm average), but it also presented micro-pores, as shown in Fig. 1a. Overall, the gypsum showed a significant higher pore volume than clay.

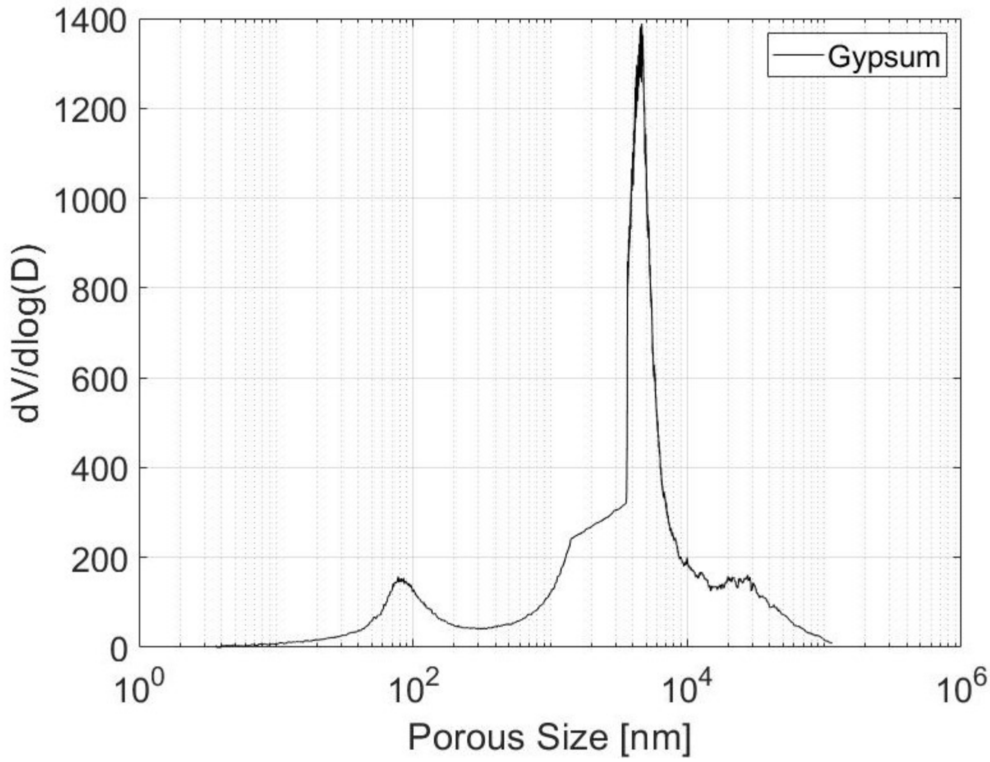
[c1] *Text added.*

Table 1: Material Properties

Material	$\rho_{dry}(kg/m^3)$	$\mu[-]$	$\Phi(\%)$	$V_p(mm^3/g)$	$S_p(m^2/g)$	$D_p(nm)$
Clay	1258 ±19	13±1	45 ±4	320 ±37	9 ±3	141 ±40
Gypsum	856 ±10	9±2	62 ±1	651 ±105	8±4	338±122



(a) Clay



(b) Gypsum

Figure 1: Pore distribution

2.2. Methods

The standard and modified moisture buffering test followed the general guidelines of the NORDTEST protocol [5]. The specimens were exposed to six cyclic humidity and temperature sinusoidal changes. Each cycle consisted of 8 hours of high humidity and 16 hours of low humidity. Temperature cycles were inversely proportional to the RH function (8h of low temperature and 16h of high temperature), as daily temperature variations in unconditioned buildings are opposite to RH fluctuation. Materials were exposed initially only to temperature or RH sinusoidal cycles, while the other factor was kept constant, in order to understand which of the two environmental factors influenced the dynamic sorption capacity most. Tests were repeated three times respectively at different constant temperature (18°C, 23°C and 28°C) and RH (33%, 54% and 75%), as shown in Table 2.

Table 2: Preconditioning and test temperature and RH settings.

Tests	**Pre Conditioning**	**T** (°C)	**RH** (%)
RH Sinu 18	18°C 54%RH	18	Sinusoidal Fluctuation
RH Sinu 23	23°C 54%RH	23	Sinusoidal Fluctuation
RH Sinu 28	28°C 54%RH	28	Sinusoidal Fluctuation
T Sinu 33	23°C 33%RH	Sinusoidal Fluctuation	33
T Sinu 54	23°C 54%RH	Sinusoidal Fluctuation	54
T Sinu 75	23°C 75%RH	Sinusoidal Fluctuation	75
TRH Sinu	23°C 54%RH	Sinusoidal Fluctuation	Sinusoidal Fluctuation

The change in weight of the specimens was monitored every minute with Ohaus Pioneer mass balances (±0.01 g readability) surrounded by a net (Fig. 2) that reduced the air speed to less than 0.1 m/s. The air speed was measured with a hot wire anemometer (Extech 407119). Spot measurements were taken above the specimens. Temperature and RH in the environmental chamber were monitored with Tiny Tag TV 4505 humidity and temperature sensors for confirmation of the chamber programmed behaviour. Two sensors were placed few centimetres above the two specimens inside the netted volume in order to monitor the environmental condition on the materials. Considering the internal size of the chamber is 550 x 443 x 551 mm, the specimen was placed toward the top of the chamber (at 432 mm from the bottom), to avoid the direct influence of the inlet and outlet fan at the back of the chamber. More details about the chamber can be found in [21]. The accuracy of the Tiny Tag sensors and climatic chamber (ACS Compact Test Chambers DY110)was ±3%RH and ±1%RH respectively, and 0.5°C and 0.3°C for temperature.

As temperature and RH in the control room environment room were different from the environmental conditions set for the tests (Table 2, the samples were further pre-conditioned for 24h in the climatic chamber at different temperatures and RH, depending on the environmental conditions the specimens were to be subjected during the test. In this way the material could reach the moisture balance with the environment at the specific temperature and RH of the test, as shown in Table 2.

