Hygrothermal performance of External Thermal Insulation Composite Systems (ETICS): experimental monitoring and numerical simulation

Francisco Gonçalves[1]

Supervisors: Inês Flores-Colen[1,2], Giovanni Borsoi[2]

[1] Civil Engineering Department (DECivil), Instituto Superior Técnico, University of Lisbon

[2] Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, University of Lisbon

ABSTRACT

External thermal insulation systems (ETICS) have been used in Europe since the 1950s, both in new construction and in rehabilitation works. These constructive systems can, however, present surface anomalies over time, such as microcracks and stains. Biological colonization and degradation of the ETICS façades, favoured by the high relative humidity of the Atlantic coast and by the properties of the system, is among the most widely diffused anomalies in Portugal. Thus, it is necessary to study and understand the hygrothermal performance of ETICS in view of their location and characteristics. This work firstly aims at monitoring ETICS through an experimental campaign. Four systems with different thickness, composition and characteristics were placed in two distinct environments, i.e., on the roof of two buildings located in an urban and in a semi-rural environment. Results showed that the specimens located in a semi-rural environment (FCT/UNL) recorded higher temperatures, thus contributing to the lowest relative humidity values, if compared to the urban environment (LNEC). Relative humidity values can also be related to the water absorption capacity of the systems, since the specimens with a higher water absorption capacity had fewer hours in which the relative humidity exceeded 100%. The presence of humidity on the surface of the systems is directly related to the risk of biological development. Furthermore, a comparison between the obtained results and the simulated results, using WUFI PRO, was carried out, concluding that the simulated temperature values are closed to the experimental values. However, it was not possible to obtain a reliable simulation of the relative humidity, due to some limitations of the software.

Keywords: ETICS; Sensors; Relative humidity; Temperature; Biological colonization; WUFI PRO

INTRODUCTION

Exterior thermal insulation systems (ETICS) have been used in Europe since the 1950s (firstly in Scandinavian countries and Germany), and more frequently after the first energy crisis in the 1970s [1]. These systems present thermal and acoustic insulation properties, relative ease of application and moderate cost [2]. The use of ETICS in Portugal significantly grew from about 200,000 m^2 in 2006, to over 2.400.000 m^2 in 2010 [1], and about 7.000.000 m^2 in 2020 [3].

ETICS have been applied in several types of construction, namely in collective housing, terraced or single family houses, public buildings, among others [4]. Despite the wide diversity of buildings where these systems can be applied, there are some exceptions. In fact, the application of ETICS should be avoided in buildings with thick and porous walls (e.g., historical buildings), since high levels of moisture, associated to the low permeability of the finishing render of the system, can change its functioning, originating or accelerating degradation processes [4], [5].

This type of system allows the reduction of thermal bridges and overall heat loss. Thus, ETICS can enhance the energy-efficiency and reduce the maintenance cost of the building, by reducing the heating and cooling needs of the environment. An improvement of the thermal comfort during summer, due to the ability to regulate indoor temperature, and also in winter, by increasing useful solar gains [6], [7], can be achieved. On the other hand, ETICS have poor impact resistance, which is a critical aspect in accessible areas, often prone to accidental impacts of objects or vandalism (e.g., in schools or in areas of high housing density). This anomaly generally leads to aesthetic alterations and favoured the penetration of water in the system, generating stains and mould growth.

Blaich [7], [8] (Empa, Switzerland), with a pioneering study on the hygrothermal behaviour of ETICS, identified surface humidification as a crucial factor for the appearance and development of microorganisms. It was concluded that moisture was generated from surface condensation, mostly due to the reduction of temperature during the night, as well as from the rainfall incident on the façade.

These results were later confirmed by researchers from the Fraunhofer Institute for Building Physics (IBP) [9], [10], which also identified the composition and drying process of the materials composing the system as crucial factors for the surface moisture content [9], [10].

IBP researchers [9] widely studied also surface condensation, highlighting that this phenomenon mainly occurred when the dew point temperature was higher than the exterior surface temperature. It was concluded that the thickness of the thermal insulation increased the probability of condensation, the heat flux from inside the building lower.

Putterman *et al.* concluded that plaster samples with high moisture content collected in situ, were those that also showed a more significant development of microorganisms. Several numerical simulations were carried out understand the origin of the moisture [11], [12], concluding that the moisture content in the render of ETICS was higher than in monolithic walls, especially when the dew point temperature was higher than the surface temperature. However, the relative humidity never reached 100% in those periods.

Von Werder *et al.* [13], [14] through evaluated the hygric properties of two types of plaster (synthetic and mineral) laboratory tests and in situ tests. The results indicated that the plasters with lower absorption coefficient were those with higher relative humidity values for longer periods of time.

Barreira *et al.* [7] studied the hygrothermal behaviour of façades with ETICS systems, facing the four cardinal points. The numerical simulations allowed to understand that the condensations on the exterior surfaces were conditioned by the exterior relative humidity, incident atmospheric radiation and by the temperature of the exterior air. The authors also evidenced that the amount of rainfall on the façades was influenced by its orientation, wind direction and speed, and building height [15].

With regard to bio-susceptibility in ETICS systems, Jurgen Blaich showed that synthetic binders integrated into the render intensified the problem of microorganism growth, due to water retention pioneering in the surface for long periods. On the other hand, the biological development was less favourable in plasters based on mineral binders, due to higher water permeability of these materials [7], [8], [16].

