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RESPONSE OF WATTLE AND DAUB WALLS TO CONDENSATION PROBLEMS[1]

RESPUESTA DE LOS MUROS DE QUINCHA AL RIESGO DE CONDENSACIÓN

RESPOSTA DAS PAREDES DE QUINCHA AO RISCO DE CONDENSAÇÃO

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RESUMEN

La respuesta de los muros de tierra frente a la humedad es un tema de relevancia al momento de evaluar la condensación superficial e intersticial. Por ello, en el siguiente artículo se analizó el comportamiento frente a la humedad de tres construcciones con muros de quincha, teniendo en cuenta las diferentes capas de revoque de barro y de cañas de Castilla. Primero, se evaluó respecto de la Norma Iram 11.625 y con los datos de temperatura exterior de diseño, la temperatura interior de diseño y las propiedades térmicas de los materiales. Se obtuvieron los valores de temperatura superficial y de rocío para cada caso. Se observó que, en ningún caso, se produjo condensación superficial y que en la capa cercana a la caña exterior existía, en todos los casos, la posibilidad de condensación intersticial, la cual puede ser optimizada mediante el uso de una aislación por la cara exterior o interior según la condición climática. A partir de mediciones in situ con dataloggers hobo, se tomaron registros de temperatura y humedad relativa interior y exterior para invierno. Se trazaron las curvas de temperatura superficial y de rocío y se advirtió que en todos los casos los valores de la temperatura de rocío son menores a la temperatura superficial, verificándose la falta de condensación superficial.

Palabras clave
quincha, humedad relativa, condensación superficial, condensación intersticial.

ABSTRACT

The response of earthen walls to humidity is a relevant issue when evaluating surface and interstitial condensation. This article analyzed the behavior against the humidity of three buildings with wattle and daub walls, taking into account the different layers of mud plaster and Castilla reeds. First, these were evaluated using the Iram 11.625 Standard and with the outdoor design data temperature, the indoor design temperature, and the thermal properties of the materials, obtaining the surface and dew temperature values for each case. It was observed that surface condensation did not occur in any case and for interstitial condensation, in all cases, in the layer close to the exterior reed there was the possibility of condensation, which can be optimized by using insulation on the outer or inner face depending on the climatic conditions. Based on in situ measurements with hobo dataloggers, indoor and outdoor temperature and relative humidity records were taken for winter. Surface and dew temperature curves were plotted and it was observed that in all cases the dew temperature values are lower than the surface temperature, verifying the lack of surface condensation.

Keywords
wattle and daub, relative humidity, surface condensation, interstitial condensation.

RESUMO

A resposta das paredes de terra à humidade é uma questão relevante ao avaliar a condensação superficial e intersticial. Por este motivo, no presente artigo foi analisado o comportamento com relação à humidade de três edifícios com paredes de quincha, levando em consideração as diferentes camadas de reboque de barro e de canas-do-reino (*Arundo donax*). Primeiramente, foram avaliadas, em relação ao Padrão Iram 11.625 e com os dados de temperatura externa de projeto, a temperatura interna de projeto e as propriedades térmicas dos materiais. Foram obtidos os valores de temperatura superficial e de orvalho para cada caso. Observou-se que em nenhum caso ocorreu condensação superficial e que na camada próxima da cana exterior existia em todos os casos a possibilidade de condensação intersticial, a qual pode ser otimizada mediante a utilização de isolamento na face externa ou interna, dependendo das condições climáticas. Com base em medições *in situ* com dataloggers hobo, foram realizados registros de temperatura e umidade relativa interior e exterior para o inverno. Foram traçadas curvas de temperatura da superfície e temperatura do orvalho e observou-se que em todos os casos os valores da temperatura do orvalho são inferiores à temperatura da superfície, verificando a ausência de condensação superficial.

Palavras-chave
quincha, umidade relativa, condensação superficial, condensação intersticial.

INTRODUCTION

The behavior of earthen walls and environmental humidity is a recurring question when considering both interior and exterior plaster because there is an assumption that earthen walls breathe, absorbing and releasing moisture from the environment (Hung Anh & Pásztory, 2021).

