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A Discussion on Winter Indoor Hygrothermal Conditions and Hygroscopic Behaviour of Plasters in Southern Europe

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Abstract: In Southern European countries, due to the specific climate, economy and culture, a permanent heating practice during winter is not widely adopted. This may have a significant effect on the performance of indoor coating materials, typically tested considering hygrothermal conditions in the range of 33–75% relative humidity (RH) and 20–25 °C, which are common in continuously heated buildings. In this study, the indoor climate of four bedrooms located in Lisbon, Portugal, was monitored under operational conditions. Based on the data monitored in the case studies, characteristic ranges of indoor hygrothermal conditions were defined and compared to those considered in standard test procedures. In addition, numerical simulations were adopted to compare the hygroscopic performance of four plasters under operational conditions observed on-site. Results show that the four rooms, intermittently heated or unheated, do not provide comfort conditions over 50% of the wintertime, with temperatures lower and RH higher than the ones recommended by the standards. The MBVs resulting from simulations (under operational conditions) are qualitatively in agreement with the MBVs obtained under standard testing conditions. Nonetheless, future studies are recommended to evaluate if standard tests are quantitatively representative of the hygroscopic performance of coating materials in the Southern European scenario.

Keywords: hygrothermal comfort; indoor climate; moisture buffering; hygroscopic behaviour; southern Mediterranean countries; hygrometric regulation

Citation: Ranesi, A.; Posani, M.; Veiga, R.; Faria, P. A Discussion on Winter Indoor Hygrothermal Conditions and Hygroscopic Behaviour of Plasters in Southern Europe. *Infrastructures* **2022**, *7*, 38. https://doi.org/10.3390/infrastructures7030038

Academic Editor: Enrico Zacchei

Received: 14 February 2022
Accepted: 7 March 2022
Published: 9 March 2022

1. Introduction

The importance of indoor environmental quality (IEQ) is currently largely acknowledged, due to the extended amount of time people spend indoors [1]. Consequently, the study of parameters such as indoor thermal comfort [2–4], indoor air quality [5], perceived quality [6] and the correlation with human health [7] gained importance in research. In this context, increasing attention has been paid to the use of building materials [8] and hygroscopic coating systems [9,10] that can help to passively regulate indoor relative humidity (RH). The idea is to exploit the moisture buffering ability of the materials to regulate indoor hygrometric conditions. Indeed, hygroscopic materials tend to adsorb moisture when RH rises and then release it when the air becomes drier [11], thus moderating the peaks in indoor RH and reducing operational energy demands [12,13] while passively improving indoor comfort [14].

To evaluate and compare the moisture buffering ability of materials, the NORDTEST protocol [15,16] is often adopted. This test procedure was defined by a research group working on the specific scenario of North European countries [17] and it is based on the hypothesis of continuously heated buildings (e.g., indoor set-point temperature of 23 °C [18]). The methodology was defined considering an occupancy of 8 h per day, which is typical of offices and bedrooms [19]. Three possible ranges of RH were proposed, and the one normally adopted spans from 33% to 75%. Even though some other procedures exist, for instance ISO 24353 [20], the NORDTEST method is the most largely adopted one, because it provides a quantitative evaluation of the moisture buffering capacity [17] through a single parameter: the practical Moisture Buffering Value (MBV). Hence, this test procedure allows to compare the potential effectiveness of different hygroscopic materials and coating systems through their MBVs.

Despite the great contribution provided by the introduction of the NORDTEST procedure, some doubts may arise when it is adopted in the context of Southern European countries. In fact, in Southern Europe, a permanent heating practice is not commonly adopted, especially in residential buildings [21]. On one hand, this is a consequence of the milder winter conditions. On the other, the combination of low incomes and high energy costs leads to a general "Lack of Motivation to Heat", which is extremely high in Portugal, Romania and Greece, and lower but still relevant in other Southern European countries such as Spain, Croatia and Italy [21]. In this context, a relevant share of the population is found to be unable to keep the house adequately warm [22,23]. Due to the low indoor temperatures (T), high RH levels can be expected. The scenario of Southern Europe may thus require a complementary approach that differs from the standard test conditions defined for the case of Northern Europe by the NORDTEST protocol.

This study aims to evaluate the indoor hygrothermal conditions in four case studies located in Lisbon (Portugal) and intends to open a discussion on the applicability of standard tests on the moisture buffering ability of building materials, in the context of Southern Europe. The detailed methodology is schematized in Figure 1.

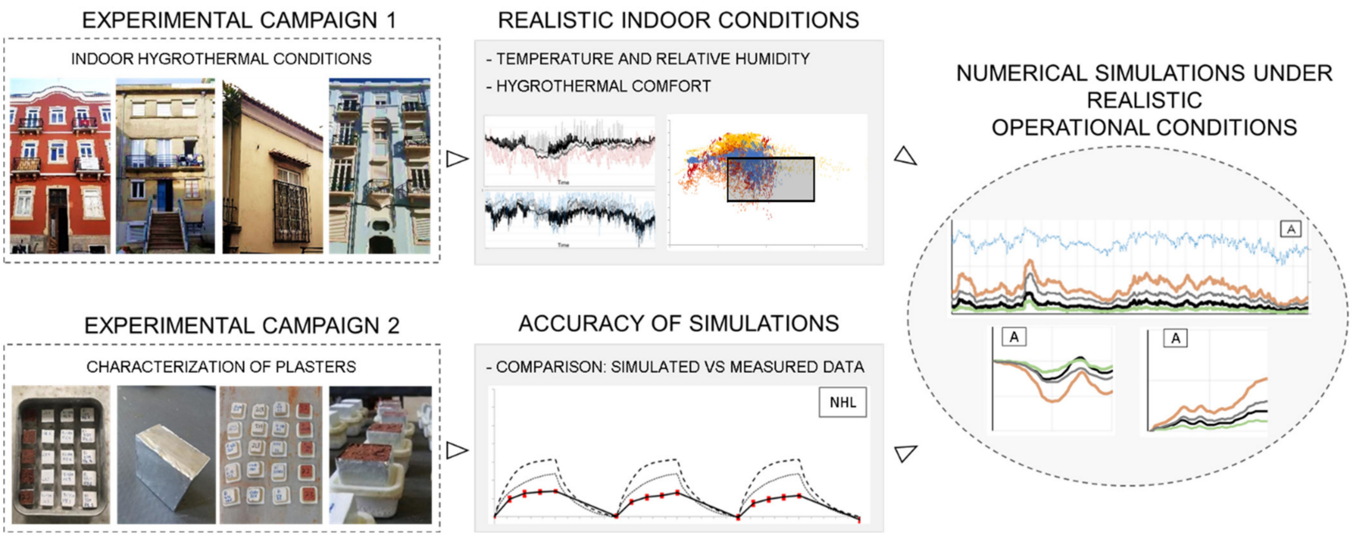

Figure 1. Schematic representation of the methodology followed in the study.