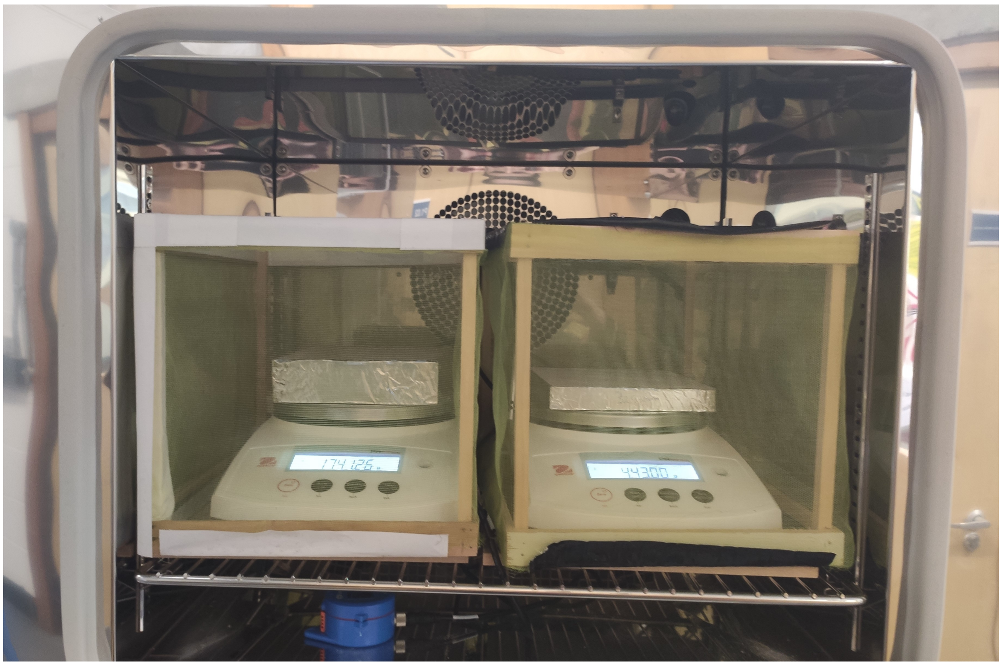


Figure 2: Moisture buffering set up in the climatic chamber

The experimental RH and temperature sinusoidal variations are illustrated in Fig. 3. Different to the NORDTEST, the RH increase is represented by the positive section of the sinusoidal curve. The mean value and the starting RH humidification point was set to 54%, until it gradually reaches 75% and then back to 54%. The climatic chamber increases the RH circa every hour in the 8h. The humidity decrease phase starts at 54%, and the RH slightly decreases every two hours until it reaches the minimum 33%, and then again up to 54%. The climatic chamber cannot reproduce a perfect sinusoidal curve, for this reason sinusoidal variations were approximated to a quasi sinusoidal curve, where the transition from high to low humidity (and vice versa) is distributed in eight smaller steps. The transition between one step to the other was regulated, by setting a variable "slope" for the humidification and de-humidification respectively, which allowed a gradual increase of RH in between two steps. The slope is a setting of the climatic chamber that progressively increases the environmental conditions until the next temperature/RH is achieved. For the temperature, the curve was set to start at 23°C, reaching within the 8 hours the minimum temperature of 18.0°C, succeeded by a 16 hour period ranging between 23.0°C to 28.0°C. Details of the temperature and RH curves can be seen in Table 3. The temperature interval was selected, in accordance to the ASHRAE Standard 55, as acceptable operating temperatures in buildings [22]. The temperature curve was programmed similarly to the RH one. The climatic chamber allows for simultaneous temperature and RH variations. When there is a change of temperature or RH, the chamber increases or decreases the amount of moist air. Due to its high level of accuracy, the chamber is able to auto-control the settings. The Moisture Buffering Value (MBV) was calculated, to discuss its suitability to the modified testing, and was expressed in $g/(m^2\%RH)$, as described in [5].

To predict the behaviour of the samples to simultaneous temperature and RH sinusoidal variation, the mass change curves, exposed respectively to variable temperature and constant RH, and variable RH and constant temperature, were arithmetically averaged. The predicted curves were then compared to the experimental results. The "TRH Sinu" test (Fig. 3c) were performed as the previous ones, where the change in mass of the specimen, room temperature and RH were monitored, while the climatic chamber was programmed to both vary temperature and RH simultaneously.

The choice to control the RH rather than the water vapour production was due to the functioning of the climatic chamber. The machine injects an unquantified amount of water into the supply air stream of the chamber, to keep the humidity level at the target RH. RH is the ratio of the actual amount of water vapour in the air and its saturation pressure, which are both values dependent on the temperature. To have a better understanding of the effect of temperature variation on moisture buffering, moisture content in the air should be measured instead. However, controlling the amount of water released in the chamber was not possible. This led the choice of RH as variable together with temperature, which is, commonly, used as indicator of the humidity level in buildings.

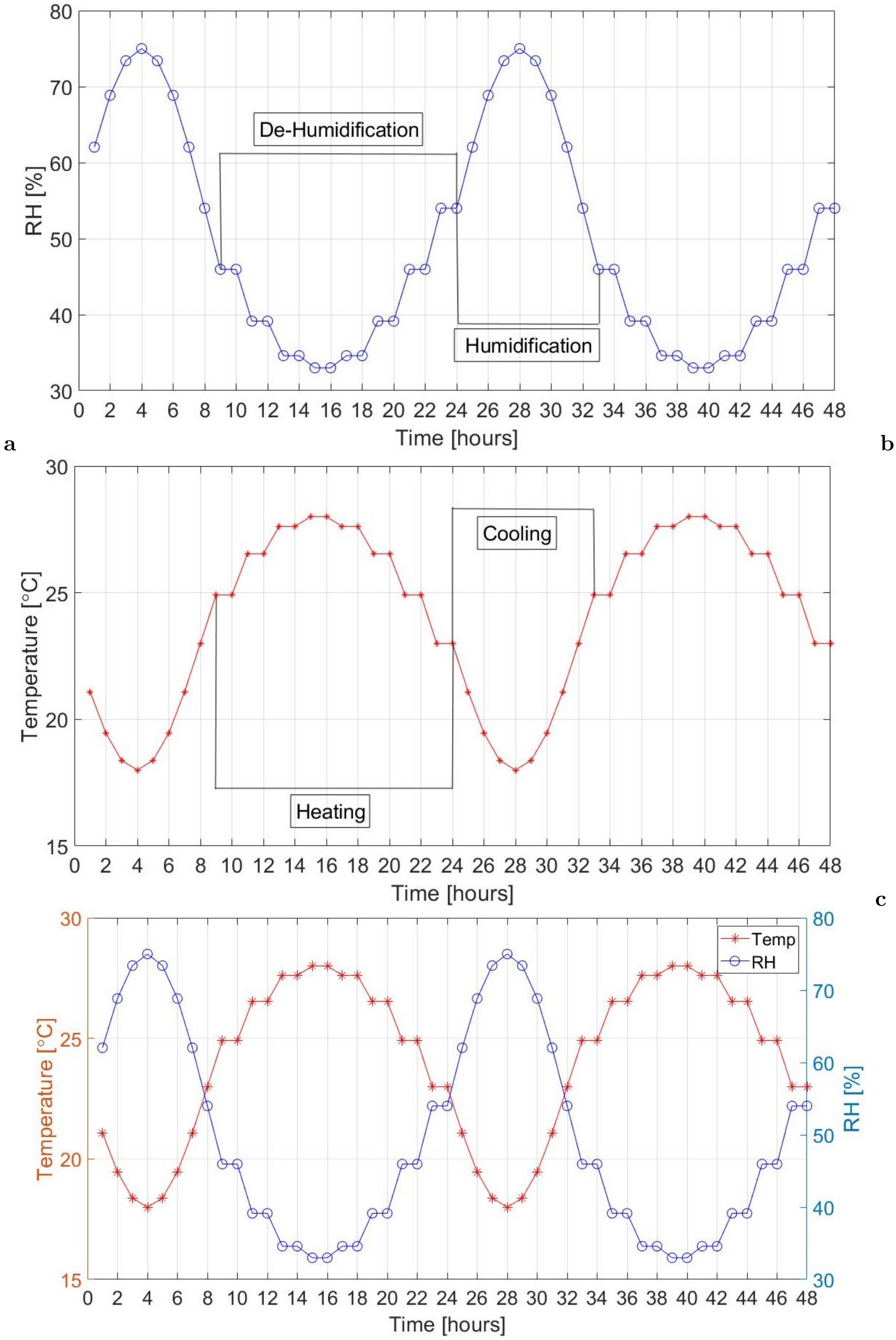


Figure 3: Relative humidity sinusoidal fluctuation (**a**),temperature sinusoidal variation (**b**) and simultaneous variations (**c**).

Table 3: Temperature and RH steps and time frame (hours) in detail

Steps	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RH	54.00	62.04	68.85	73.40	75.00	73.40	68.85	62.04	54.00	45.96	39.15	34.60	33.00	34.60	39.15	45.96	54.00
Temperature	23.00	24.91	26.54	27.62	28.00	18.38	19.46	21.09	23.00	24.91	26.54	27.62	28.00	27.62	26.54	24.91	23.00
Hours	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2

3. Results and Analysis

3.1. Observations of the test chamber performance

The ability of the climatic chamber to maintain the sinusoidal variation, was compared to measurement from the Tiny Tags. The average data of the two RH and temperature sensors were shown to be in good agreement (less than 0.02°C and 2% RH variations). The independent RH and temperature measurement confirmed that the chamber maintained the desired environmental conditions with only minor deviations. Fig. 4 shows the actual average temperature and RH compared with the target curves. In Fig. 4a and b the temperature followed the programmed curve, showing a sinusoidal trend. The measured curve did not perfectly match the maximum and minimum target temperature, but there was less than 0.8°C shift, and the amplitude of the temperature fluctuations was preserved. Humidity presented small fluctuation, due to temperature variations. However, RH variations were less than ±1.5%, and the average was 1.5% RH higher that the programmed 75%RH (Fig. 4a) and 0.5% below the programmed 33% (Fig. 4b). In "RH Sinu 23" (Fig. 4c) a better match was found, as temperature is only ±0.4°C above the target temperature and there is a good agreement with the RH curve. When temperature and RH vary simultaneously (Fig. 4d) similar deviations for the RH curve were observed, but there was a good match for the temperature curve.

Overall, the climatic chamber responded accurately and quickly to the temperature and RH variations. The variations of the environmental conditions between steps were not significant (usually were around 1°C 2%RH). Between one step and the other a “slope” was set that subdivided each step to gradually reach the target temperature and RH.