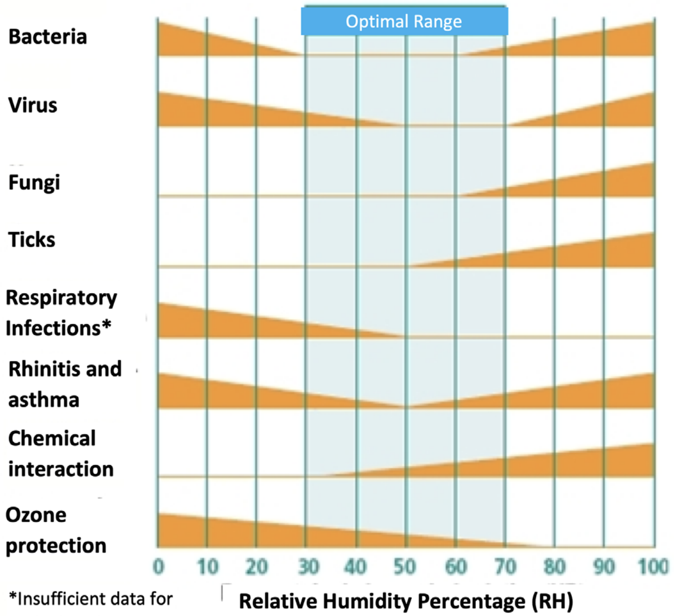
The response of building materials to humidity is a recurring topic of study, which seeks to determine how this can affect both positively and negatively (Berger, Guernouti, Woloszyn, & Buhe, 2015) (del Río *et al.*, 2021) the comfort of the indoor environment or to the durability of such materials (Arundel, Sterling, Biggin & Sterling, 1986; Hamdaoui, Benzaama, Mendili & Chateigner, 2021). Several authors have analyzed raw earth from a hygrothermal point of view, considering that it behaves as a thermal (Costa-Carrapiço, Croxford, Raslan & González, 2022; Alassaad, Touati, Levacher & Sebaibi, 2021) and hygrometric regulator that slows down and attenuates heat waves and stabilizes indoor relative humidity faster than other building materials, where the built walls and ceiling must come into play as environmental stabilizers (Giada, Caponetto & Sebaibi, 2021). Nocera, 2019; Eshoj & Padfield, 1993; Padfield, 1998). Gernot Minke was one of the pioneers in researching the dampening capacity of earthen walls against moisture (Minke, 2005; Colinart *et al.*, 2020). Other works have focused on the hygrothermal analysis of earth constructions, making simulations with programs such as Energy Plus (McGregor, Heath, Shea & Lawrence, 2014; Rode & Grau, 2008; Abadie & Mendoca, 2009; Ramos & Freitas, 2011). Research made on raw earth bricks shows the tendency of the apparent density to reach equilibrium moisture, where the higher the apparent density of the adobe, the higher the percentage of the equilibrium moisture content (Zhang, Sang & Han, 2020; Liuzzi, Hall, Stefanizzi & Casey, 2013). According to Hall and Allinson (2009a), rammed earth materials stabilized the dry density and the apparent porosity is inversely related, therefore, higher porosity results in increased capillary absorption and water vapor permeability. However, the total hygroscopic storage capacity seems to vary little as a result of mixture parameters and soil granulometry (Hall & Allinson, 2009b; Hall & Casey, 2012). In a study carried out by Labat, Magniont, Oudhof, and Aubert (2016), on straw and clay mixtures, it was observed that they have a dampening effect on the relative humidity. In simulations related to relative humidity absorption and the drying of walls (Labat *et al.*, 2016; Asphaug, Andenas, Geving, Time & Kvande, 2022; Fouchal, Gouny, Maillard, Ulmet & Rossignol, 2015) the favorable influence of interior earthen plasters was evidenced (Nematchoua, Tchinda, Orosa & Andreas, 2015).

Thus, the humidity of the indoor environment plays an important role in the comfort and preservation of materials. In terms of comfort, indoor relative humidity should remain between 20% and 80% for any indoor temperature condition (Miranda, 2007), as well as preserve building materials susceptible to physical changes such as wood and agglomerates, among others (Coscollano Rodríguez, 2002).

Generally, it is about maintaining control of the temperature, with this being the most important parameter to establish comfort, but it is important to point out that when the absolute humidity is constant, the relative humidity of the air varies according to the prevailing temperature. In this way, it is also necessary to control the relative humidity of rooms, since people have a better tolerance to low relative humidity. Nevertheless, when the relative humidity falls below 20%, the mucous membranes dry out, and below 30%, electrical discharges usually occur due to static electricity (Gea-Izquierdo, 2022). On the other hand, when the relative humidity values of indoor environments are high, they favor the development of organisms such as mold and dust mites, which can cause allergic reactions. Indeed, this is one of the main causes of respiratory issues, which affects users' well-being and comfort (Martínez, Sarmiento & Urquieta, 2005).

Extreme humidity is, thus, very harmful both to inhabitants' health and thermal comfort. Figure 1 shows that the range between 30% and 60% relative humidity (for an air temperature of 20°C–22°C) provides the best environmental conditions because the growth of both bacteria and biological organisms and the speed at which chemical interactions occur are minimized. With a relative humidity of 50%, the average mortality of certain microorganisms increases; a value that decreases if that percentage changes, either up or down (Cárdenas Llamas & Hernández Mendoza, 2003; Style, 2022).