The monitoring was performed during winter, when the passive relative humidity regulation can be significant since windows are kept closed for most of the time. Moreover, it was possible to verify the complaints of the bedrooms' users, who reported the spaces to be cold and moist during winter. The dataset, thus obtained, was examined to evaluate the fluctuation of indoor RH to be compared to the scenario adopted in the NORDTEST. To facilitate the comparison between real conditions and testing ones, the data were recorded in bedrooms, which better represents (for residential) the type of space (occupation for 1/3 of the day) considered in the NORDTEST. The indoor climate data obtained on-site were then used as input in numerical simulations, to evaluate the hygroscopic behaviour of different plasters under realistic operational conditions. Results were compared to the

MBVs of the plasters obtained under standard conditions (via laboratory tests), to assess if they were representative of their potential hygroscopic behaviour under the observed real conditions.

2. Materials and Methods

2.1. Case Studies Selected and Indoor Monitoring Campaign

Four case studies were selected for the experimental indoor monitoring campaign. In each one, the air temperature (T) and relative humidity (RH) were continuously recorded during winter 2021. The four buildings are located in the core of the city of Lisbon, and their location is displayed in Figure 2. All the buildings were built before the first Portuguese regulation on thermal requirements for buildings was published [24]. This is a very common condition in the Portuguese building stock, where 85% of the building stock, reported in 2011, dated back to before the 1990s [25]. The bedrooms under study are subjected to one-person occupancy and they are intermittently heated by the users with electric-heating devices, or not heated at all.

Figure 2. Selected case studies: location in the map of Lisbon, building facades, and plans of the monitored bedrooms (openings: interior door and outdoor-facing window). In each room, a red dot indicates the position of the data-logger used to monitor the indoor hygrothermal conditions.

Case study A, Figure 2A, is located in a three-floor building whose envelope was recently refurbished. The bedroom considered is on the 1st floor, and it has an area of about 7.5 m^2. It has one external wall, which is north-oriented, and a balcony. Case study B, Figure 2B, is located in a building that looks like the result of a social housing project of the second half of the 20th century. The bedroom selected is on the upper ground floor and has an area of about 8.4 m^2. It has one external wall, north-oriented, with one window. Case study C, Figure 2C, is a room of a detached house with an individual owner. The bedroom analysed is on the upper ground floor and it has an area of about 7.5 m^2. The bedroom has one external wall, west-oriented, with a window. Case study D, Figure 2D, is located on the 3rd and last floor of an apartment building. It has a floor area of about 11 m^2 and one external wall with a balcony, west-oriented.

The indoor monitoring campaign was performed by means of two data-loggers HOBO UX100-003 (accuracy: ±0.21 °C, ±3.5% for 25–85% RH and 5% out of this range) and two HOBO U12-013 (accuracy: ±0.35 °C, ±2.5% for 10–90% RH and 5% out of this range). The sampling interval adopted was 10 min and the final hygrothermal data were defined as the hourly average values of T and RH obtained from the recordings, as in previous studies [26,27]. The data-loggers were positioned inside paper boxes (open on the top) to avoid the interference of drafts and solar radiation in the measurements. Furthermore, the equipment was located on the top of different pieces of furniture, at 70–180 cm from the floor, to minimize direct interactions between the bedrooms' users and the sensors. Finally, a minimum distance of 10 cm was kept between the walls and the data-loggers. The hourly data of outdoor T and RH were provided by the Portuguese Institute of Sea and Atmosphere (IPMA) [28], from a local meteorological station.

The monitoring campaign was performed during winter because it is the period when a passive regulation of RH can be very beneficial for improving hygrothermal comfort. Indeed, during winter the air change rates are low because windows are kept closed for most of the time, and the lower the air change rates the higher the potential impact of the materials on indoor RH [10]. In addition, due to the typically moderate use of heating in Southern Europe, high RH levels can occur. Wintertime was approximated considering the period 15 November–31 March, based on the degree days' calculation. Since the Portuguese legislation [29] that defines the degree days does not include a specific identification for the starting and ending date of the heating period (which is hereby considered to define wintertime), an Italian standard was taken as a reference [30]. This choice was considered suitable for the scope since both Portugal and Italy are Southern European countries, and the selected period appeared representative of wintertime in Lisbon.

2.2. Statistical Analysis of Indoor Hygrothermal Conditions and Indoor Comfort

Once the set of hygrothermal data from the case studies was acquired, it was statistically evaluated through cumulative frequency plots. The 25th and 75th percentiles, also known as the upper and lower quartiles [31], were considered to identify a typical range of indoor conditions. Similarly, a wider range was defined by using the 10th and 90th percentiles.

To evaluate whether the indoor environments were cold and moist, as reported by the bedroom users, the data obtained in the monitoring were compared to the comfort requirements found in the literature. Indoor comfort depends on a variety of factors that can be difficult to forecast for residential buildings, due to the uncertainty on the activities performed, the variability of clothing, the uncontrolled use of the windows, and so forth. Thus, calculations concerning the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), as indicated in standards ISO 7730 [32] and ASHRAE 55 [33], are disregarded in favour of a more simplified evaluation. A zone of acceptable hygrothermal comfort was defined according to the following observations. During winter the temperature should be higher than 16 °C to guarantee neutral or comfort sensation for the occupants, as referred by Peeters et al. [34] for bedrooms. Standard EN 16798-1 [35] indicates a maximum temperature of 25 °C for bedrooms belonging to category III (acceptable, moderate level of expectation on indoor comfort). In addition, standard EN 15,251 [36] suggests an RH level within the range 20–70%, for buildings in category III. Therefore, in order to account for an additional indication of the literature, the minimum acceptable RH level was increased to 30% [7], to avoid excessive drying out of the skin and of the mucous membranes.

2.3. Plaster Characterization

Four plastering mortars were selected to be used in the simulations. The mortars were prepared by mechanical mixing and water was added to achieve suitable workability (assessed through flow table test [37]). The mortars and their consistence were the following:

E—commercial plaster based on clayish earth produced by EMBARRO [38] with a consistence by flow table of 170 ± 10 mm;
CL—1:3 volumetric ratio of hydrate air lime CL 90-S and siliceous sand (0–4 mm) with a consistence by flow table of 151 ± 5 mm;
NHL—1:3 volumetric ratio of natural hydraulic lime NHL3.5 and siliceous sand (0–4 mm) with a consistence by flow table of 150 ± 5 mm;
Cem—1:4 volumetric ratio of CEM II/B-L 32.5N and siliceous sand (0–2 mm) with a consistence by flow table of 140 ± 3 mm.