Von Werder et al. [13], [14]. also concluded that mineral binder renders were more susceptible to biological growth than synthetic binder renders. Synthetic binder renders without added biocide were more affected by mould growth.

MATERIALS AND METHODS

➢ *General Considerations*

In the experimental campaign, 4 systems (Figure 1A) with dimension 15 x 15 cm and variable thickness were monitored (Table 1). The samples were placed in two different metallic racks with a 45º inclination, facing south, in order to maximize the number of hours of sun exposure (Figure 1B). The racks were placed in the rooftop of two buildings, one in an urban environment in Northern Lisbon (Portugal), the other in a semi-rural environment in Almada (5km south of Lisbon). Both locations are located few kilometres from the Atlantic Ocean.

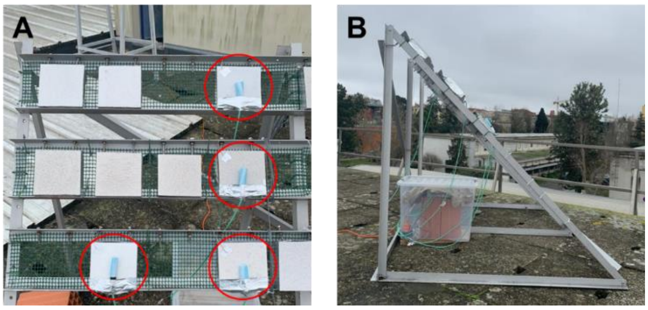

Figure 1: a) *ETICS specimens with the temperature and humidity sensors (red circles);* ***b)*** *Metallic rack with 45º inclination and protection box of the logger.*

➢ *ETICS Systems*

In the experimental campaign, 4 ETICS systems (S2, S4, S8 and S9) were chosen from a larger set of systems, studied within the WGB_Shield project [17]. The selection was made with the aim of studying systems with different thermal insulator, base coat and finishing layer.

Table 1: *Composition of the selected system*

Systems	Thermal insulation	Base layer	Finishing layer
S2	EPS	Cement mortar	Acrylic coating
S4	ICB	Hydraulic lime + Cement	Aerated lime + hydraulic binder
S8	MW	Cement mortar	Acrylic coating
S9	ICB	Natural hydraulic lime mortar	Aqueous silicate paint

➢ ***Humidity Sensors***

Capacitive relative humidity sensors (Honeywell HIH-4000) were adopted in order to monitor the moisture content in the different ETICS systems. These sensor have an electrical current consumption of only 200 µA, thus being ideal for low-power systems that are also battery operated [18], [19], and proper resistance to weathering and atmospheric pollutants [18].

➢ ***Temperature Sensors***

Thermocouples (Twin Twisted Pair Thermocouple Cable) were used as temperature sensors. The operation of this equipment is based on the Seebeck effect [20], which is based on the fact that the junction of two metals generates an electrical voltage. As soon as a temperature difference is detected between the joined ends and the free ends of the metals, a potential difference is generated and measured by a voltmeter [21]. These sensors are suitable for measurements in a wide range (-270 °C / 400 °C) [22].

➢ ***Logger***

A MZLOG04SAP datalogger (Figure 2) was used to collect and store the data. The datalogger allows monitoring 14 analogic channels in parallel, compatible with sensors with voltage output up to 8 µV. The logger was programmed to collect data every with a 1 minute time interval, and automatically register the average every 10 minutes.

The fourteen inputs of the datalogger are differential in voltage mode, allowing the connection of sensors with differentiated masses and eliminating electromagnetic noise [23]. The MZLOG04SAP is connected to an external voltage source (no battery was used for standalone power supply), having a current consumption of about 140 mA. The values recorded by this device have an absolute error in voltage corresponding to 2 µV. The logger has a storage capacity that allows 14,560 records with date and time [23]. The collection of the data recorded by the logger is done through USB connection to a laptop, using a dedicated software (HyperTerminal – V. 7.0).

➢ ***Experimental study***

Two equivalent sets of the ETICS were placed on the rooftop of two buildings in Lisbon (one in a urban environment, at LNEC; the other in a semi-rural environment at FCT-NOVA). The specimens were fixed on a metal rack, facing south and with a 45º inclination, with the aim of maximizing the number of hours of solar exposure (12 hours per day on average). Two sensors, one for humidity and one for temperature, were then placed in the surface each specimen, and connected to the logger. The logger was placed within a polyethylene box, in order to protect it from weathering, using also a sachet of silica gel to prevent moisture condensation on the circuit or wiring (Figure 2a).

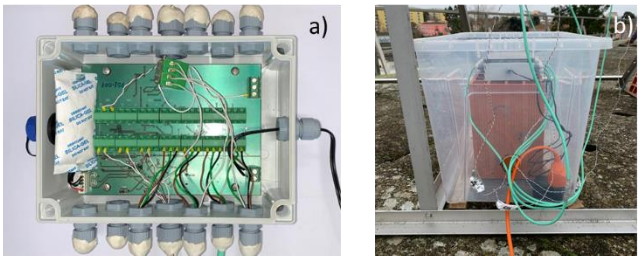

Figure 2: a) *Logger circuit and wiring* ***b)*** *Set-up of the logger in the polyethylene box.*

Data collection was programmed using the HyperTerminal program - version 7.0, setting up the measurement intervals. The logger registered the respective voltage measured at each sensor, and the internal temperature of the logger. The device has the capacity to store more than 3 months of data collected without interruption, however, data was collected at least twice a week in order to be able to detect any errors in the sensors or simply to check their performance. It is worth noting that the humidity sensors are highly sensitive to sunlight and a slight surface oxidation was observed on some sensors, possibly affecting their performance.