The effect that environmental humidity produces on people's health can affect the nose, throat, and eyes, and there has also been an increase in asthma problems, all mainly related to airways, as can be seen in Figure 1. In addition, humidity favors the proliferation of bacteria in the air, making the air inside the house harmful to health. The only



*Insufficient data for RH higher than 50%

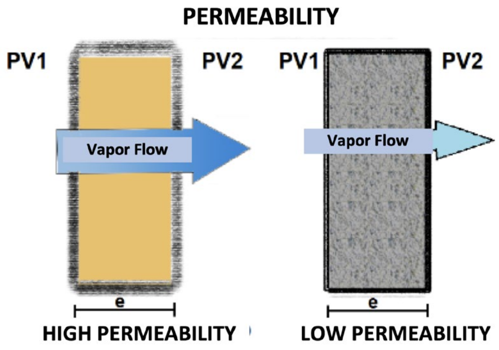


Figure 1. Optimal relative humidity range for a healthy environment. Source: Fisair, 2022, p. 2.
Figure 2. Material permeability. Source: Prepared by the authors using Fresno (2021).

way to solve these problems is by stabilizing the relative humidity and improving the air quality of the indoor environment, for which it is necessary to dehumidify, if the air is very humid and, if it is very dry, humidifying is required (Cardoso, Puzhi & Zhinin, 2016). This is one of the reasons why the control of relative humidity inside homes is becoming an important part of the analysis for indoor air quality and thermal comfort.

During winter, lower outdoor air temperatures are recorded, namely, the air is colder and more humid. When this air enters the dwelling, it begins to heat up, causing moisture loss. Inside, the dry air absorbs moisture to reach its equilibrium, a moment where it neither gains nor loses moisture, and the dry air absorbs the moisture of the materials that are in the immediate surroundings, such as the case of materials used in the enclosing walls, causing walls to dry, which is why it is not convenient for the relative humidity to vary quickly (Cárdenas Llamas & Hernández Mendoza, 2003).

MOISTURE CHARACTERISTICS

There are numerous ways humidity can manifest itself in a house depending on its location and origin: it can come from the construction, the soil, and the atmosphere, and be produced by condensation and/or accidentally (Martínez *et al.*, 2005; Sanfulgencio Tomé, 2017; Romero Alonso, 2022).

Figure 2 links permeability, which considers the diameter of construction materials' pores, and the geometry of the voids, which give the material the ability to allow water vapor to pass when a pressure difference between their faces is produced. The permeability value can be obtained, when permeability is linked to the thickness of the material, (Fresno, 2021).

Condensation is considered the phenomenon that allows water vapor in the atmosphere to transform into liquid water upon cooling. It is important to understand some definitions associated with humidity, such as relative humidity and dew point. Relative humidity (RH) is the amount of water that is in the air at a given temperature, compared to the maximum amount of water vapor that the air can contain at that temperature under saturation conditions. If there is a given amount of water vapor in the environment at a certain temperature, the "dew point" becomes that minimum temperature at which the environment becomes saturated with water vapor. Therefore, as long as the air temperature remains above that of dew there will be no condensation. However, if the air temperature drops, there will be condensation (Corporación de Desarrollo Tecnológico y Cámara Chilena de la Construcción, 2012).

According to Minke (2005), mud can adsorb and release moisture faster and in greater quantities than other building materials. According to studies conducted

Project Name		
CHARACTERISTICS OF THE PLACE		
Name of the Locality		Mendoza
Height above Sea Level	m	823
Bioenvironmental Zone (x)		4
Enclosure type		M
Winter design indoor temperature (x)	°C	18
Winter design outdoor temperature (x)	°C	-0,3
Design's indoor relative humidity	%	69
Design's outdoor relative humidity	%	90
Indoor vapor pressure	kPa	1,59
Outdoor vapor pressure	kPa	0,6
CHARACTERISTICS OF THE ENCLOSURE		
Denomination		
Winter air chamber resistance	m^2.K/W	
Winter indoor surface resistance	m^2.K/W	0,17
Winter outdoor surface resistance	m^2.K/W	0,04
Outdoor surface (color) absorption coefficient		0,75
Summer air chamber resistance	m^2.K/W	
Summer indoor surface resistance	m^2.K/W	
Summer outdoor surface resistance	m^2.K/W	

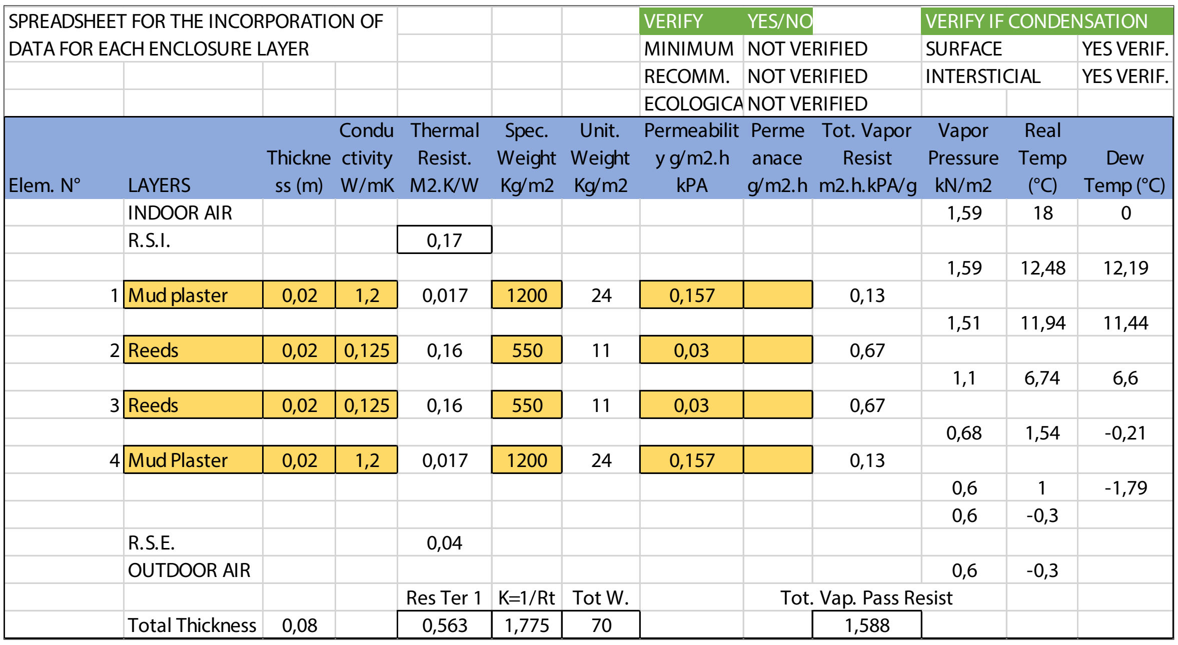
Figure 3. General data to verify the condensation risk. Source: Preparation by the authors based on Gonzalo, Ledesma, Nota, and Martínez (2000, p. 2).