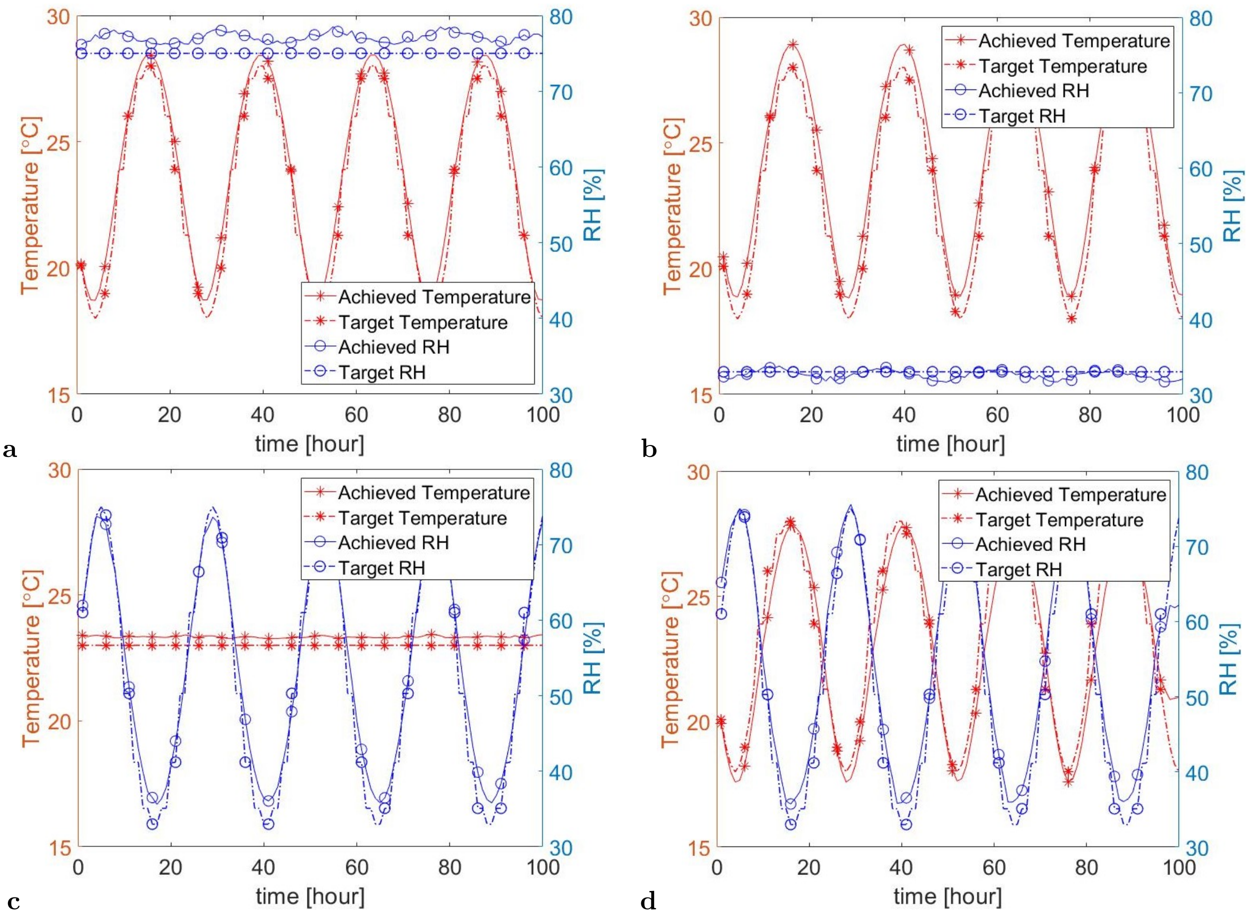


Figure 4: Temperature sinusoidal variation at 75% (**a**) and 33% (**b**); RH sinusoidal variation at 23°C (**c**); temperature and RH sinusoidal fluctuation (**d**).

3.2. Comparison of square wave and sinusoidal variations

The dynamic sorption curves, obtained by performing a standard NORDTEST and the sinusoidal tests, were compared in Fig. 5. In both cases temperature was kept constant at 23°C and the humidity varied between 75% and 33% RH in 24h. The main difference between the two methods is in the humidification process. In the NORDTEST humidity instantaneously jumps from high to low (and vice versa), and remains constant for 8 hours of humidification and 16 hours of de-humidification. Differently, in the sinusoidal test RH gradually reaches the maximum and minimum humidity level. As shown in Table 3, the chamber increased the humidity from 73.9% RH to 75%RH within 1 hour of the humidification. After 30 minutes the RH was above 74%. The same procedure was applied when the RH jumps back from 75% to 73.4%RH. Overall, the RH between 74.5%RH and 75%RH was maintained for around one hour. The de-humidification process was similar but it took two hours to reach the minimum. Table 4 shows the main differences. When sinusoidal RH variations were applied, the adsorption capacity dropped by 46% for clay and 60% for gypsum. The desorption is less effected by the change of the humidity function, as it was reduced only of the 14% for clay and 17% for gypsum. The reason of the small impact on the desorption is due to the longer de-humidification phase (16 hours). The transition between RH steps in the desoprtion can be considered as quasi-steady, as the specimens had longer time to balance their moisture content with the environment.

Overall, the moisture buffering capacity was lower, presenting a lower MBV value for both materials. The difference between the adsorption and desorption is also smaller than in the NORDTEST, due to the lower adsorption capacity of the materials during the humidification. Another important aspect is the response speed of the specimens to humidity variations. In the NORDTEST the specimens quickly responded to humidity changes, presenting a synchronised response of the plasters with the humidity variations. The specimens started releasing moisture at the moment the RH in the chamber dropped to 33% and vice versa. In the sinusoidal test the materials reached the maximum moisture content 2 hours after the RH reached its peak. Accordingly, the materials do not respond as quick as in the NORDTEST, when humidity gradually changes.

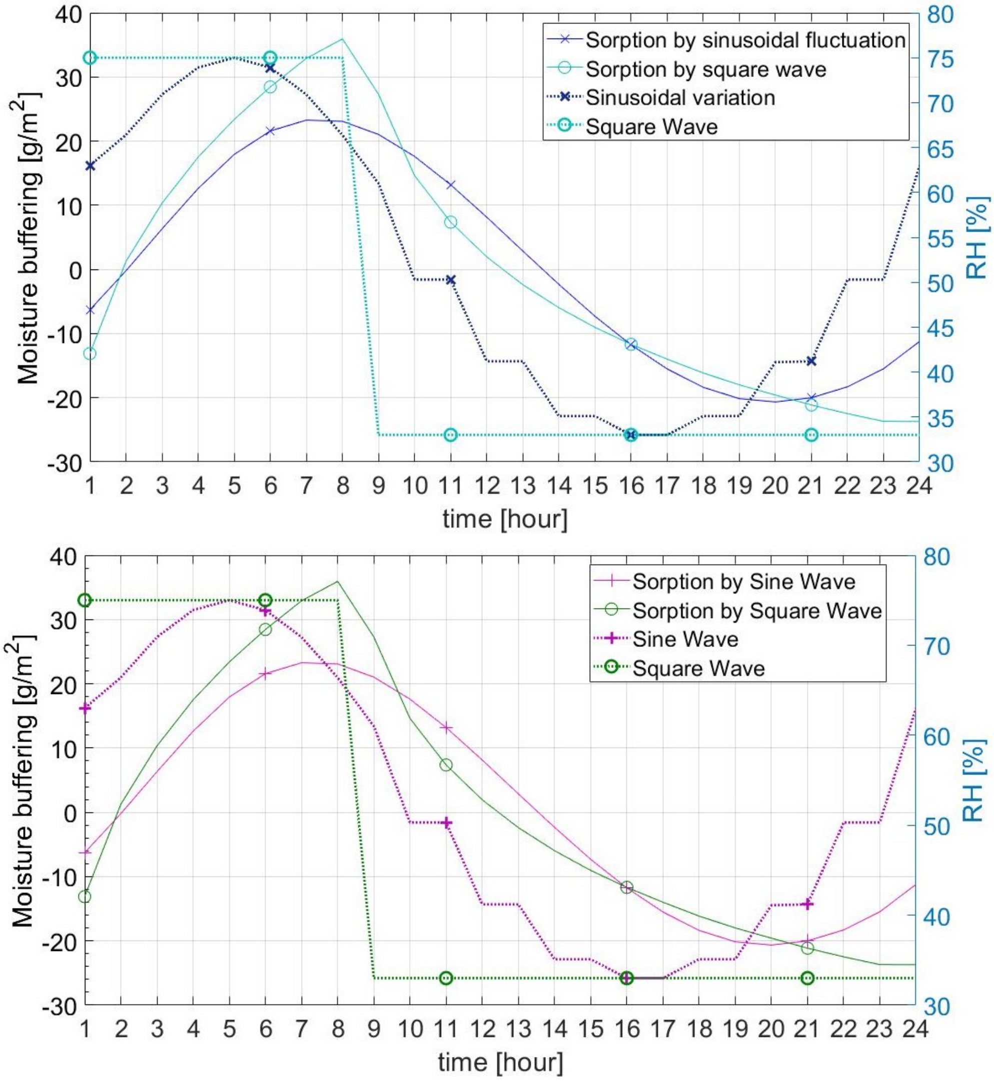


Figure 5: Comparison NORDTEST and sinusoidal RH variation for clay (**a**) and gypsum (**b**).