The sensors were thus protected using a polyethylene tissue, which prevented the passage of liquid water, however, allowing water vapor permeability (Figure 3b). In addition, a thermal-resistant silicone-based sealant was used on the back of the sensor and on the unprotected metal wiring (Figure 3a).

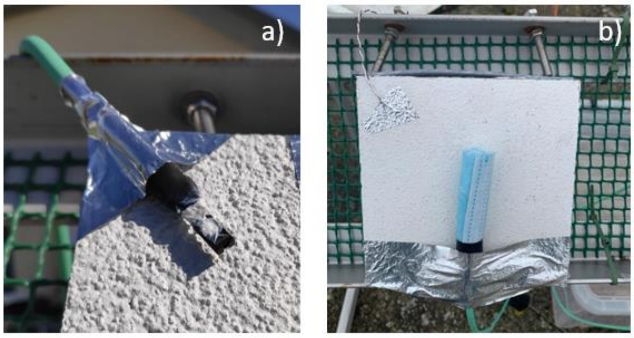

Figure 3: a) *Silicone* sealant on the rear side of the RH sensor***; b)*** *Sensor protection with polyethylene tissue.*

➢ ***Data Modeling***

The data collected by the logger was imported in .txt formats via HyperTerminal, and then processed in the Excel program. The data, measured in microvolts, were converted to temperature (°C) and relative humidity (%).

The following formula [24], [25] is applied for the temperature conversion, as indicated by the manufacturer:

$$T = \frac{p_1 \cdot (V - V0) + p_2 \cdot (V - V0)^2 + p_3 \cdot (V - V0)^3 + p_4 \cdot (V - V0)^4}{1 + q_1 \cdot (V - V0) + q_2 \cdot (V - V0)^2 + q_3 \cdot (V - V0)^3} + T0 + T_{int.}$$

Where T is the surface temperature of the specimen; V the voltage measured at the temperature sensor; T_{int} the internal temperature of the logger; p_1, p_2, p_3, and p_4 the volt to temperature fit coefficients; V_0 the initial voltage coefficient; T_0 the initial temperature coefficient and q_1, q_2, and q_3 the voltage to temperature adjustment coefficients. In the case of relative humidity, the formula applied is as follows [19]:

$$HR = \frac{V - offset}{slope}$$

Where HR is the relative humidity at the surface of the specimen at 25ºC; V is the voltage measured at the humidity sensor; offset and slope are predefined parameters.

- ***WUFI***

WUFI PRO, which focuses on the analysis of multi-layered elements, such as ETICS, was chosen. This software simulates the hygrothermal performance of the composite insulation system under specific external and internal weather conditions [26], [27]. This one-dimensional hygrothermal model takes into account the most recent findings on vapor diffusion and moisture transport in building materials [28].

Input data on the building components, the calculation and the climate conditions are firstly introduced in the software. Table 2 and 3 describes the calculation parameters for specimen S2. The simulations were made establishing hourly intervals, in order to avoid inaccuracies in the results [7].

Table 2: *Material properties of sample S2 obtained from the data sheets and the WUFI database.*

SAMPLE S2			
Layer	*Thermal insulation*	*Base Layer*	*Finishing layer*
Material	EPS 100	Fibrated mortar	Acrylic coating
Thickness [mm]	37,70	1,75	1,12
Density [kg/m^3]	21	1195	1700
Porosity [m^3/m^3]	0,35	0,40	0,28
Specific heat [J/kgK]	1550	900	840
Thermal conductivity [W/mK]	0,036	0,470	0,371
Water vapor diffusion resistance factor [-]	21,70	15,50	86,70
Typical construction moisture value [kg/m^3]	0,18	85,00	95,00

Table 3: *Simulation parameters and their criteria/values assumed for the specimens studied.*

SIMULATION PARAMETERS	CRITERIA/VALUE
Configuration of the building element	
Orientation / Inclination	South / 45º
Coefficient of incident rainfall	$R_1 = 0; R_2 = 1$
External surface transfer coefficients	
Thermal resistance [m^2·K)/W]	Wind-dependent
Sd value [m]	Without coating
Absorption (Shortwave Radiation) [-]	Light surface (0.2)
Emissivity (Long Wave Radiation) [-]	Light surface (0.9)
Explicit Radiative Balance	yes
Ground reflectivity (shortwave) [-]	Standard Value (0.2)
Interior surface transfer coefficients	
Incident rainfall reduction factor [-]	Dependent on the inclination of the construction element (0,1)
Initial conditions in the construction element	
Humidity [%]	60
Temperature [°C]	20

RESULTS

- ***Hygrothermal analysis of specimens from the same roof***

Analysing the set of specimens on the LNEC rooftop, it was found that the average temperature shows no significant variation between the specimens in the monitoring period. The maximum variation recorded between the systems was 0.10ºC.