by the Experimental Construction Laboratory of the University of Kessel, when the indoor relative humidity is between 50% and 80%, after two days, mud bricks can adsorb 30 times more moisture than bricks fired under the same conditions. Clay mortars can regulate the relative humidity of the air and the ambient temperature, like any raw earth product, but the moisture absorption capacity can vary greatly depending on the technique and the material composition used, and, even, the additives that are included in the mass as stabilizers (Castilla, 2004). These mortars, basically comprising clay soil, are vulnerable to the direct action of water. This is the case of walls plastered with clay mixtures that tend to absorb rainwater by capillarity. The moisture absorbed is also removed as water vapor during drying. It is proven that this product permanently seeks balance with the relative humidity of the environmental air where it is used as a coating and that it allows the wall it covers to breathe. That is why it is important to evaluate, in experimental terms, the water vapor transmission capacity or the permeability that earth enclosures have (González Serrano, 2015)

Based on the premise that earthen walls are prone to being affected by environmental humidity and that they also can absorb and release moisture depending on the indoor environment requirements until reaching a hygrothermal balance, it is necessary to measure *in situ*, the actual behavior of houses with earthen walls. In this paper, the response of wattle and daub (quincha) walls to the ambient relative humidity and the possibility of interstitial and superficial condensation, is presented, using the current regulations in Argentina and comparison with experimental relative humidity records.

METHODOLOGY

In the first stage of the study, to analyze the superficial and interstitial condensation of wattle and daub walls, a theoretical analysis was made based on data provided by the IRAM 11625 (2000) standard to verify the condensation risk in walls. The data used for the analysis were: the indoor design temperature for winter, the outdoor design temperature for winter, the indoor and outdoor design relative humidity, and the indoor and outdoor surface resistance for winter, as shown in Figure 3. Then, the data related to the thermal properties of the enclosure wall's materials were completed, which, in this case, is the wattle and daub wall, mainly comprising mud and reeds. The data required were: the thickness of each wall



SPREADSHEET FOR THE INCORPORATION OF							VERIFY	YES/NO		VERIFY IF CONDENSATION		
DATA FOR EACH ENCLOSURE LAYER							MINIMUM	NOT VERIFIED		SURFACE		YES VERIF.
							RECOMM.	NOT VERIFIED		INTERSTICIAL		YES VERIF.
							ECOLOGICA	NOT VERIFIED				
Elem. N°	LAYERS	Thickness (m)	Conductivity W/mK	Thermal Resist. M2.K/W	Spec. Weight Kg/m2	Unit. Weight Kg/m2	Permeability g/m2.h kPA	Permeanace g/m2.h	Tot. Vapor Resist m2.h.kPA/g	Vapor Pressure kN/m2	Real Temp (°C)	Dew Temp (°C)
	INDOOR AIR									1,59	18	0
	R.S.I.			0,17								
										1,59	12,48	12,19
1	Mud plaster	0,02	1,2	0,017	1200	24	0,157		0,13			
										1,51	11,94	11,44
2	Reeds	0,02	0,125	0,16	550	11	0,03		0,67			
										1,1	6,74	6,6
3	Reeds	0,02	0,125	0,16	550	11	0,03		0,67			
										0,68	1,54	-0,21
4	Mud Plaster	0,02	1,2	0,017	1200	24	0,157		0,13			
										0,6	1	-1,79
										0,6	-0,3	
	R.S.E.			0,04								
	OUTDOOR AIR									0,6	-0,3	
				Res Ter 1	K=1/Rt	Tot W.			Tot. Vap. Pass Resist			
	Total Thickness	0,08		0,563	1,775	70			1,588			

Figure 4. Spreadsheet for surface temperature and dew point temperature. Source: Preparation by the authors using Gonzalo et al., 2000, p. 2.

layer, the thermal conductivity of the materials, and the permeability (Figure 4).

The verification of the risk of surface condensation and the interstitial condensation curves for each layer of the wall were obtained for each case using the data from both spreadsheets.