Table 4: Sorption capacity and MBV of clay and gypsum under square wave ans sinusoidal humidity variations

Properties	Clay		Gypsum	
	Square	Sine	Square	Sine
MBV [$g/m^2\%RH$]	1.45	1.05	1.95	1.42
Adsorption [g/m^2]	33.93	23.27	49.48	30.82
Desorption [g/m^2]	23.70	20.65	34.82	29.07

The lower sinusoidal MBV reduced the classification of both materials Fig. 6. Clay dropped to the lower limit of good, while gypsum moved away from the excellent category to good. However, the MBV is applicable only to the NORDTEST and should not be applied to the modified test, as the theoretical assumption of the MBV are based on the square wave function. Both the [12] and the [13] do not refer to this value and do not use the NORDTEST classification system, but it is an easy way to compare the overall sorption variations between the two tests.

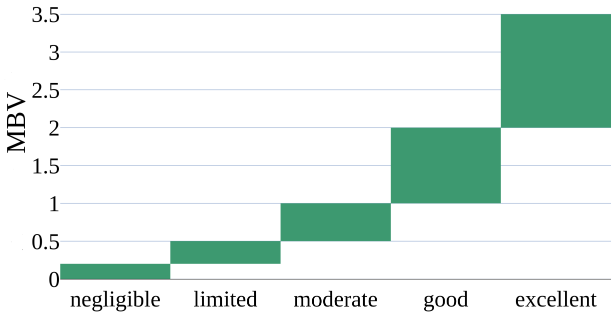


Figure 6: NORDTEST Classification

3.3. Response of the samples to alternate temperature and RH variations

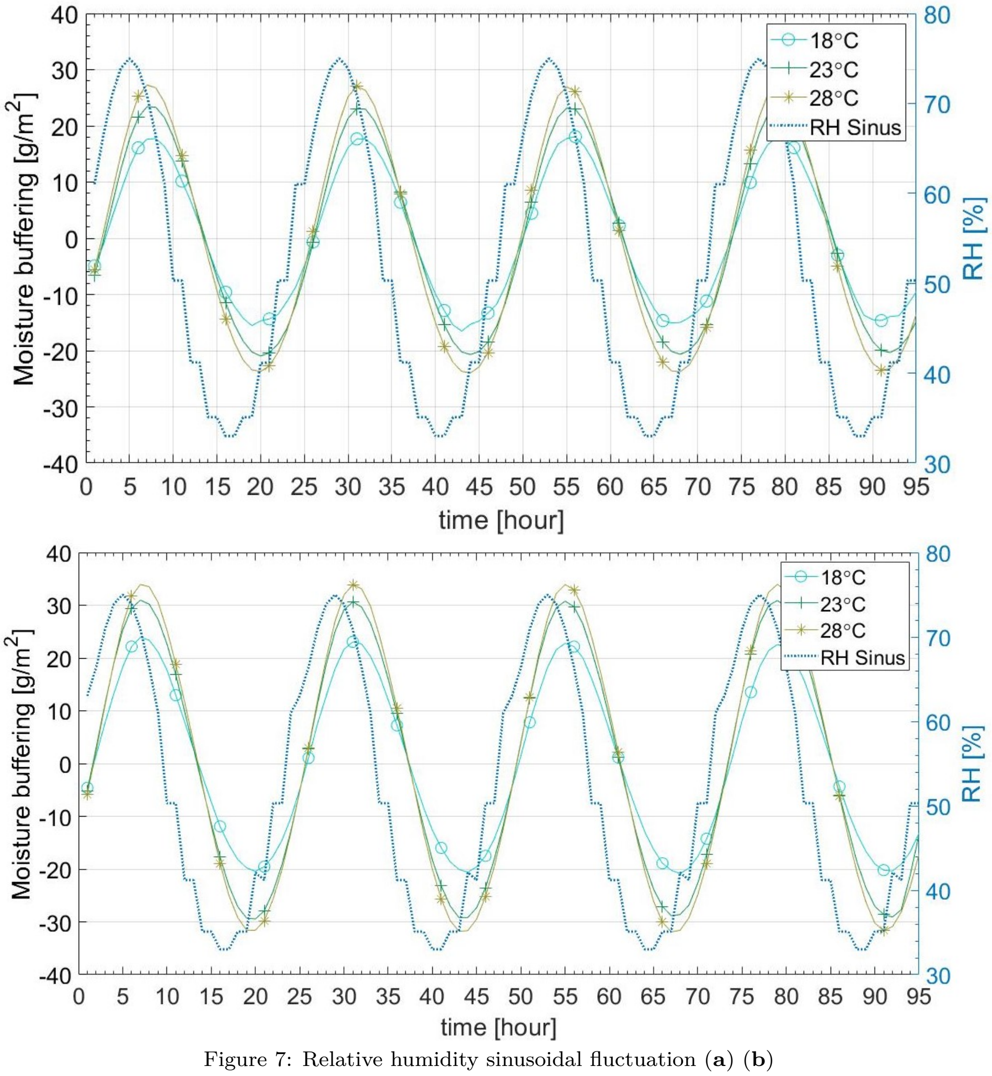
The gypsum and clay dynamic sorption curve under the temperature and humidity variations are shown in Fig. 7. Fig. 7a and b illustrate the response of clay and gypsum to the sinusoidal RH variation at three different temperatures. Temperature clearly influenced the sorption capacity of both materials. High temperatures yielded a greater amplitude of the curves, while lower temperatures generated a smaller moisture uptake and release. At 28°C clay adsorbed 53% more than at 18°C and 31% more than at 23°C (peak to average). The desorption presented lower values (23.65 g/m^2 at 28°C and 15.45 g/m^2 at 18°C), but there is still an important difference of the moisture buffering capacity between 18°C and 28°C (53% difference). Overall, the Coefficient of Variation (CoV) at 18°C, 23°C and 28°C was below 2.12%, 0.16% and 0.32% respectively. Gypsum presented a greater moisture buffering capacity than clay, but it was still influenced by the temperature in the same way. It stored and released respectively 23.08 and 20.55 g/m^2 at 28°C, while its sorption capacity dropped around 50% at 18°C both in the adsorption and desorption phase, as shown in Fig. 7b. The CoV for gypsum at 18°C, 23°C and 28°C was below 1.70%, 0.69% and 0.86% respectively.

Independently to the temperature applied to gypsum, all curves exhibited a delay of around 2 hours in response to RH function peak points, while clay presented a higher lag at lower temperatures. In general, the reason of the lag is due to the short time in the adsorption phase for the specimens to balance their moisture content with the environment humidity. As the water vapour permeability decrease with the temperature [23], clay might have a lower water vapour permeability at 18°C. Consequently, it takes longer for the specimen to balance, which explain the higher delay for clay. In general, this correlation is valid for both plasters, which explains the increase of the sorption capacity with the temperature. However, clay might be more sensitive, due to its porous composition.