A detailed description and characterization of the plastering mortars can be found in a previous study [39]. The Moisture Buffering Values (MBVs) were calculated considering the experimental results obtained following the NORDTEST protocol [17] and the ISO 24353 standard [20]. MBVs were calculated on the average of five specimens for each plaster ($40 \times 40 \times 20$ mm^3). According to the NORDTEST protocol [17], the specimens were cyclically exposed to steps of RH 33% (16 h)–75% (8 h) until quasi-steady-state equilibrium was reached. When tested according to the ISO 24353 [20], the cyclic condition of *middle humidity level* (12 h at 75% RH followed by 12 h at 50% RH) was chosen. Temperature was fixed at 23 ± 0.5 °C during the entire test in both cases. The difference between the two methods lies in the range of RH considered (minimum of 33% or 50%) and in the period of exposure to different hygrometric conditions (12–12 h; 16–8 h). The MBV results are reported in Table 1.

Table 1. Plaster MBVs (g/m^2·%RH) according to the NORDTEST and ISO 24353 testing protocols.

Plaster	NORDTEST	ISO 24353
E	1.493 ± 0.09	1.327 ± 0.08
CL	0.416 ± 0.04	0.267 ± 0.03
NHL	0.799 ± 0.03	0.537 ± 0.02
Cem	0.843 ± 0.07	0.660 ± 0.05

The physical and hygric characterization of the plasters was performed in previous studies [39–42]. The material properties needed for the simulations were defined following the indication of Posani, Veiga and Freitas [43], based on the results of the experimental campaigns. Thermal properties were considered of minor importance in this study, and they were thus approximated using the values provided in the WUFI database [44] for similar materials. The main data adopted for the simulations are summarized in Table 2.

Table 2. Plaster properties adopted in numerical simulations.

Plaster	P_o (%)	ρ_{Dry} (kg/m^3)	μ (–)	A_w (kg/m^{2}s$^{0.5}$)	* λ_{Dry} (W/(mK))
E	29.9	1743	9.07	0.50	0.5
CL	25.8	1720	7.43	1.71	0.7
NHL	26.2	1779	9.32	2.40	0.7
Cem	20.2	1919	20.42	0.43	1.2

Notation: Po—open porosity, ρ_{Dry}—dry bulk density, μ—water resistance factor, A_w—capillary water absorption, λ_{Dry}—thermal conductivity, * not measured but approximated considering values from WUFI database.

The sorption isotherm is recognized to be one of the most important material properties when simulating the impact of hygroscopic materials on indoor RH [45]. They were defined for both the adsorption and desorption phases, according to standard ISO 12571 [46]. Five specimens ($40 \times 40 \times 20$ mm^3) for each plaster were tested. They were first dried at 60 °C, then they were kept under constant hygrothermal conditions until equilibrium was reached, using a climatic chamber FITOCLIMA 700EDTU. The steps of RH considered were the following: 30%, 50%, 70%, 80%, and 95% RH, while the temperature was constantly kept at 23 ± 0.5 °C.

2.4. Numerical Simulations

The software adopted for mono-dimensional hygrothermal simulations is WUFI Pro 5 [44], which allows performing mono-dimensional hygrothermal simulations of multi-layered wall cross-sections under realistic climatic conditions. This software was chosen for several reasons. First, it offers a detailed calculation model of combined heat and moisture transport, which includes liquid transport, vapour diffusion, and hygroscopic behaviour of porous materials [44]. Furthermore, WUFI Pro has been validated through several years of field and laboratory testing [47–51], and it is widely adopted to investigate passive regulation of humidity due to hygroscopic building materials [52–55]. In addition, the software allows introducing material properties as input data, thus plasters can be modelled according to the information obtained in laboratory tests. Additionally, the software accounts for hourly data of boundary conditions, thus the indoor climate can be introduced in the model based on the microclimate monitoring performed in the case studies.

In this study, numerical simulations are first adopted to reproduce the standard test on moisture adsorption/desorption defined by ISO 24353 [20]. The results numerically obtained are compared to the experimental results observed in the laboratory. The accuracy of the model for representing the hygroscopic behaviour of the plasters is consequently discussed. The plasters are then simulated considering the indoor climatic conditions measured on-site and the results are discussed in comparison with MBV experimentally obtained. The comparison aims to evaluate if standard test conditions are representative of materials adopted in the context of Southern Europe, where indoor climatic conditions can become colder and moister than in northern countries, due to the different heating habits.

2.4.1. Simulations under Standard Conditions

Dynamic numerical simulations have been largely applied to study the hygroscopic behaviour of building materials. Nonetheless, modelling hygroscopic materials requires some simplifications, in particular concerning their sorption isotherm. Building materials can show a residual moisture content at the end of desorption, due to the effect of capillary forces which make the uptake of water molecules in the porous network easier than their removal [56]. This behaviour is also known as moisture hysteresis [57]. Thus, the curves obtained during the adsorption and desorption phases can be quite different from each other.

In WUFI software, the sorption isotherm is assumed as a bijective function, thus two separate curves cannot be introduced for adsorption and desorption, and a simplification must be adopted. In the literature, two approaches emerge for operating this simplification: some studies consider the adsorption isotherm only [58], and others use the average values obtained combining adsorption and desorption curves [59]. Both simplifications are applied in this research and evaluated. The materials modelled according to the two approaches are simulated under the standard conditions adopted in the laboratory test as in ISO 24353 [20]. Then, the results obtained with the two simplifications are compared to those measured in the laboratory. Based on the outcomes of this comparison, the simplification offering more accurate results is chosen for the forthcoming simulations. The NORDTEST procedure was not replicated via numerical simulation due to the very little data available, namely only one measurement after each phase of adsorption or desorption. Consequently, it was of minor interest for the sake of comparing measured and simulated values.

More in detail, this first set of simulations is performed as follows. First, the materials were modelled as horizontal components, having a thickness of 2 cm, and a sealing material was applied on the bottom (a vapour barrier with a S_d = 1500 m). The lateral sealing is not modelled since the simulations run under the hypothesis of an infinite plane component, thus the conditions at the border do not influence the results. The upper and lower boundary conditions adopted are those of the experimental test, namely a constant temperature of 23 °C and cycles of 12 h of constant RH, which is alternatively kept at 75% or 50%. To replicate the test performed in the laboratory, the initial condition of the material is 23 °C and moisture content stabilized at 63% RH. The results of the first 4 cycles, i.e., a total of 48 h, are not represented, while the following ones are reported in comparison to those measured in the laboratory, in terms of moisture content per unit of surface in the samples.

2.4.2. Simulations under Realistic Operational Conditions

The plasters are then simulated under realistic operational conditions, considering the indoor data recorded on-site and a typical Portuguese wall assembly.

Since all case studies have different walls, a typical configuration is adopted to have comparable results, while being representative of the Portuguese building stock. The geometry consists of a whole-brick structure, 34 cm thick, as characteristic of traditional Portuguese brick-masonry walls with medium thickness [60]. On the exterior side, 2 cm of lime-cement render is considered, finished with acrylic paint, to account for a typically refurbished façade. At the indoor-facing side of the wall, a 2 cm thick layer of plaster is adopted (E, CL, NHL, and Cem, alternatively). The initial conditions in the plasters are assumed as in equilibrium with air at 20 °C and 60% RH, which is considered to be a realistic assumption, based on the indoor hygrothermal data observed on-site. Outdoor boundary conditions are defined using typical weather data of Lisbon, namely those provided in the Test Reference Year from the WUFI database. At the interior side of the walls, the microclimate adopted is the one recorded on-site during winter, in the four case studies, alternatively.