The input data to make the condensation calculation are as follows: the outdoor design temperature, using the minimum design temperature stated in IRAM 11603 (2012) of the analyzed localities which, in this case, are the Argentine cities of Mendoza, Uspallata, and Malargüe. For the outdoor relative humidity, a value of 90% was used. In case studies where the construction is for a house, the indoor design temperature is 18°C, and the interior relative humidity will be a function of the outdoor design temperature for each locality. Another parameter that should be considered is the wall surface thermal resistance that the IRAM sets at 0.17 m^2K/W indoors and 0.04 m2K/W outdoors (IRAM 11601, 2002).

Within the thermal characteristics of the enclosure's materials, the thermal conductivity and permeability affect each of the wattle and daub wall layers. In this work, the layers comprise an internal lattice of 2 to 3-cm diameter Catilla reeds (*Arundo donax*) filled with a mixture of sand-clay and straw mud, and the finished walls are between 7cm for the first case and 30cm thick, depending on the case analyzed and filling technique used.

In the second stage, using a datalogger-recorded indoor and outdoor temperature and relative humidity data, the wall's surface and dew point temperatures were determined for the three analyzed constructions and the surface thermal properties of the wattle and daub walls' materials. These were then reflected in two curves, to compare their response against the theoretical analysis made based on the IRAM 11.625 Standard.

BIOCLIMATIC CHARACTERISTICS

Mendoza

Mendoza presents itself as a Mediterranean and continental province, located in a temperate zone with an arid to semi-arid climate, forming part of the arid region known as the "South American Arid Diagonal" (Bernabeu, 2019). The cause of aridity in Mendoza is the presence of the Andes Mountain Range, which acts as a barrier that prevents moisture from passing from the Pacific Ocean. The effect of this orographic condition is known as "Shadow Desert" (Ministry of the Environment, 2009). The temperatures have an important annual oscillation: in summer, it is warm and average temperatures are above 25°C and, some days, this is the minimum. Winter is cold and dry, with average temperatures below 10°C, occasional night frosts, and little precipitation. According to data collected by the National Meteorological Service (2022), for the period from 1991 – 2000, the maximum and minimum temperatures for any time of the year can be seen. Figure 5 shows the temperature values recorded between 1991- 2000 at the Mendoza Observatory Weather Station. For the winter, an absolute minimum temperature of -5.5°C was recorded and, in summer, the absolute maximum temperature record was 39.4°C (Figure 5) (longitude: 68°52'47" W; latitude: 32°53'29" S; altitude: 750 masl).

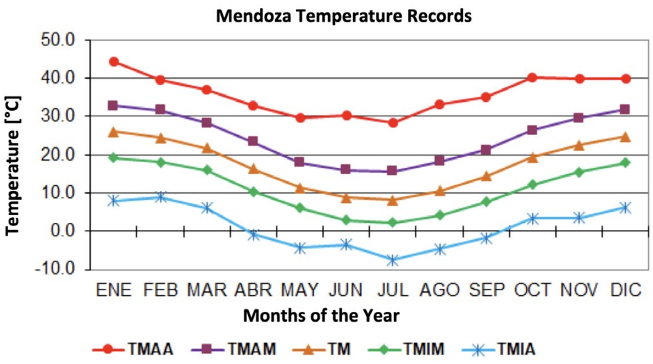


Figure 5. Absolute and average maximum and minimum monthly temperatures for Mendoza. Source: (Esteves Miramont, 2017). TMAA = Absolute maximum temperature (°C). TMAM = Average maximum temperature (°C). TM = Average temperature (°C). TMIM = Average minimum temperature (°C). TMIA = Absolute minimum temperature (°C). Source: Esteves Miramont (2017, p. 185).

Malargüe

The city of Malargüe is located 421 km south of Mendoza. It has an IVb and V temperate-cold to cold bioclimatic zone (Norma IRAM 11.603, 2012), with an arid continental-type climate, with an average rainfall of 200 mm. Malargüe is characterized by having the Andes Mountain Range to the west, while the central-east is occupied by the Payunia volcanic massif, and the central area by the sunken zone of the Llancanelo Lagoon, forming a wetland (EcuRed, 2021). Summers are cool, with average temperatures between 19°C and 20.6°C, and winters are cold, with average temperatures of 4°C.

Figure 6 illustrates the temperature values recorded between 1991- 2000 at the Malargüe Airport Weather Station: absolute minimum temperature of -17.2°C for the winter and, for summer, absolute maximum temperatures of 36°C (longitude: 69°35 W; latitude: 32°3' S; altitude: 1425 masl).

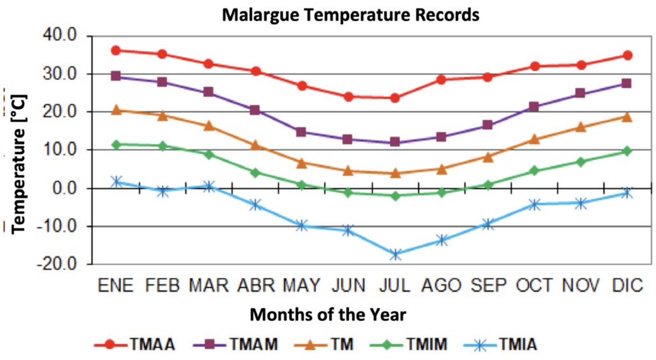


Figure 6. Absolute maximum and minimum temperatures and monthly averages for Malargüe. Source: Esteves Miramont (2017, p. 185).