Although the variation is relatively low, specimen S8 (acrylic finishing) recorded higher average temperatures in the month of September (Table 4). In this month, specimens S2, S4 and S9 registered on average 0.06ºC, 0.09ºC and 0.10ºC less than specimen S8, respectively. In the remaining months of the experimental campaign, specimen S2 (acrylic finish) recorded the highest average temperatures (Table 4). On average, specimens S4, S8 and S9 recorded 0.08ºC, 0.01ºC and 0.05ºC less than specimen S2, respectively. Specimens S4 (lime-based finish) and S9 (silicate) are, therefore, the systems with the lowest average temperatures.

Table 4: *Average temperature (ºC) recorded in the specimens at the LNEC rooftop.*

	Sample S2	Sample S4	Sample S8	Sample S9
September	27,86	27,83	27,92	27,82
October	21,34	21,29	21,33	21,30
November	21,68	21,60	21,65	21,64
December	17,08	16,97	17,08	17,02

Table 5 presents the number of hours when the dew point temperature exceeded the surface temperature recorded on the specimens. It was found that specimen S2 (acrylic finish, cement base and EPS insulation) had a higher number of hours of surface condensation in December (about 3.67 hours), compared to the other specimens. Specimens S4, S8 and S9 were also found to have similar average values (about 3.15 hours), and the maximum variation between these three specimens was 0.25 hours (15 minutes).

Table 5: *Number of hours that the surface temperature was exceeded by the dew point temperature*

	LNEC			
	Sample S2	Sample S4	Sample S8	Sample S9
September	0,00	0,00	0,00	0,00
October	2,17	3,00	1,67	2,50
November	2,33	2,17	2,50	2,50
December	11,50	7,67	7,83	8,00
Average	4,00	3,21	3,00	3,25

With regard to the average relative humidity (Figure 4), the S2 system recorded higher values in September and October. In these two months, system S2 presented higher average relative humidity (7.29%), if compared to the other specimens. In the month of September, specimens S4, S8 and S9 recorded on average 7.75%, 6.02% and 9.82% less than specimen S2, respectively. In October, specimens S4, S8 and S9 averaged 7.73%, 4.00% and 8.44% less than specimen S2, respectively.

In November and December, the specimen that recorded higher average relative humidity values was system S4 (lime finished, Figure 4), presenting on average 4.82% more relative humidity than the other specimens. In November, specimens S2, S8 and S9 recorded on average 1.92%, 3.04% and 2.53% less relative humidity than specimen S4, respectively, with even higher differences in December (7.11%, 7.19% and 7.16%, respectively).

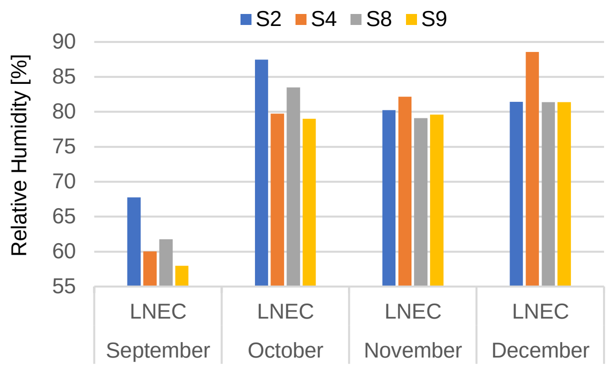

Figure 4: *Average relative air humidity in the specimens of LNEC roof.*

Analysing the set of specimens on the FCT/UNL rooftop, it was found that the average temperature throughout the monitoring period, as seen on the LNEC specimens, does not vary significantly between specimens. The maximum variation recorded among all the systems was 0.11ºC.

Specimen S8 recorded again the highest values for average temperature in the month of September (Table 6). On average, specimens S2, S4 and S9 recorded 0.02ºC, 0.09ºC and 0.11ºC less than specimen S8, respectively. In October, November and December, specimen S2 recorded higher average temperatures (Table 6). Specimens S4, S8 and S9 recorded on average 0.11ºC, 0.01ºC and 0.07ºC less than specimen S8, respectively. As also observed for specimens on the LNEC rooftop, specimens with acrylic finishes (S2 and S8) show slightly higher average temperature values than lime (S4) or silicate (S9) based systems.

Table 6: *Average temperature (ºC) recorded throughout the experimental campaign on the FCT-NOVA roof specimens.*

	LNEC			
	Sample S2	Sample S4	Sample S8	Sample S9
September	28,18	28,12	28,20	28,10
October	23,00	22,89	23,00	22,94
November	22,09	21,98	22,08	22,03
December	19,06	18,95	19,04	18,97

Analysing the average relative humidity (Figure 5), similarly to what was recorded on the LNEC rooftop, the S2 system recorded the highest values (in average 1.16%) in September and October. Comparing the values of the other specimens, system S2 recorded, in September, 2.24%, 2.79% and 1.18% more than specimens S4, S8 and S9, respectively. As for October, specimens S4, S8 and S9 recorded on average 1.10%, 2.95% and 0.92% less than specimen S2, respectively.

As it happened at LNEC, specimen S4 recorded the highest average relative humidity values in November and December (colder months) (Figure 5). Concerning the month of November, it was found that specimens

S2, S8 and S9 recorded on average 1.06%, 5.01% and 2.43% less relative humidity than specimen S4, respectively.