Results are evaluated in terms of moisture content in the plaster, per unit of surface. Then, the variation of moisture content in the plasters is observed in detail during a 2-day period. Based on the results, the hygroscopic behaviour observed under realistic operational conditions is discussed and compared to the results obtained in terms of MBV in standard tests.

3. Results and Discussion

3.1. Indoor Climate

Figure 3 shows the hourly data of T and RH obtained in the indoor environmental monitoring, versus the ones recorded by IPMA for the outdoor climate, from November 2020 to March 2021. According to the collected data, during winter the outdoor temperature and relative humidity were in the ranges 1–26 °C and 40–100% RH, respectively, with T being lower than 16 °C for most of the time and RH being generally above 75%. Regarding indoor climates, hygrothermal conditions were in the ranges of 10–28 °C and 21–90% RH in the period considered.

3.2. Statistical Evaluation

To analyse the typical range of variation of indoor T and RH, a statistical evaluation was performed, and the results are shown in Figure 4.

The curve of accumulated frequency shows that the lower threshold value considered in the NORDTEST is not very representative of the indoor hygrometric conditions analysed. Indeed, this condition was never reached in case studies C and D, while such low levels of RH, namely below 35%, are obtained for less than 5% of the time in the other two case studies. This result indicates that an RH level around 33% is not representative of a typical daily low point of RH, but it is more of an exceptional condition, in the case studies considered. This outcome is coherent with the heating strategy adopted in the case studies. While continuous heating may lead to low levels of RH, intermittent or absent heating leads to lower indoor temperatures, with consequently higher RH levels.

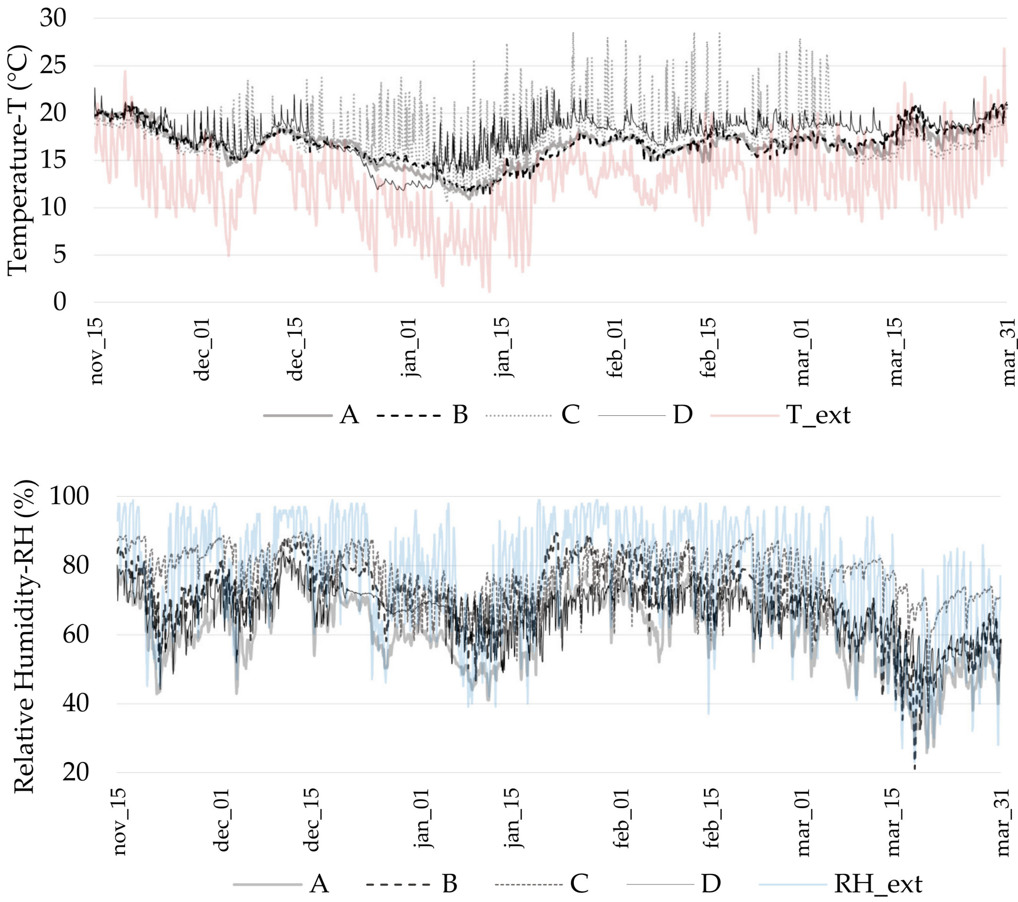

Figure 3. Hourly average air temperature (°C) and relative humidity (%) data recorded by IPMA in the city of Lisbon and the same parameters recorded in the four bedrooms (A, B, C and D), for the period 15 November 2020–31 March 2021.

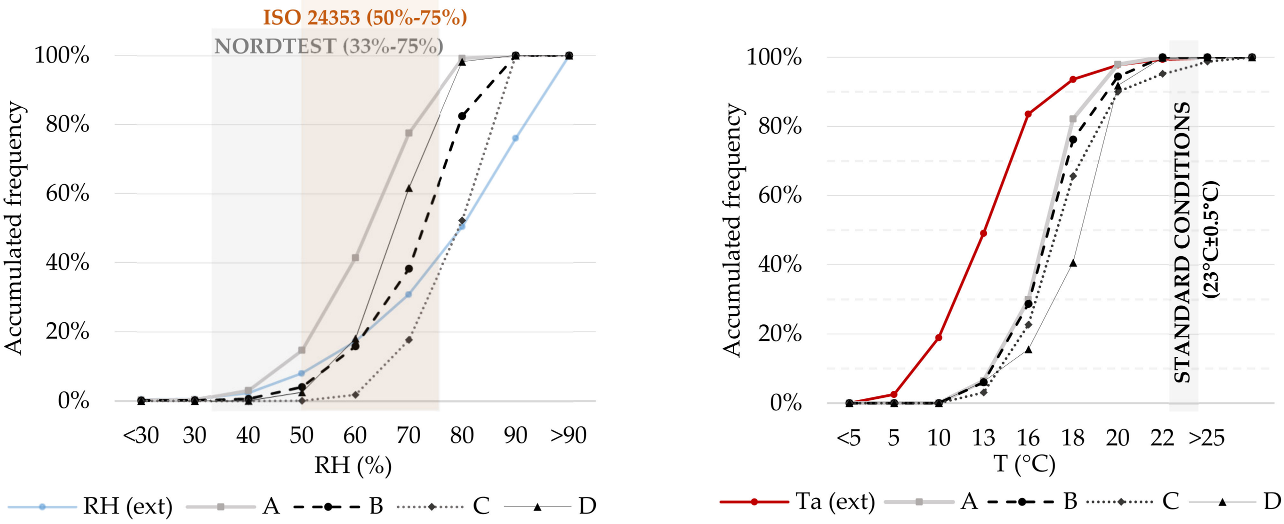

Figure 4. Frequency distribution of hourly RH and T data recorded in the four bedrooms under study in Lisbon and in the outdoor climate, from November 2020 to March 2022.