The sorption response of clay and gypsum to sinusoidal temperature fluctuations is represented in Fig. 7c and d. The curves did not stabilise at 33% and 75% RH, which is probably due to the preconditioning period being too short. Due to the significant temperature difference between the control environment room, where samples were stored, and the testing environmental conditions, the specimens could not balance their moisture content in the 24h preconditioning before the start of the test. However, results were consistent and the sorption amplitude of clay was steady. Clay presented respectively an average sorption capacity (peak to peak) of 5.45 and 6.82 g/m^2 at 33% and 75% with CoV below 5.26% and 8.63% between each cycle respectively. Similar logic was followed for gypsum at 75%, which had an average sorption capacity of 7.01 and 11.35 g/m^2 at 33%RH and 75%RH with CoV below 3.04% and 3.97%.

Observing the mass variation, when subjected to temperature sinusoidal variation, the sorption capacity in Fig. 8c and d is significantly lower than under RH fluctuation (83% and 82% for clay and gypsum, respectively). The difference between the "T Sine 33" and the ones at "T Sine 54" and "T Sine 75" was respectively 15% and 78% lower for clay, and 43% and 53% lower for gypsum. The time lag response of the materials to temperature variations changes was in both cases 1 hour, as shown in Table 5 and Table 6. This means the sorption curves reach the peak after the temperature peak regardless of the sorption capacity at each RH. Table 5 and Table 6 summarises all the results obtained for clay and gypsum specimens. It is clear that other than the temperature influence on the sorption capacity, RH has still an important role. Increasing the environment RH led to the variability of the water vapour permeability of the materials. As [24] demonstrated, the water vapour permeability of materials increases, when the RH increases, which explains the raise of the sorption capacity with RH.

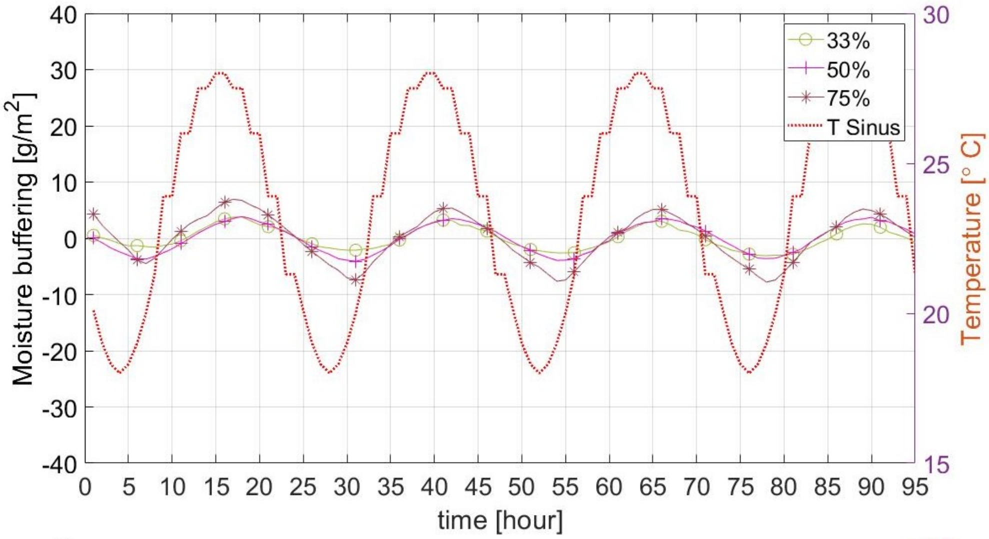
Friedman's two way analysis of variance was performed on related samples, to determine if there is a statistical significance between each sorption curve. A confidence interval of 95% and a significance level of 5% were considered. The null hypothesis was that the distribution of the three sorption curves, subjected to three different temperatures and RH, were the same. The significance value (Adjusted Sigma) was adjusted by the Bonferroni correction for multiple tests. Results showed in most cases there are statistical differences between the three curves both in Fig. 8c and d and tests performed under RH sinusoidal function (adjusted sigma value below 0.043). Only the distribution of the sorption curves between "T Sinu 33" and" T Sinu 54" both for clay and gypsum, and T Sinu 18 and T Sinu 23 for gypsum were not statistically different.



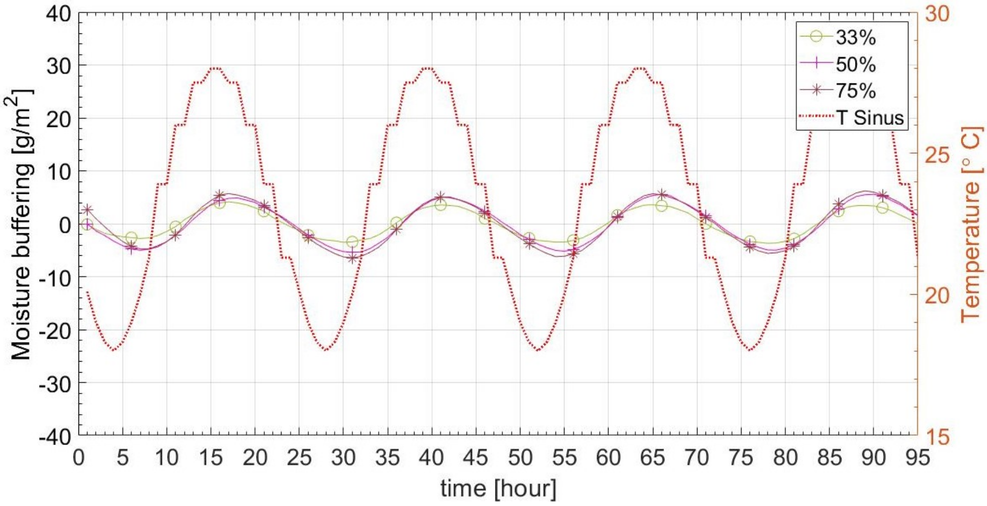
a

b

Figure 7: Relative humidity sinusoidal fluctuation (**a**) (**b**)



c



d

Figure 8: Temperature sinusoidal variation (**c**) (**d**).

Table 5: Results of the moisture buffering analysis of clay alternatively at constant temperature and RH.

Curves	**Adsorption** (g/m^2)	**Desorption** (g/m^2)	**Hygric Lag (h)**
RH Sinu 18	17.75	15.45	3
RH Sinu 23	23.27	20.65	2
RH Sinu 28	27.08	23.67	2
T Sinu 33	3.16	2.30	1
T Sinu 54	3.64	3.80	1
T Sinu 75	5.63	6.67	1

Table 6: Results of the moisture buffering analysis of gypsum alternatively at constant temperature and RH.

Curves	Adsorption (g/m^2)	Desorption (g/m^2)	Hygric Lag (h)
RH Sinu 18	23.08	20.55	2
RH Sinu 23	30.82	29.07	2
RH Sinu 28	33.93	31.73	2
T Sinu 33	3.68	3.24	1
T Sinu 54	5.28	5.14	1
T Sinu 75	5.66	5.70	1

3.4. Response of the samples to simultaneous temperature and RH variations

The response of clay and gypsum to simultaneous temperature and RH variations is shown in Fig. 9. It is evident that by storing 33.43 and releasing 34.20 g/m^2 gypsum performed better than clay (11.78 and 14.82 g/m^2 more than clay).

The time lag of the two curves both present 4 hours delays with respect to the RH sinusoidal curve. This is more than the delay of the sorption curve to humidity changes under RH sinusoidal fluctuation (2h) and the delay of change in mass of samples under temperature sinusoidal variation (1h).

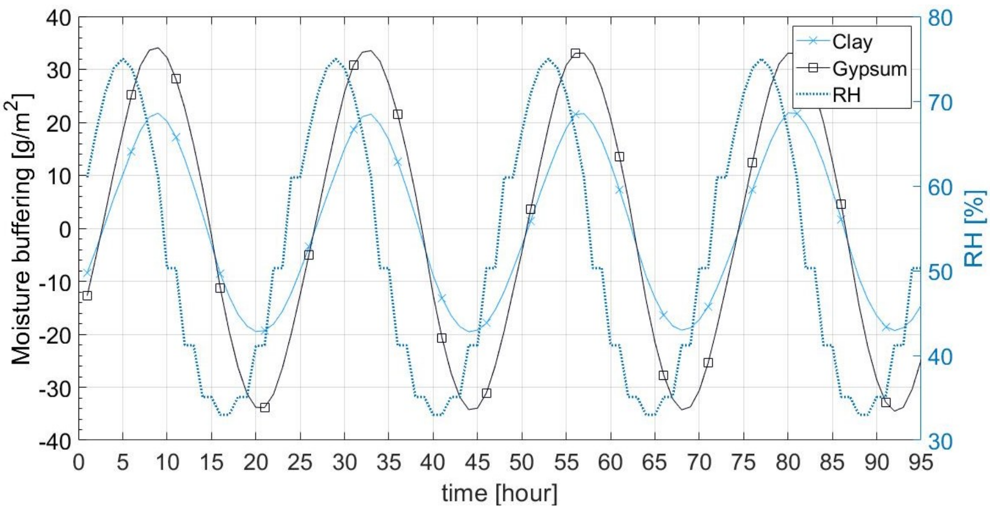


Figure 9: Mass change of clay and gypsum, when subjected to simultaneous temperature and RH variation.