Uspallata

It is located 110 km from Mendoza, and according to IRAM 11.603 (Argentine Institute of Standardization and Certification), it belongs to bioclimatic zone V with cold climate characteristics. Like Malargüe, Uspallata is a mountainous area with cool summers and average temperatures of 19°C, and cold winters and average temperatures of 4°C. Figure 7 shows the temperature values recorded between 1991- 2000 at the Uspallata Meteorological Station: absolute minimum temperature of -15°C for winter and, for summer, absolute maximum temperatures of 36.4°C (longitude: 69°33 W; latitude: 32°6' S; altitude: 1891 masl).

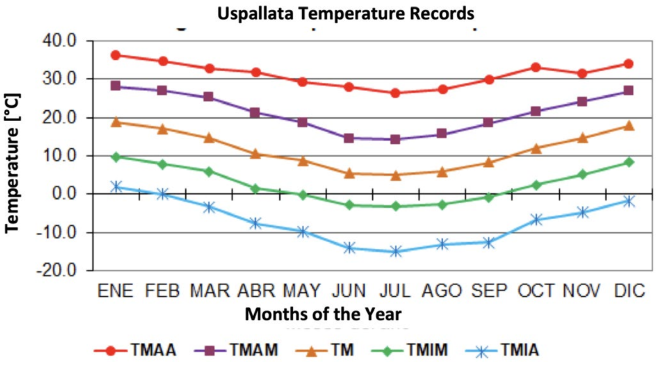


Figure 7. Absolute maximum and minimum and average monthly temperatures for Uspallata. Source: Esteves Miramont (2017, p. 185).

RESULTS

From the theoretical data obtained above, the CEEMACON program spreadsheet was completed.

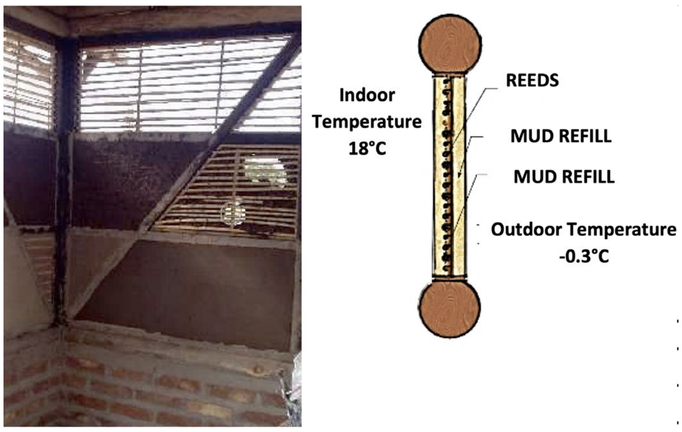


Figure 8. Experimental workshop in the construction stage. Detail of wattle and daub wall's assembly. Source: Preparation by the authors.

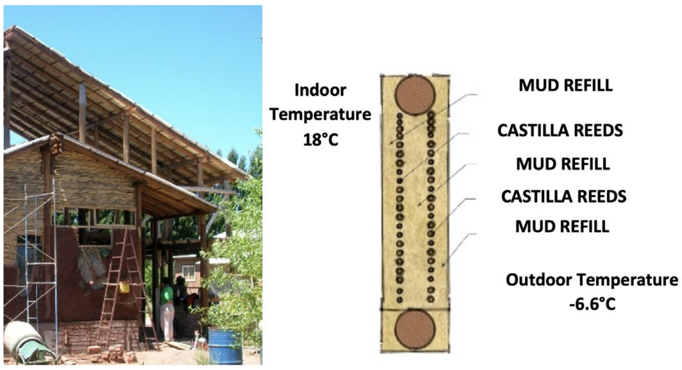


Figure 10. Malargüe International Eco Hostel, in the construction stage. Source: Preparation by the authors.

SURFACE CONDENSATION VERIFICATION - WORKSHOP

INDOOR SURFACE CONDITIONS	UNIT	VALUE	VERIFICATION
Indoor Vapor Pressure	kPa	1.59	
Outdoor Vapor Pressure	kPa	0.60	
Temperature Difference (Ti-Te)	ºC	18.30	
Indoor Surface Resistance	m^2.K/W	0.17	
Indoor Surface Temperature Drop.	ºC	5.52	
Indoor Surface Temperature	ºC	12.48	
Indoor Surface Dew Temperature	ºC	12.19	NO CONDENSATION