As far as the upper limit value of the NORDTEST is concerned, i.e., 75% RH, it seems quite representative of a typical condition of high RH in case studies A and D. In these two rooms, indoor hygrometric conditions are below this value at least 80% of wintertime.

On the contrary, much higher RH levels can be found in case studies B and C, where an RH above 75% is detected during 60% and 40% of the winter period, respectively. Even for temperature, the standard range considered in laboratory testing (23 °C ± 0.5 °C) does not seem to represent typical indoor conditions in the analysed bedrooms. Indeed, temperatures below 22.5 °C are found for more than 90% of the time in all the rooms taken into analysis.

The outcomes of the monitoring seem consistent with previous indoor monitoring campaigns performed in buildings located in Portugal. Indeed, in a study on a prototype of an un-refurbished classroom [3], on social housing [61], and on residential apartments [62], RH levels were frequently falling in the range 50–80% RH during winter. In addition, in the three studies, indoor temperature was found to be below 22.5 °C for almost the whole winter period considered in the monitoring (entire winter in [3,62], and only February in [61]).

In order to have a representation of a typical range for indoor RH and T fluctuations, two intervals are hereby considered: the 90th–10th percentile (P90–P10%) and the more restrictive interval 75th–25th percentile (P75%, P25%). Considering all case studies, the average values of P25% and P75% are 63%—16 °C and 76%—18.5 °C, whereas the average values obtained for P10% and P90% are 56%—14.5 °C and 82%—19.5 °C, as reported in Figure 5.

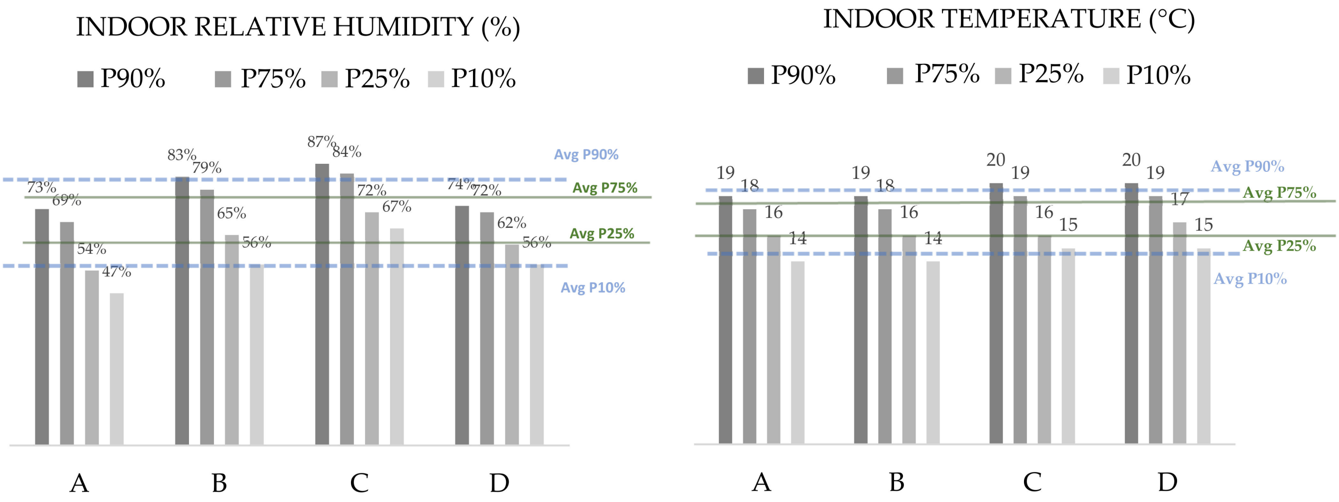

Figure 5. Values of the 90th, 75th, 25th, and 10th percentiles in the dataset of indoor relative humidity and temperature recorded in each case study, during winter. The blue and green lines indicate the average values obtained from the percentiles of the 4 case studies.

According to this analysis, a typical range of fluctuation would be 63–76% RH and 16–18.5 °C (considering 25th–75th percentiles), or 56–82% for RH and 14.5–19.5 °C (accounting for 10th–90th percentiles). The proposed ranges are hereby assumed as representative of the indoor climates considered, and they are compared to the indication of ISO 24353 [20] and NORDTEST [17] for the RH range to consider during the tests.

From the qualitative comparison provided in Figure 6, the step 50–75% RH suggested by ISO 24353 [20] for a "middle humidity level" appears to better estimate the indoor datasets than the NORDTEST. In the latter, the minimum RH appears extremely lower than the values of indoor RH registered, and it is significantly below the limits estimated with P10% and P25%. This difference between typical testing conditions and real climates might result in an overestimation of the potential benefits of hygroscopic materials applied in the Southern European context. In fact, the conditions of the NORDTEST have a greater range of RH and a much lower minimum value, which would probably result in higher MBV of the materials than at "more realistic conditions". For this reason, it could be valuable to have further studies aimed to evaluate the scenario of Southern European countries and a possible complementary approach to adopt for applications of hygroscopic materials within this context. Regarding the temperature, both the methods (ISO and NORDTEST) account for a T of 23 ± 0.5 °C, which is quite far from the ranges hereby observed (16–18.5 °C and 14.5–19.5 °C). Even though the effect of T on the moisture buffering capacity of building materials is hardly ever investigated, according to Mazhoud et al. [63] a linear correlation between T and MBV exists, probably for the effect of T on saturation vapour pressure [64]. The possibility of considering a specific temperature for Southern European countries might be an option to consider in future investigations.