The "TRH Sinu" curves were compared with the "RH Sinu 23" and "T Sinu 50", to try to identify the impact of temperature and RH on the sorption capacity. The "TRH Sinu" curves had similar behaviour of the "RH Sinu 23" curves for both materials, whilst "TRH Sinu" showed an opposite trend of "T Sinu 50" (Fig. 10). However, "RH Sinu 23" did not perfectly match "TRH Sinu" in both cases. Clay "RH Sinu 23" adsorbed and releases 7.50% and 6.55% more moisture than "TRH Sinu", while for gypsum 8.50% and 17.61% less. The hygric lag is also different, presenting in both cases 2 hours delays between the two curves. It is evident temperature did not interfere significantly with the sorption capacity of the materials, but it delayed the response speed of the plasters to humidity variations.

Interestingly, the two plasters presented a different behaviour in the sorption process. The effect of the temperature variations on "TRH Sinu" reduced the sorption capacity of clay, while gypsum improved its moisture buffering capacity, when temperature varies sinusoidally. The discrepancy in the materials' behaviour, can be due to the plasters' porous structures and size. As [25] explained, moisture transport, which includes either vapour and liquid transport mechanisms, depends on to the pore geometry. Water vapour transport takes place in the macro-pores and its driving potential is the water vapour pressure, whilst liquid transport takes place in the micro pores, where the driving force can either be the relative humidity and the capillary pressure [26, 27]. The clay was mainly composed of macro-porous, which are mainly responsible of the water vapour transport. Gypsum was more sensitive to moisture [28]), because it had both micro and macro-pores, which activated both the vapour and liquid transport simultaneously. [29] mentioned even though it is not possible to define the overriding influence of a specific pore size range, it is evident that a greater volume of pores in the micron-range increase the vapour permeability, sorption isotherm and moisture buffering capacity of hygric properties of the materials.

As [30, 31] demonstrated, liquid transport is sensitive to temperature, as the water vapour permeability is effected by temperature at high RH levels. It was found that higher is the temperature, higher is the permeability, showing bigger variation in materials with high porosity. This would explain the increase of the gypsum sorption capacity, when also temperature varied. [32] highlighted there might be temperature influences in the vapour sorption process (in particular during the desorption), but there it was not consistent with all materials, probably due to their pore structure. However, studies for the verification of the temperature effect on moisture transport were carried in steady state environments, following the dry and wet cup test procedures for the determination of the water vapour permeability [23, 30]. In a dynamic environment, it is necessary to consider the continuous variation of sorption isotherm, due to the continuous temperature variations. The moisture content balance changes each temperature step, as well as the water vapour permeability. The variable RH also influences the permeability, especially at higher RH levels [24]. The simultaneous variation of both environmental parameters may activate other processes ,and, as [31] highlighted, temperature and pore geometry might produce independent effect on the hygric properties.

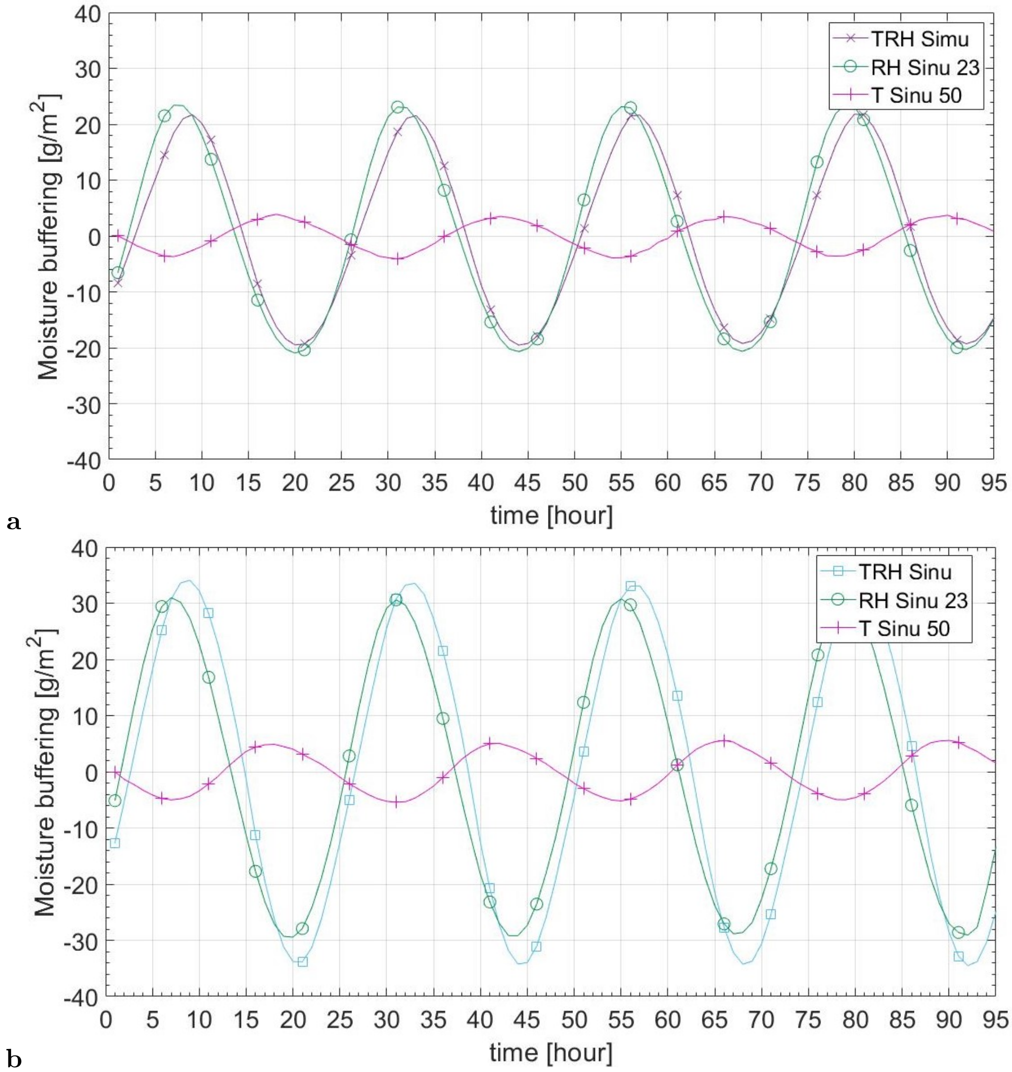


Figure 10: Measured mass change of clay (**a**) and gypsum (**b**) at simultaneous temperature and RH compared with mass change at 23°C and 54% RH.

4. Discussion

4.1. Predicted Sorption Curve

It is clear that the most important environmental factor in moisture buffering is the humidity level (specimens adsorbed more than 80% more moisture, when humidity varies), as shown in Fig. 10. Temperature still influences the response in the plaster, as its fluctuation impact the moisture sorption and it delays the materials' response. However, the effect of temperature and RH may change, if both vary simultaneously, as shown in "TRH Sinu". To investigate the individual effects of these two factors on samples subjected to dynamic temperature and RH fluctuation, the sorption curves at constant temperature were arithmetically averaged with the sorption curves at constant RH, as shown in Fig. 11. Nine curves were generated, by combining the curves obtained at three different temperatures (Fig. 7a and b) and the curves at three different RH (Fig. 7c and d).