In December, the difference between specimen S4 and the others was relatively similar, with specimens S2, S8 and S9 registering on average 0.88%, 5.02% and 1.15% less than specimen S4, respectively. It is worth noting that S8 system is considerably rough (1.0 mm) [53], namely 50% more than specimens S4 and S9 and 20% more than specimen S2. The greater roughness of specimen S8 can affect the surface tension of the water [29] and thus water retention.

➢ ***Hygrothermal analysis of specimens from different rooftops***

The specimens on the FCT-NOVA rooftop had higher average temperatures than the specimens on the LNEC rooftop. The maximum variation recorded between all systems was 1.98ºC (in December for specimens S2 and S4). In the same month, specimens S8 and S9 recorded a maximum variation of 1.96ºC and 1.95ºC, respectively.

Regarding the average relative humidity (Table 7), the LNEC specimens had higher values. The maximum variation among different sites was in December, when LNEC specimens recorded, on average, 8.94% more relative humidity than FCT-NOVA specimens. In the remaining months, the variation was on average 5.28%, 6.37% and 7.89% in September, October and November, respectively.

Analysing the relative humidity of each set of specimens (each system in different rooftops), it was found that the greatest difference was recorded in specimen S8 (about 9.18%). Systems S2, S4 and S9 recorded on average more 8.26%, 6.33% and 3.18% relative humidity, respectively.

Table 7: *Average relative air humidity (%) recorded throughout the experimental campaign.*

		S2	S4	S8	S9
September	LNEC	67,78	60,03	61,76	59,76
	FCT-NOVA	60,95	58,71	58,16	57,96
October	LNEC	87,47	79,74	83,47	79,02
	FCT-NOVA	78,30	77,20	75,36	77,38
November	LNEC	80,23	82,15	79,11	79,62
	FCT-NOVA	75,02	76,08	71,06	73,65
December	LNEC	81,46	88,56	81,37	81,40
	FCT-NOVA	76,57	77,46	72,44	76,31

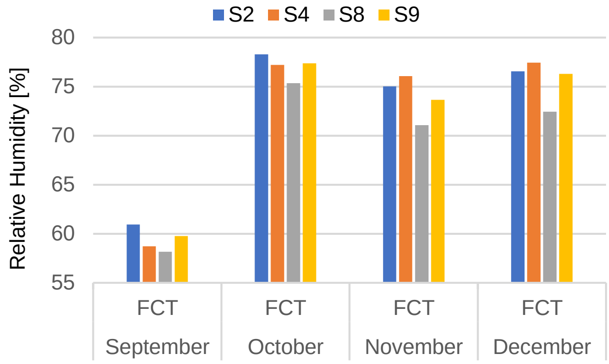

Figure 5: *Average relative air humidity in the specimens of FCT roof.*

DISCUSSION

➢ ***Specimens in the same roof***

The low temperature variation among S2 and S8 can be associated to the composition of the systems. In fact, although both composed of similar cementitious basecoat, these systems differed for the thermal insulation layer (EPS for S2, and MW in S8) and slightly for the acrylic finishing layer (S8 is considerably rougher, i.e., with thicker mineral fillers).

Considering the month of September, specimen S8 always recorded the highest values, which can be attributed to the high thermal conductivity of the components of the system. In the WGB_Shield project, laboratory tests were performed to determine the thermal conductivity of the insulation of each of the ETICS systems. It was found that S8 had the highest value (0.0564 W/m/K), among the four systems, after two months of natural aging [30]. Furthermore, it was found that moisture absorption in the insulating layer significantly increased the thermal conductivity, affecting the performance of the system [17].

Sample S2 had the highest number of hours of surface condensation. Other authors reported that the application of paints in ETICS systems, obtained through the addition of specific inorganic additives (e.g., pigments) could significantly reduce the risk of occurrence of condensation, as the surface temperature increased [11].

In fact, S2 is finished with an acrylic-based paint, and its surface temperature, as mentioned earlier, was among the highest recorded, along with S8 (also with acrylic finishing). However, the reduction of condensation phenomenon did not occur in the S2 system (Figure 6). This phenomenon can be associated to the thermal insulator (EPS in the case of S2). Conversely, specimen S8 has MW, which is notoriously more hygroscopic, as insulation layer.

***Figure 6**: Photographic record of visible surface condensation on specimen S2 of the FCT/UNL roof.*

According to the thermal conductivity tests performed, within the WGB_Shield project, it was found that the thermal insulating layer of S2 (EPS) presented a lower thermal conductivity (0.0372 W/m/K) than that (MW) of S8 (0.0403 W/m/K) [53]. This can induce a higher heat transmission from the thermal insulator to the finish layer of the S8 system, slightly increasing the surface temperature and reducing condensation phenomena.

Künzel & Sedlbauer [9] and IBP researchers [11] reported that surface condensation occurred on all exterior surfaces, being more evident on systems with a thin exterior layer. Specimen S2 is the system with the lowest thickness (Table 1) among the specimens studied, which may justify a greater number of hours of condensation. Furthermore, the thermal conductivity of the acrylic finishing (S2) is lower than the other finishing layers (lime-based and silicate-based paint).

As previously mentioned, the S2 system was the one that recorded higher values of relative humidity in September and October, both in the LNEC and FCT-NOVA rooftops. It was reported that surface condensation occurred mainly when the dew point temperature was higher than the outside surface temperature [9]. Specimen S2 is the system that presents the highest number of hours of condensation. Additionally, system S2 obtained the most efficient water performance [30], i.e. absorbed less condensed water, which accumulates on the surface, possibly increasing the surface relative humidity of this system.