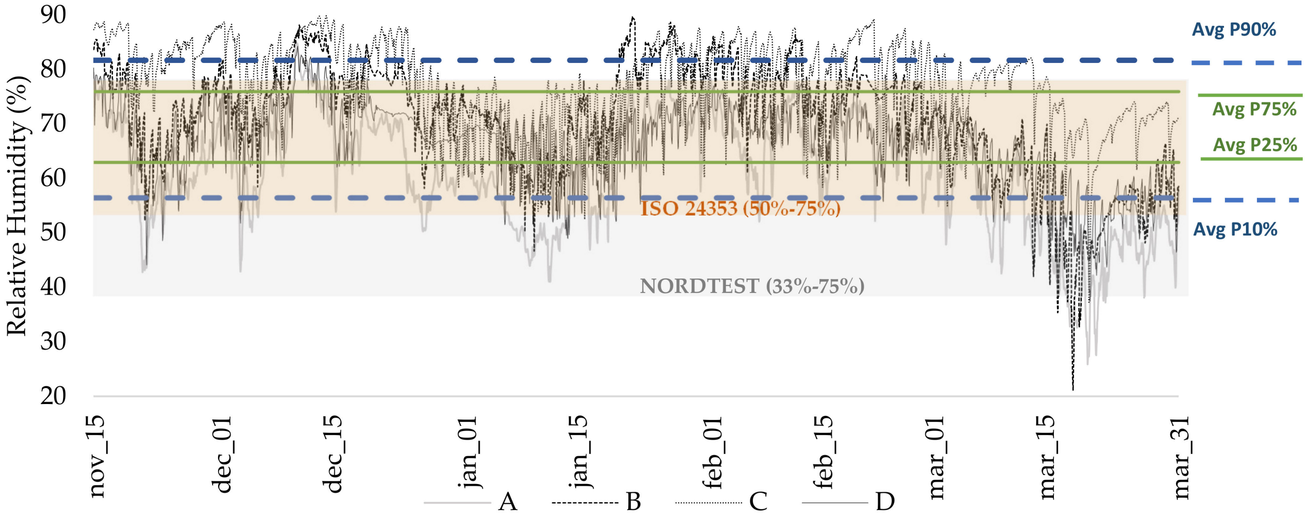

Figure 6. Indoor RH in each of the four bedrooms. The blue and green lines indicate the average values found in the case studies, in terms of 10th, 25th, 75th and 90th percentile of RH. For comparison, the ranges of RH considered in the NORDTEST [17] and the ISO 24353 [20] are also reported, in grey and orange hatches, respectively.

3.3. Indoor Comfort

Comparing the datasets obtained via indoor monitoring with the comfort zone roughly defined through four points in Figure 7, it emerges that all case studies are out of the hygrothermal comfort area for a large share of wintertime. In case studies A and D indoor RH and T are out of the comfort zone for at least 50% of wintertime, a percentage that increases to 75% and about 90% in case studies B and C, respectively.

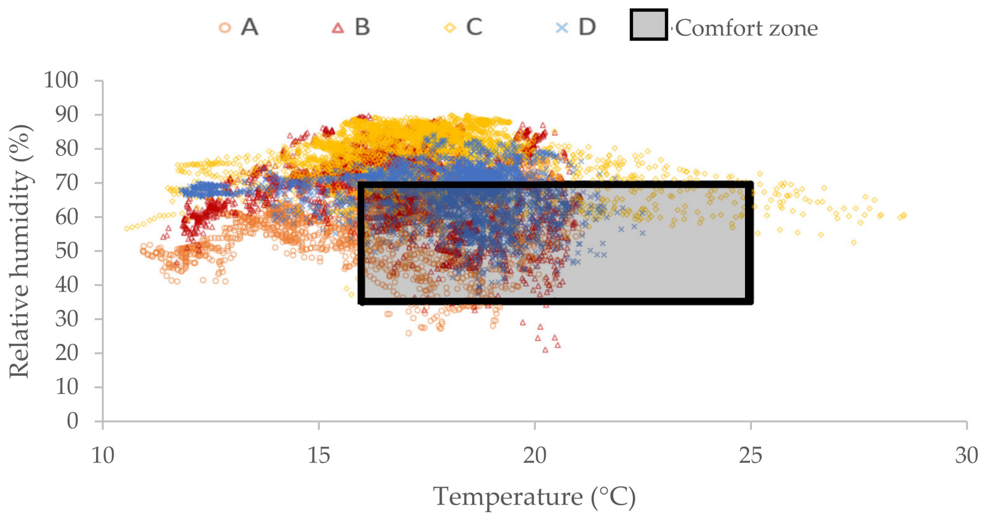

Figure 7. Graphic comparison between the hygrothermal datasets registered on-site in case studies A to D, and the comfort zone defined through 4 points (16;30); (16;70); (25;30); (25;70).

The comparison reported in Figure 7 shows that discomfort conditions are mainly due to high RH and/or low T. This result is in agreement with the feedback given by the users and with the observation raised in the literature concerning the typical lack of comfort in Southern European residential spaces.

3.4. Sorption Isotherms of the Plasters

The sorption isotherms of the plasters are shown in Figure 8. For each plaster, the adsorption and the desorption phases are represented by a continuous and a dotted line, respectively. All the plasters present some hysteresis, showing a residual moisture content at the end of the desorption phase. For E and NHL plasters, the hysteresis is very low, and the adsorption and desorption curves almost overlap. The other two plasters, CL and CEM, have higher hysteresis.

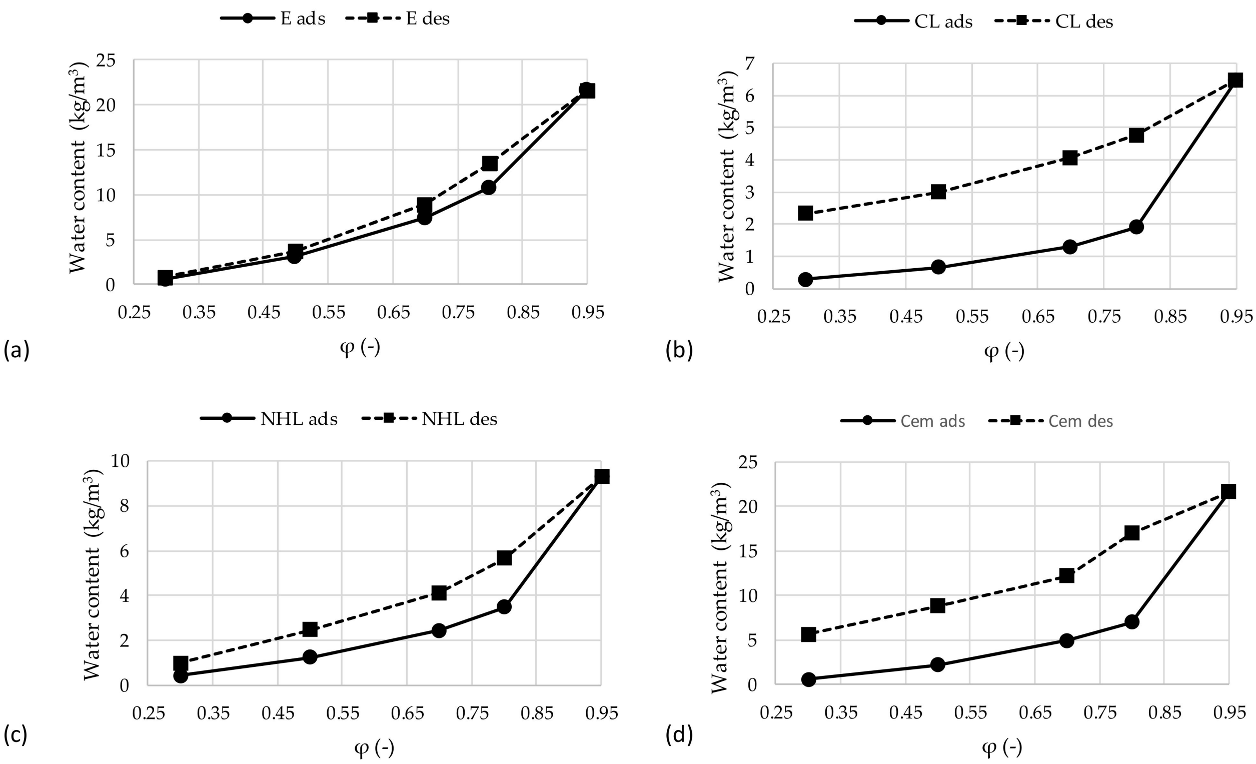

Figure 8. Sorption isotherms of the mortars based on: (**a**) earth; (**b**) air lime CL90-S; (**c**) natural hydraulic lime NHL 3.5 and (**d**) cement II/B-L 32.5N.