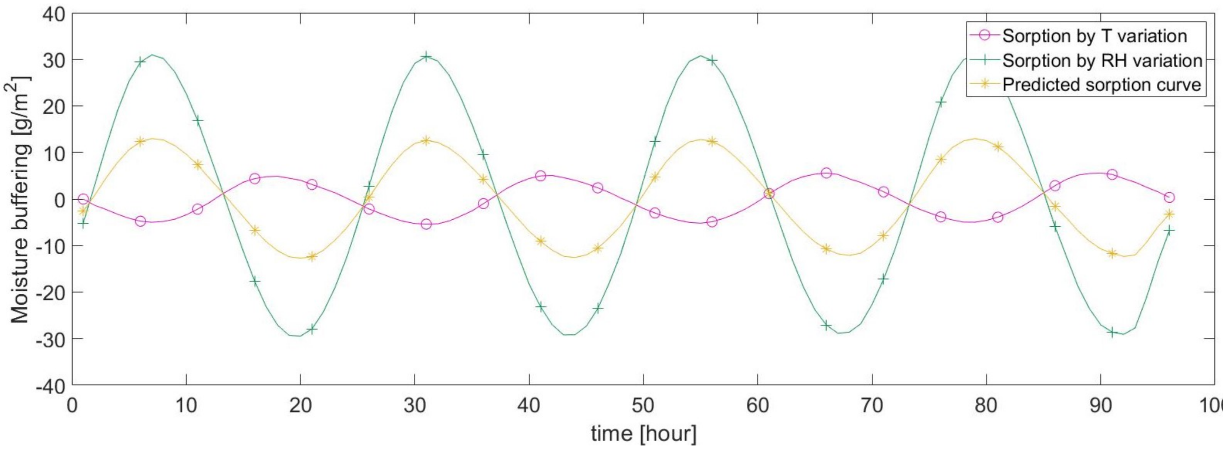


Figure 11: Example of predicted curve with combined RH and temperature variation of gypsum.

The results were obtained from the combination of the experimental sorption curves for clay (a) and gypsum (b), while Table 7 and Table 8 represent the data for all the predicted curves, that were given descriptive names representing typical environments. The results of some of the predicted curves are shown in Fig. 12. Dry and Humid correspond respectively to 33% and 75% RH respectively, and Cold and Hot to 18°C and 28°C. With this method it was possible to directly compare the measured sorption curve in Fig. 9 with the predicted ones, as well as it also gave information about the material performances in different climates.

The combination of RH and temperature variation reduced the sorption capacity in the predicted curves, and in most cases it did not shift the time response of gypsum, whilst for clay the delays increased when the temperature and humidity decreased, as shown in Table 5 and Table 6.

When the temperature was lower, the sorption capacity decreased independently of the humidity level. This shows that temperature played an important role in moisture buffering and it should not be excluded in the evaluation of the sorption capacity of materials. Moreover, clay and gypsum responded better to humid environmental conditions rather than dry, probably due to the activation of liquid transport mechanisms. Looking at Table 8 and Table 7, both materials presented in dry and humid environments a smaller desorption capacity compared to the adsorption, but there was a significant increase of water adsorbed in the humid cases, which indicated the higher influence of the environment on the adsorption, rather than on the desorption. However, even though gypsum had higher sorption capacity than clay, clay showed a better behaviour in the adsorption, as the gap between the adsorption in dry and humid environments was bigger than gypsum.

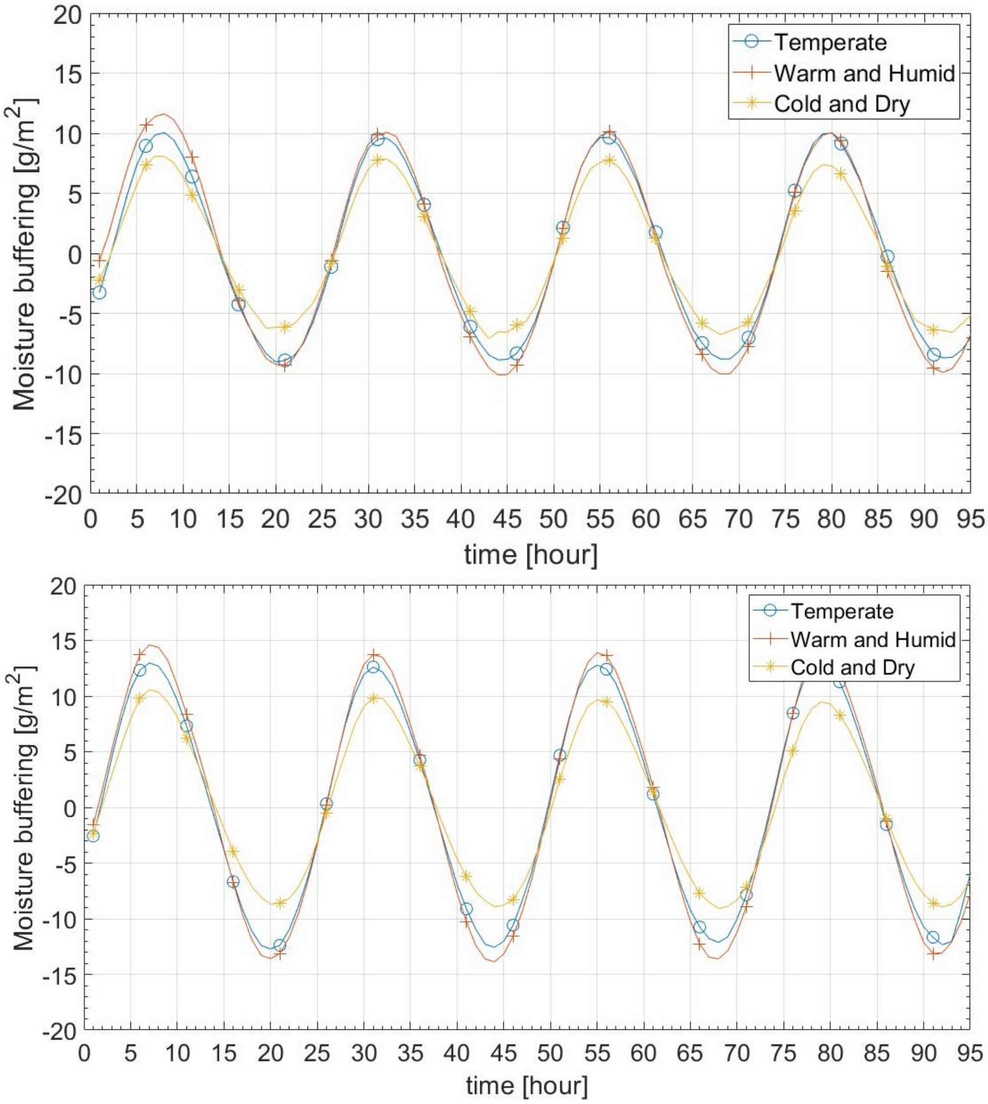


Figure 12: Predicted sorption curves for clay (**a**) and gypsum (**b**.)

Table 7: Theoretical results of the moisture buffering analysis of clay.

Curves	**Adsorption** (g/m^2)	**Desorption** (g/m^2)	**Hygric Lag (h)**
Cold and Dry	6.35	5.68	4
Cold and Humid	7.74	6.50	3
Mild	9.82	8.85	3
Warm and Dry	10.46	9.83	3
Warm and Humid	12.39	10.93	2

4.2. Comparison between the Measured and Predicted Sorption Curve

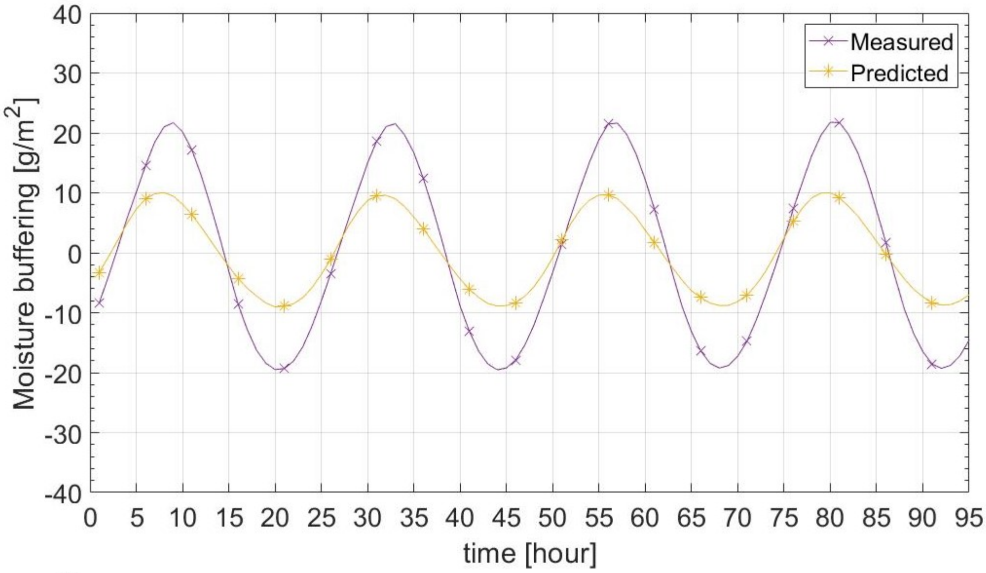
The mild curve was taken as reference for the comparison with the measured sorption curve both for clay and gypsum, as it was hypothesised the experimental curve had similar average boundary condition

Table 8: Theoretical results of the moisture buffering analysis of gypsum.