System S8 recorded the lowest values of average relative humidity. According to the analysis of the water performance of the ETICS in the WGB_Shield project, specimen S8 recorded the highest value of water absorption (1.465 kg/m2) [30]. This system recorded also the highest absolute maximum temperatures, which, couples with the high water absorption capacity, can decrease the relative humidity at the surface.

- ***Specimens from different roof***

During the experimental campaign there was a greater tendency to record higher temperature values on the FCT-NOVA rooftop. Analysing the data collected during the period from 1 pm to 4 pm (more intense solar radiation), it can be seen that the average temperatures recorded on the FCT-NOVA specimens are higher (in average 1.50°C) than the average temperatures of the LNEC specimens, thus contributing to the higher average temperatures recorded on the FC-NOVA specimens.

This difference can be attributed not only by the fact that Lisbon has slightly higher wind intensity values (about 8km/h more than Caparica), but also by the number of hours of solar exposure (0.2 hours more in Caparica), according to data provided by IPMA [31]–[34]. Although the specimens are located on the rooftop of buildings and face south for more intense sun exposure, a higher spatial roughness can be found in Lisbon; thus, the FCT-NOVA specimens, being closer to the west zone (sunset zone), ended up with more hours of sun exposure.

Analyzing the data provided by IPMA, referring to the meteorological station in Lisbon, and the data from the meteorological station located on the rooftop of the FCT-NOVA, it is possible to verify that the average temperature is constantly higher (on average 0.62ºC) in the Costa da Caparica area than in the urban area of Lisbon. According to the map of the average annual temperature in Continental Portugal, the coastal zone of the Setúbal district presented, on average, slightly higher temperatures, if compared to the urban area of Lisbon, thus confirming the values collected [35].

From October to December, the specimens had lower absolute minimum temperatures at LNEC than at FCT-NOVA (about 2.63ºC on average), differing from the values recorded in September (difference of 0.06ºC between FCT-NOVA and LNEC). This discrepancy can be justified by the wind intensity, is higher in the Lisbon area [36]. In the month of September, this difference is lower, being this month considered weak dry, with high temperatures and low wind intensity [31].

Analyzing the relative humidity in each cover, as mentioned before, it was found that the LNEC reooftop registered higher values during the experimental campaign. Eva Barreira [3], mentioned that the presence of obstacles influenced the nocturnal surface temperature. Through *in situ* evaluation, this author concluded, that the presence of an obstacle caused an increase in night surface temperature, and consequently a decrease in surface condensation. Although the LNEC rooftop is located in the center of Lisbon, where the building density creates special roughness of buildings, the surface temperature and consequently the relative humidity was higher.

➢ ***WUFI simulations***

When comparing the simulated data with the experimental values, it can be seen that a more pronounced discrepancy between the measured and simulated temperature values was detected on November 19th, 2020. This difference can be attributed to the fact that, according to IPMA data, the month of November was the second warmest month since the year 2000, with day 19th standing out in the Lisbon region as the warmest day during the entire month [33].

Barreira and Peixoto de Freitas evidenced that the correspondence between the simulated and experimentally obtained results is less evident on days of higher temperature [37], in accordance with the data obtained in this work. The authors mentioned that the interference of the sun directly influences the behavior of the specimens, either when it acts directly on the specimens, or through the emission/reflection of radiation by the soil.

Comparing the average, minimum and maximum temperature values measured during the experimental campaign with the simulated results for specimen S2, the difference is less pronounced, with a greater difference only observed in the maximum temperature values, i.e., when the solar radiation directly hits the specimens. As mentioned by Barreira and Peixoto de Freitas [38], the approximation between the simulated and measured values is lower when the sky is clear, confirming the direct influence of the sun, not only when it falls directly on the specimens, but also during the night, when the solar energy absorbed by the soil is re-emitted. These phenomena are not considered by WUFI 6.5 (or are oversimplified) thus causing variations between the simulated and measured values when the sky is clear [7].

When evaluating the measured and simulated relative humidity during the entire experimental campaign, a relatively sharp discrepancy is also verified. Barreira [7] concluded that WUFI PRO provides no valid simulation of the relative humidity, especially in periods of incident rain. When rain falls directly on the specimens, the simulated relative humidity values reach 100% only while raining. The software does not take into account the period during which the specimens remain wet, after the incidence of rain has ended. Since the program is not able to take into account the accumulated rain on the surface of the specimens, it only considers its influence on moisture transfer through the materials that compose the system [7], [39].

CONCLUSIONS

ETICS systems have been increasingly applied in Portugal, due to their ease of application, cost-effectiveness and contribution to the energy efficiency of building envelope. However, although not considerably altering the thermal performance of the systems, the formation of stains and mold growth is a rather common pathology in this type of system, inducing an aesthetical degradation of the building façade.

The literature review highlighted that the studies carried out by the scientific community contributed to an advance in the knowledge of the hygrothermal behavior of ETICS systems. However, these studies were mostly conducted in central and northern Europe, thus, it is necessary to evaluate the behavior of these systems based on the climatic conditions of Portugal. Hence, this dissertation intended to increase the knowledge of the hygrothermal performance of ETICS systems.