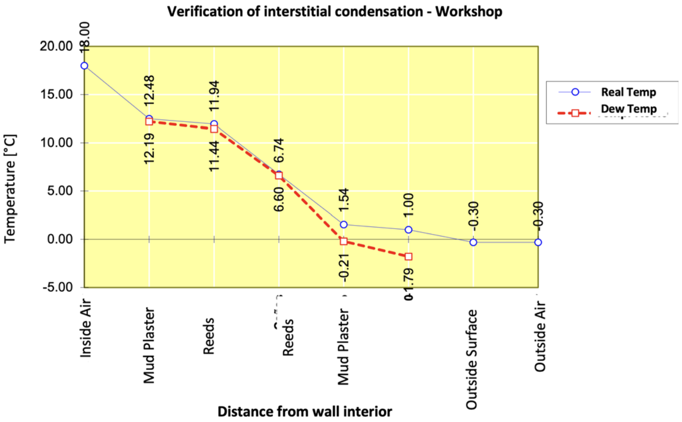


Figure 9. Verification of surface condensation and interstitial condensation of the experimental workshop. Source: Preparation by the authors.

xls (Gonzalo *et al.*, 2000) and the dew temperature curves and actual temperature of each layer were determined, thus defining the presence of risk of superficial and/or interstitial condensation.

THEORETICAL ANALYSIS: VERIFICATION OF SURFACE AND INTERSTITIAL CONDENSATION

Case 1: Experimental workshop (EW)

The analyzed wattle and daub wall is seen for the experimental Workshop, located in Mendoza. This comprises a lattice of Castilla reeds in the middle of the wall, filled with a mud mixture, comprising sand–clay and straw, to obtain a 0.075m thick wall (Figure 8).

The verification of the risk of surface condensation and the interstitial condensation curves were obtained with data on the indoor air, outdoor air, and wall materials' properties (Figure 9). It was verified that no surface condensation occurred, because the wall's surface temperature is always higher than the dew temperature. Also, there is no interstitial condensation on any of the wall's layers. However, it is noted that, in the area near the cane close to the outside, the real temperature is very close to the dew temperature, with the risk that this entails if it should condense. Therefore, to prevent some interstitial condensation from occurring, the wall's behavior could be improved by incorporating an insulating material or element that works as a vapor barrier on the inner face (Fernández & Esteves, 2004; Beinhauer, 2009).

Case 2: Malargüe International Eco Hostel

The second example is from the International Eco Hostel, in the Department of Malargüe, south of the province of Mendoza. For its construction, materials from the area were used, including clay, reeds, wood, and straw. The wattle and daub walls are formed with a Castilla reed framework as a formwork. Then, it was filled with mud between the reeds, and as a wall finish, they were covered with the same mud mixture (Figure 10), to reach a wall thickness between 0.20m and 0.30m thick. An average thickness of 0.25m was considered for this analysis.

SURFACE CONDENSATION VERIFICATION - WORKSHOP

INDOOR SURFACE CONDITIONS	UNIT	VALUE	VERIFICATION
Indoor Vapor Pressure	kPa	1.47	
Outdoor Vapor Pressure	kPa	0.38	
Temperature Difference (Ti-Te)	ºC	24.60	
Indoor Surface Resistance	m^2.K/W	0.17	
Indoor Surface Temperature Drop.	ºC	5.38	
Indoor Surface Temperature	ºC	12.62	
Indoor Surface Dew Temperature	ºC	10.15	NO CONDENSATION

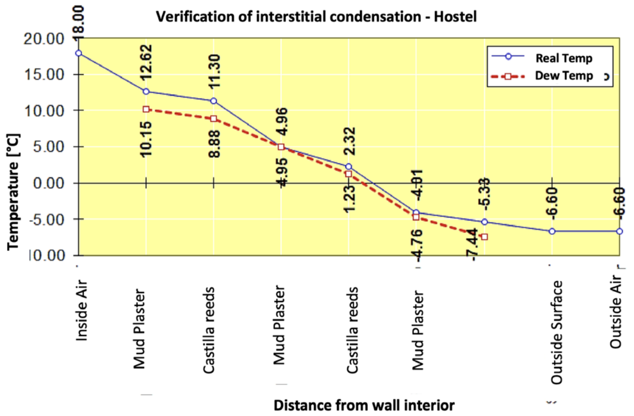


Figure 11. Verification of surface and interstitial condensation of the International Eco Hostel of Malargüe. Source: Preparation by the authors.

Using the climatic data of the place, from IRAM 11603, and the thermal properties of the enclosure's materials, the wattle and daub wall's behavior against condensation was obtained for the cold zone of Malargüe and it was verified that, in theory, surface condensation does not occur and neither does interstitial condensation (Figure 11). However, in the layer close to mud filling, the possibility of condensation is appreciated. In this situation, it is necessary to resort to adding a vapor barrier. It is advisable to insulate the walls on the outer face to reduce the risk of interstitial condensation because the wall will be closer to the indoor temperature, which contributes to the dew point temperature not being reached inside. If the option of insulating the inner face is taken, the wall will be colder and the risk of interstitial condensation will increase, so it will need to use a vapor barrier on the inner side of the house to eliminate the possibility of interstitial condensation (Corporación de Desarrollo Tecnológico y Cámara Chilena de la Construcción, 2012).