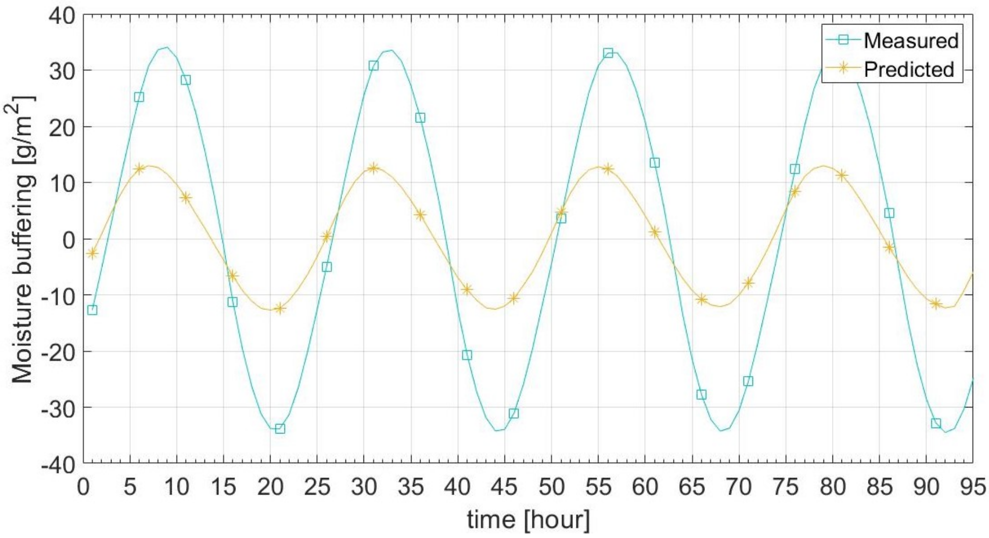
Curves	**Adsorption** (g/m^2)	**Desorption** (g/m^2)	**Hygric Lag (h)**
Cold and Humid	8.69	8.10	2
Cold and Dry	9.88	8.93	2
Mild	12.84	12.44	2
Warm and Humid	14.12	13.53	2
Warm and Dry	15.30	14.36	2

than in the "mild" predicted curve (average temperature and RH were 23°C and 54%).

The differences between the predicted and measured sorption curves are illustrated in Fig. 13. It is evident the mean curve, obtained by averaging the sorption curve at constant temperature and the one at constant RH, was not representative of the effective curve, obtained when materials were subjected to simultaneous temperature and RH variations. The measured curve for clay adsorbed peak to peak 22.38 (g/m^2) more with respect to the calculated one (Fig. 13a). In gypsum this difference was more noticeable, as the predicted curve adsorbed 42.34 (g/m^2) less peak to peak (Fig. 13b).



a



b

Figure 13: Measured mass change of clay (**a**) and gypsum (**b**) at simultaneous temperature and RH compared with the combined mass variation curves.

As already mentioned, the reason of this discrepancy is due to the pore structure and moisture transport mechanisms activated, due to the simultaneous temperature and RH fluctuation. The sorption capacity of materials with higher percentage of micro-pores might be more influenced by the temperature variations, than the one composed mainly of macro-pores. Moreover, it was demonstrated water vapour permeability is dependant on the humidity level of the environment. Above 55% the permeability increases exponentially with the humidity [24], which means the predicted "mild" curve, average of T Sinu 54, might not be representative, as liquid transport might not been activated. which is not representative by giving the same weight to temperature and humidity variations in the empirical approach.

In summary, Table 9 shows the adsorption, desorption and MBVs of the predicted and experimental curve. Both cases presented a MBV below the moderate class in the NORDTEST classification (Fig. 6), and gypsum and clay moisture buffering capacity was significantly lower than the equivalent values obtained in the standard NORDTEST and (Table 4), if square wave variations were applied on the same materials. The MBV classification and MBV values are not effective to dynamic temperature environments, as the theoretical formulation of the MBV is based on the assumption temperature is constant and materials' performances varies linearly with [5]. As the NORDEST prescribes an isotherm environment, the MBV might not be applicable in dynamic realistic scenario. For this reason, temperature variation should be integrated in the formulations of MBV, as different temperatures lead to different material's responses. It is also necessary to consider the hygric lag, as complementary parameter for the understating of the dynamic sorption capacity of materials.

Table 9: Adsorption [g/m^2], Desorption [g/m^2] and MBV [$g/m^2\%RH$] obtained from the predicted and experimental sorption curve

Curves	Clay			Gypsum		
	Adsorption	Desorption	MBV	Adsorption	Desorption	MBV
Mild	9.82	-8.85	0.44	12.84	-12.44	0.60
T Simu	21.65	-19.38	0.98	33.43	-34.20	1.61

5. Conclusions

The complexity of the response of materials to simultaneous temperature and RH fluctuation has been highlighted. It has demonstrated the role of temperature and sinusoidal daily fluctuation in the dynamic sorption capacity of plaster materials.

Moisture buffering capacity of clay and gypsum was determined experimentally, by substituting the humidity square curve variation in the NORDTEST with a sinusoidal curve. The modified test considered indoor RH as a quasi harmonic function, and introduces also the influence of temperature on moisture buffering. As the impact of temperature on the materials sorption capacity was not known, two different tests were performed to understand individually the effect of temperature and RH sinusoidal variation on the specimens. The obtained results were then combined, to compare them with the resulting sorption curve obtained, when samples are simultaneously subjected to sinusoidal temperature and RH variation.

Clay and gypsum presented different responses to humidity and temperature changes. However, both materials showed similarity in their adsorption capacity, when subjected to sinusoidal variation of temperature at constant RH and vice versa: when increasing temperature or RH, their sorption capacity increased. Temperature did not impact as much as humidity the adsorption and desorption of materials (approximately 17% of the total adsorbed water vapour). On the contrary, temperature delayed materials' response to humidity changes. However, when temperature and RH changed simultaneously, differences between the response of clay and plaster were observed, which can only be attributed to the activation of other processes related to the material composition and properties. Overall, it can be stated:

- There are significant differences, when RH variations do not follow quasi steady function, as the NORDTEST does. The quick variation of the RH function leads to incapacity of specimens to reach the balance, causing hygric lags.
- Temperature has effect both on sorption capacity and hygric lag, due to its influence on the sorption isotherm and water vapour permeability. It also effects the liquid transport in the micro-pores. In general, higher is the temperature, higher the water vapour permeability is, as well as the equilibrium moisture content increases.
- RH has an effect on the sorption capacity of the materials, effecting mainly the liquid transport mechanism and the water vapour permeability. Higher is the RH, higher water vapour permeability is.

This study highlights the need to investigate more into the correlation between temperature and moisture buffering and also gave input to improve the existing protocols, as it did not only compare the moisture buffering performances of materials in terms of mass change, but it also gave information on the hygric lag of the response of materials to sinusoidal daily variation. The significance of this study is to improve the understanding of moisture buffering capacity, and to introduce new way of testing, in order to optimise finishing materials and increase their ability to improve the indoor air quality. An analysis of material performances in different climates, and under sinusoidal temperature and RH variations, can lead to a more realistic understanding of their capacity to passively regulate humidity, to reduce the use of energy consuming systems.

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