The experimental campaign lead to the following conclusions:

- The *in situ* evaluation of the different specimens, exposed in different environments, showed that the surface temperature minimally varied with the composition of each system. However, the results showed that the influence of the location is a preponderant factor in the hygrothermal behavior. The systems located on the rooftop of the FCT-NOVA constantly recorded the highest temperatures, thus contributing to the lowest values of relative humidity.

- It was verified that specimen S4 (finished with lime) presented the lowest temperatures and, consequently, the highest values of relative humidity. On the other hand, specimen S8 presented lower relative humidity and higher temperature values. It was also confirmed that a suitable drying capacity, combined with the thermal conductivity of the system, can contribute to the reduction of surface condensation and consequently biological development.

- The presence of moisture can also be related to the water absorption and drying capacity of each system. In fact, it was found that the specimens with a higher capillary absorption had a lower number of hours in which the relative humidity exceeded 100%, and vice versa. A balance among water absorption and drying capacity is thus fundamental for an adequate hygrothermal behavior of the system. It is worth noting that the retention of moisture in the system can alter the thermal performance of the system.

- It was confirmed that the roughness of the systems can play a key role. The rougher the surface, the higher the influence on the surface tension of water, favoring water evaporation and preventing favorable conditions for biological development.

- There was no clear relationship between surface condensation and the number of hours in which the relative surface humidity equaled or exceeded 100%, indicating that the drying capacity and vapor permeability of the finishing coat play a key role. However, the presence of moisture on the surface of the specimens was found to increase the risk of biological development. Specimen S4 was the one that presented the highest number of hours when the relative humidity exceeded 100%, being the specimen with potentially the highest biological susceptibility.

- The results obtained using WUFI PRO were found to be close to the experimental results. The most relevant difference is related to the maximum temperature values. On the other hand, when comparing the experimental values of the relative humidity to the simulated ones, a higher discrepancy is found. The program does not allow a reliable simulation of the relative humidity, since the numerical model does not consider the period of time when the surface remains wet after the rainy period ends.

➢ ***Future developments***

The results obtained in this dissertation showed that

further research work on the hygrothermal behavior of ETICS systems is needed. Future studies should focus on the following tasks:

- Study the biological development in each system, using the hygrothermal data collected;

- Identify the typology of microorganisms with a higher tendency to develop on building façades with ETICS systems, characterizing the favorable conditions for their development and taking into account the type of microorganism and the type of support.

- Evaluate the hygrothermal performance of facades due to the presence of spatial obstacles.

- Evaluate the hygrothermal performance of North-oriented façades, which normally present a higher biological susceptibility.

- Carry out experimental campaigns and case studies in different Portuguese cities, for a longer period of time, in order to simulate the hygrothermal behavior of an ETICS façade throughout the year, taking into account its location.

- Monitor specimens facing North, being the orientation with less sun exposure, increasing the relative humidity and consequently increasing the biological susceptibility.

REFERENCES

[1] B. Amaro, D. Saraiva, J. De Brito, and I. Flores-Colen, "Inspection and diagnosis system of ETICS on walls," *Constr. Build. Mater.*, vol. 47, pp. 1257–1267, 2013.

[2] J. Parracha, A. Cortay, G. Borsoi, R. Veiga, and L. Nunes, "Evaluation of ETICS Characteristics that Affect Surface Mould Development," XV International Conference on Durability of Building Materials and Components, pp.209-216, Barcelona, 2020.

[3] "APFAC." https://www.apfac.pt/ (accessed Jun. 12, 2021).

[4] V. Peixoto De Freitas and P. F. Gonçalves, "Isolamento térmico de fachadas pelo exterior - Reboco delgado armado sobre poliestireno expandido," FEUP, Formação Continua 65-66, 2005.

[5] APFAC, "Manual ETICS," 2018.

[6] T. Lopes, "Fenómenos De Pré-Patologia Em Manutenção De Edifícios Aplicação Ao Revestimento ETICS," Dissertação de Mestrado, FEUP. Porto, Portugal, 2005.

[7] E. Barreira, "Degradação Biológica De Fachadas Com Sitemas De Isolamento Térmico Pelo Exterior Devida Ao Desempenho Higrotérmico.," Tese de Doutoramento. FEUP, Porto, Portugal, 2010.

[8] J. Blaich, "La détérioration des bâtiments. Analyse et prévention," EMPA, Dübendorf, Suisse, 1999.

[9] H. Kunzel and K. Sedlbauer, "Biological growth on stucco. Performance of exterior envelopes of whole buildings VIII: Integration of building envelopes.," ASHRAE, Florida, USA, 2001.

[10] W. Zillig, K. Lenz, K. Sedlbauer, and M. Krus, "Condensation on façades – Influence of construction type and orientation," Research in Building Physics, pp. 437-444. K. U. Leuven, Leuven, Belgium, 2003.

[11] K. Lengsfeld and M. Krus, "Microorganism on façades-reasons, consequences and measures," Fraunhofer-Institute for Building Physics (IBP), Holzkirchen, Germany, 2004.

[12] M. Krus, C. Fitz, A. Holm, and K. Sedlbauer, "Prevention of algae and mould growth on facades by coatings with lowered long-wave emission," Institute for Building Physics - Report, 2006.

[13] J. Von Werder and H. Venzmer, "New diagnostic strategies to quantify algal growth on façade materials – An important step in advancing product development.," 12th Symposium for Building Physics, Vol. 2, pp. 963-972. Technische Universitat Dresden, Dresden, Germany, 2007.