3.5. Simulations

3.5.1. Simulations under Standard Conditions

Figure 9 shows the results of numerical simulations compared to those obtained in the experimental characterization of the plasters. Numerical simulations were run both considering the average of adsorption and desorption curves—simulated (AVG)—and only accounting for the adsorption curve—simulated (ADS). For E and Cem, the two curves (AVG and ADS) are almost overlapped. On the contrary, CL and especially NHL show more relevant differences when different assumptions are made to simplify their sorption isotherms. Namely, more accurate results were obtained considering only the adsorption curve. Thus, for the simulations presented in the following section, this simplification (ADS) is adopted to model the sorption isotherm of the four plasters considered.

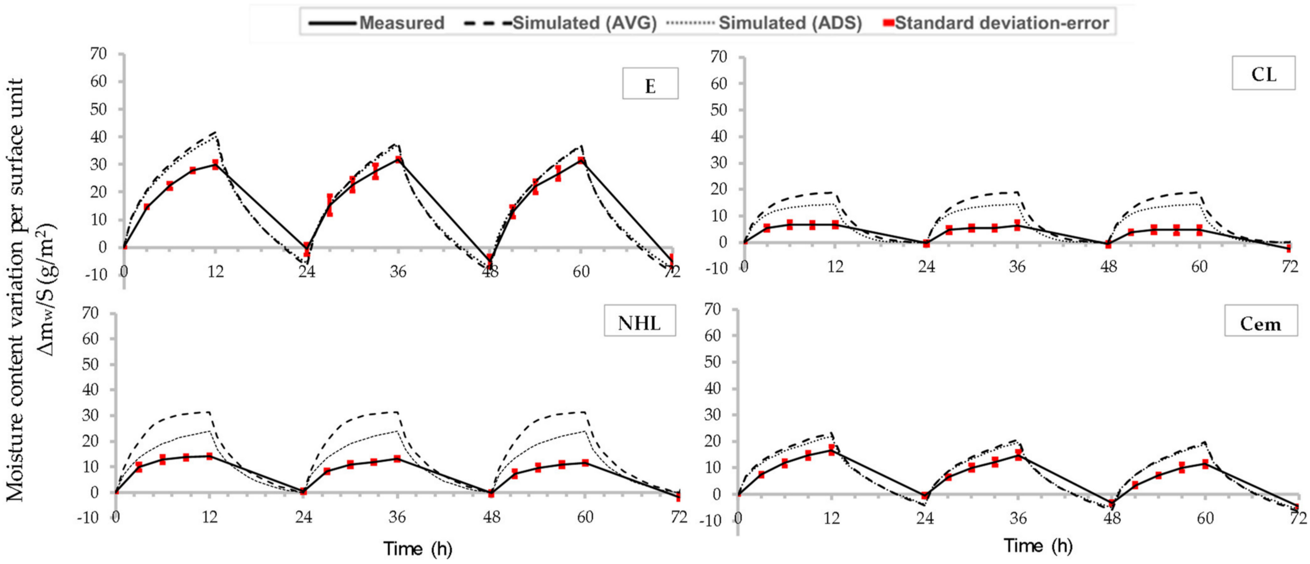

Figure 9. Three cycles of moisture content variation per unit of surface, displayed among time for each plaster: E—earth, CL—air lime, NHL—natural hydraulic lime and Cem—cement-based; *Continuous*—plaster laboratory results tested according to ISO 24353 [20] and relative standard deviation; *dashed*—hourly measures on simulation based on sorption/desorption average curve; *dotted*—hourly measures on simulation based on adsorption.

Moreover, all simulations appear to overestimate the moisture content in the materials during the adsorption process. This outcome seems less relevant for E and Cem, and more significant for CL and NHL. Nonetheless, simulations still appear representative of the different behaviour of materials, meaning that materials showing higher moisture content variation in the laboratory do also have higher changes of moisture content in the simulations. For this reason, the model adopted is considered suitable for a qualitative comparison of the hygroscopic behaviour of the plasters under realistic operational conditions.

Finally, similar differences between measured and simulated water content in building materials, during alternated cycles of high and low humidity, were also observed in previous studies [65–67].

3.5.2. Simulations under Realistic Operational Conditions

The results obtained via dynamic hygrothermal simulations under realistic operational conditions are presented in Figure 10. In the first four graphics, Figure 10a, the moisture content per unit area is represented with different colours for each plaster, for the indoor conditions of case studies A, B, C and D. The initial moisture content of plasters is assumed as the one at 60% RH, which corresponds to a different value depending on the sorption isotherm of each material. Although this difference in initial water content is noticeable, it is not relevant for the discussion on RH regulation. In this regard, what matters is the variation in the moisture content of the plaster, not its absolute value. Results shown in Figure 10a suggest that the variation of moisture content is stronger in plasters E and Cem, rather than in CL and NHL.

The fluctuation of moisture content is shown more in detail for two periods of 2 days, and the results are displayed in Figure 10b. The eight graphics reported in the figure confirm the previous observations. In all the scenarios considered, the largest fluctuations of moisture content are observed in the earthen plaster (E), followed by plasters based on cement (Cem), natural hydraulic lime (NHL) and hydrated air lime (CL), in this order. An exception is observable in the graphic on the right referring to case C, where the difference between E and Cem, and between NHL and CL, does not seem relevant. The ranking observed is in agreement with the MBVs experimentally obtained following the standard ISO 24353 [20] and the NORDTEST procedure [17]. The simulation results obtained under operational conditions show that in Southern European countries with low heating habits, the analysed standard tests used to quantify moisture buffering are qualitatively representative of the hygroscopic performance of materials under real operational conditions.