[14] J. Von Werder, H. Venzmer, N. Lesnych, and K. Lewis, "Algal defacement of façade materials – Results of long term natural weathering tests obtained by new diagnostic tools.," 8th Symposium on Building Physics in the Nordic Countries, Vol. 1, pp. 277-284. DTU, Copenhagen, Denmark, 2008.

[15] E. Barreira and V. Peixoto de Freitas, "Condensações superficiais nos ETICS - Avaliação

experimental," PATORREB 2009 – 3.º Encontro sobre Patologia e Reabilitação de Edifícios, Vol. 1, pp. 441-446. FEUP, Porto, Portugal, 2009.
[16] GEcoRPA, "Aprendendo com os erros e defeitos da construção," 2º Simpósio Internacional do CIB em Lisboa, 2003.
[17] J. L. Parracha, G. Borsoi, P. Faria, M. G. Gomes, I. Flores-Colen, and R. Veiga, "Performance parameters of ETICS: Correlating water resistance, bio-susceptibility and surface properties," *Constr. Build. Mater.*, vol. 272, Feb. 2021.
[18] M. Zhang, H. Sun, M. Li, and L. Zheng, "Development of a new type monitoring system of leaf surface temperature and humidity," *Am. Soc. Agric. Biol. Eng. Annu. Int. Meet. 2014, ASABE 2014*, vol. 3, pp. 1757–1764, 2014.
[19] H. International Inc, "HIH-4000 Series Humidity Sensors ," 2010. Accessed: Feb. 15, 2021. [Online]. Available: www.honeywell.com/sensing.
[20] K. Uchida *et al.*, "Observation of the spin Seebeck effect," *Nature*, vol. 455, no. 7214, pp. 778–781, 2008.
[21] L. Moreira, "Medição de Temperatura Usando-se Termopar," *Cerâmica Ind. Vol.3*, vol. 7, no. 5, pp. 51–53, 2002.
[22] T. P. Wang, "TE-Thermocouple Materials Paper," ASM Handbook, Vol.2, Properties and Selections: Nonferrous Alloys and Special-Purpose Materials, 1990.
[23] MEZÃO, "Manual de instalação / Manual do utilizador," 2020.
[24] Mosaic Industries, "T Type Thermocouple Calibration, Convert Type T Thermocouple Voltage to Temperature." http://www.mosaic-industries.com/embedded-systems/microcontroller-projects/temperature-measurement/thermocouple/type-t-calibration-table#type-t-calibration-equation (accessed Feb. 15, 2021).
[25] D. Potter, "Measuring Temperature with Thermocouples-a Tutorial," Aplplication note 043, National Instruments, 1996.
[26] Fraunhofer IBP, "Product overview | WUFI (en)." https://wufi.de/en/software/product-overview/ (accessed Feb. 11, 2021).
[27] Fraunhofer IBP, "WUFI® Pro | WUFI (en)." https://wufi.de/en/software/wufi-pro/ (accessed Feb. 11, 2021).
[28] Fraunhofer IBP, "WUFI (en) - HOME," *Version 3.0*. https://wufi.de/en/ (accessed Feb. 11, 2021).
[29] B. V. Toshev and D. Platikanov, "Wetting: Gibbs' superficial tension revisited," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 291, no. 1–3, pp. 177–180, Dec. 2006, doi: 10.1016/J.COLSURFA.2006.06.013.
[30] J. L. Parracha, G. Borsoi, P. Faria, M. G. Gomes, I. Flores-Colen, and R. Veiga, "Conservação e reabilitação de edifícios - Análise do desempenho à água de ETICS e influência na condutibilidade térmica," Construção Magazine, pp.12, 2020.
[31] I. P. M. A. Instituto Português do Mar e da Atmosfera, "Dados Meteorológicos - Setembro 2020."
[32] I. P. M. A. Instituto Português do Mar e da Atmosfera, "Dados Meteorológicos - Outubro 2020."
[33] I. P. M. A. Instituto Português do Mar e da Atmosfera, "Dados Meteorológicos - Novembro 2020."
[34] I. P. M. A. Instituto Português do Mar e da Atmosfera, "Dados Meteorológicos - Dezembro 2020."
[35] "Instituto Português do Mar e da Atmosfera." https://www.ipma.pt/pt/educativa/tempo.clima/ (accessed May 22, 2021).
[36] I. P. M. A. Instituto Português do Mar e da Atmosfera, "RELATÓRIO SETEMBRO 2020 - IPMA," 2020. Accessed: Jun. 10, 2021. [Online]. Available: www.ipma.pt.
[37] E. Barreira and V. P. De Freitas, "External Thermal Insulation Composite Systems: Critical Parameters for Surface Hygrothermal Behaviour," Advances in Materials Science and Engineering, pp 1-16, 2014.
[38] E. Barreira and V. P. de Freitas, "Experimental study of the hygrothermal behaviour of External Thermal Insulation Composite Systems (ETICS)," Building and Environment 63 (2013) 31-39, 2013.
[39] A. Karagiozis, G. Hadjisophocleous, and S. Cao, "Wind-driven rain distributions on two buildings," Journal of Wind Engineering and Industrial Aerodynamics, Vol 67-68, pp.559-572, 1997.