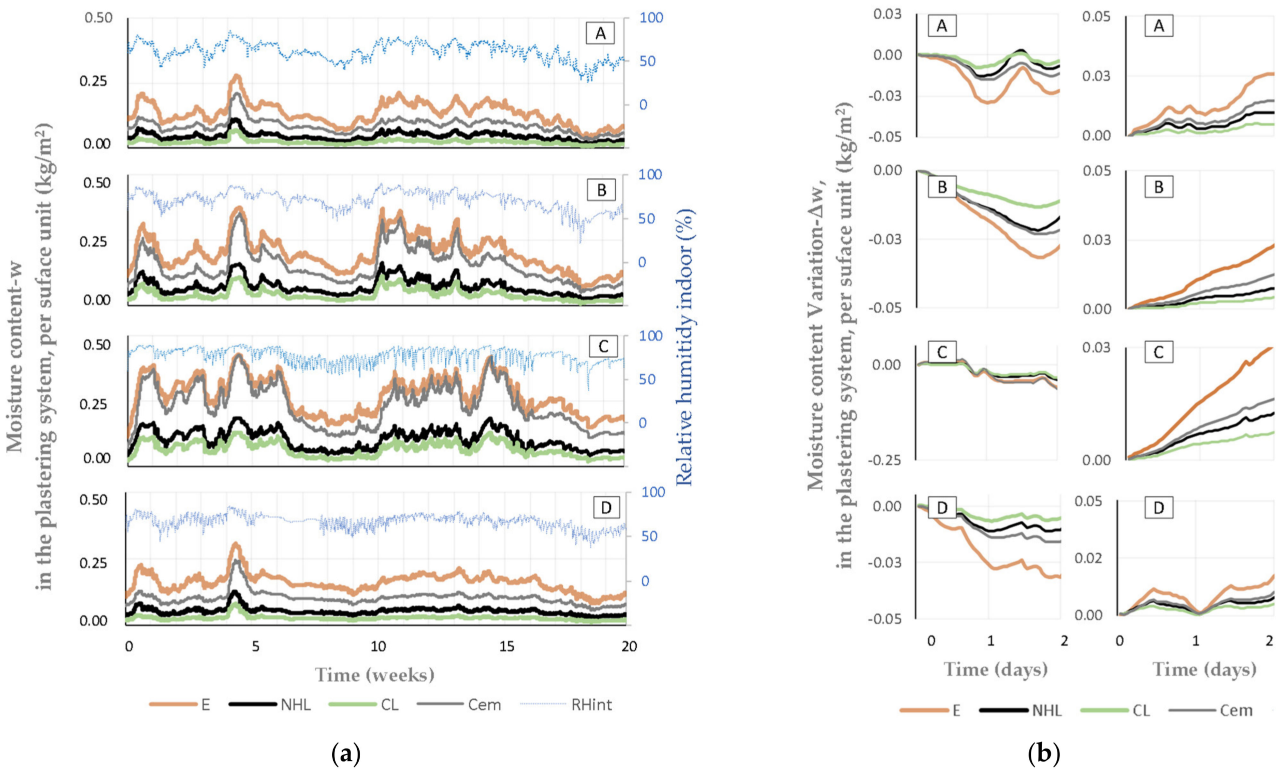

Figure 10. Simulation results of the moisture behaviour of the four plasters for each study case: (**a**) moisture content per unit of surface (m_w/S) during the entire winter period; (**b**) moisture content variation per unit of surface ($\Delta m_w/S$) during two periods of 2 days each, respectively, starting on 20 February and 21 March. From top to bottom, the graphics correspond to the results obtained considering the indoor climate recorded in case studies A, B, C and D.

Finally, the earth-based plaster, E, seems to be the most promising for further studies on indoor air quality improvement. This outcome is consistent with the observations in Cascione et al. [15], where an experimental campaign conducted at the room level showed that a clayey earth plaster was more effective than a lime-based one, for stabilizing indoor RH. Thus, earth-based plasters appear extremely appealing thanks to the additional benefits given by the low environmental impact and infinite recycling possibilities of earth [68].

4. Conclusions

This study presents the results obtained in an indoor hygrothermal monitoring campaign performed in four bedrooms of different buildings in Lisbon, during wintertime. The datasets obtained were analysed, and characteristic ranges of temperature and relative humidity were defined. Mono-dimensional dynamic hygrothermal simulation tools were adopted to simulate the hygroscopic performance of four plasters, under the operational conditions measured on-site.

The outcomes of the indoor monitoring campaign allowed to define the following conclusions:

- The microclimates of the four case studies are found to be well represented by the hygrothermal ranges of 63–76% RH and 17.5 ± 1.5 °C, which were defined considering the 25th and 75th percentiles of the dataset distributions.
- In terms of RH, the ISO 24353 sets the closest values to the characteristic ranges defined for the four case studies according to the monitoring. The standard adopts

the condition 50% to 75% RH, differently from the NORDTEST procedure, which is typically used considering the range 33–75% RH. Overall, the humidity range adopted in the ISO standard appears more representative of the microclimates observed on-site. Indeed, the lower RH value adopted in the NORDTEST (33%) is rarely reached in the datasets presented in this study. RH below this value is observed for less than 5% of the time and only in two case studies.

- Considering the temperature, the values prescribed in both the ISO 24353 standard and the NORDTEST protocol (22.5–23.5 °C) are higher than those observed in the case studies during almost the entire wintertime.
- In terms of indoor comfort, it was observed that the case studies are often out of the comfort area—over 50% of wintertime—mainly due to high relative humidity and low temperature. This outcome is consistent with the complaints of the bedrooms' users. Furthermore, it is aligned with the literature concerning the inability of keeping residential spaces sufficiently warm in Southern Europe.

Dynamic hygrothermal simulations allowed to give a rough evaluation of the moisture buffering ability of the plasters, under realistic operational conditions. The main remarks defined from the simulation results are the following:

- The fluctuation in the moisture content of the plasters was qualitatively in agreement with the ranking based on the MBV determined by both the NORDTEST procedure and ISO 24353 standard. Thus, the standard test procedures for evaluating the moisture buffering capacity of building materials might be representative also for the context of Southern European housing, despite its colder and moister indoor conditions. Further studies are needed to evaluate this point more in depth, accounting for the more accurate results obtainable through whole-building simulation models.
- The earth-based plaster, above all, showed the widest fluctuations in water content under realistic operational conditions. This result suggests that this material could be promising for passive regulation of indoor relative humidity.

Forthcoming studies will be focused on quantitatively evaluating the effect of the plasters on indoor RH regulation, by means of whole-building simulation tools. These evaluations will be used to further assess the suitability of standard tests to represent the hygroscopic behaviour of plasters in intermittently heated/unheated spaces, typical of Southern European countries.

Author Contributions: Conceptualization, investigation, writing—original draft preparation, A.R.; conceptualization, software, writing—original draft preparation, M.P.; supervision, writing—review and editing, R.V. and P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Portuguese Foundation for Science and Technology: PD/BD/150399/2019, PD/BD/135192/2017 (first and second authors are part of the Doctoral Training Programme EcoCoRe) and UIDB/04625/2020 (Civil Engineering Research and Innovation for Sustainability Unit—CERIS).

Institutional Review Board Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the support provided by CONSTRUCT-LFC (Institute of R&D in Structures and Construction at FEUP) and also by the National Laboratory for Civil Engineering, through projects PRESERVe and REuSE, as well as the help offered by IPMA, who provided for the outdoor climate dataset considered in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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