Case 3: Multipurpose Room (MR)-Uspallata

The third analysis presented is a Multipurpose Room (MR) in the town of Uspallata in the North of the province of Mendoza. Here the walls used are 0.30m thick, almost three times wider than those used in the EW. The wattle and daub walls are made up of 2.5cm or 3cm horizontal reeds, arranged vertically every 10cm, nailed from column to column, both on the outer and inner faces of the wall (Figure 12). Then, the wall was filled with the same mud mixture as in the previous case, sand – clay, and straw, until the entire wooden structure was covered and a thickness of 30cm was achieved.

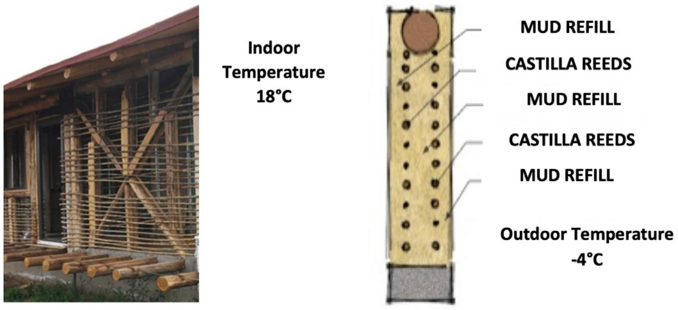


Figure 12. Multipurpose Room in the construction stage. Detail of wattle and daub wall assembly. Source: Preparation by the authors.

SURFACE CONDENSATION VERIFICATION - MR

INDOOR SURFACE CONDITIONS	UNIT	VALUE	VERIFICATION
Indoor Vapor Pressure	kPa	1.66	
Outdoor Vapor Pressure	kPa	0.51	
Temperature Difference (Ti-Te)	ºC	22.0	
Indoor Surface Resistance	m^2.K/W	0.17	
Indoor Surface Temperature Drop.	ºC	4.57	
Indoor Surface Temperature	ºC	13.43	
Indoor Surface Dew Temperature	ºC	11.00	NO CONDENSATION

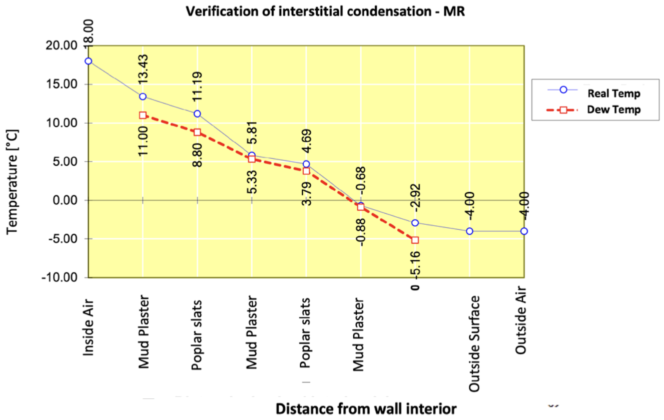


Figure 13. Verification of surface condensation and interstitial condensation of the Multipurpose Room. Source: Preparation by the authors.

It was verified that there is no risk of surface condensation or interstitial condensation, as seen in Figure 13. However, as in the previous cases, there is a possibility of surface condensation and, as indicated, it is necessary to add a vapor barrier that should always be placed on the warmer side of the enclosure: here it should be on the inside of the wall.

DISCUSSION

To corroborate the behavior of the wattle and daub walls in the three constructions analyzed in the previous point, against surface condensation and to be able to compare the theoretical results obtained from the IRAM Standard, with the *in-situ* measurement values, Hobo H08-003-02 type dataloggers model were used - which has a relative humidity measurement range of 25% to 95% (Onset, 2022) - for the temperature and humidity measurements of the Experimental Workshop. For the Malargüe International Eco-Hotel and the Multipurpose Hall, Hobo U12 dataloggers were used, which record outdoor and indoor temperature and relative humidity data, with a frequency of 15 minutes. The experience was carried out in the winter months. As previously seen, the humidity produced by condensation is caused when air saturated with steam comes into contact with cold surfaces, such as the interior walls of the house, causing the temperature to drop to the dew point. To calculate the dew point, it is necessary to connect the indoor air temperature to the vapor and saturation pressure. These three variables are linked by equation 1, equation 2, equation 3 and equation 4 (Martinez *et al.*, 2005).

$$T_{PR}=[6,54+14,526*a+0,7389*a^2+0,09486*a^3+0,4569*(P_{v1})^{0,1984}] \quad (1)$$

Where:
T_{PR}: ew point temperature [°C]
a: Vapor pressure natural logarithm.
P_v; Vapor pressure [kPa]

The data used to determine the dew point temperatures are the *in-situ* temperature and relative humidity measurements of the indoor and outdoor environment used to obtain the variables of vapor and saturation pressure.

$$a=\ln(P_v) \quad (2)$$
$$P_v=H_R*P_s \quad (3)$$
$$P_s=a(b+T_i/100)^n \quad (4)$$

Where:
H_R [%]: Indoor relative humidity measured in situ
P_S [kPa]: Saturation pressure
T_i [°C]: Indoor air temperature measured in situ
a, b, n: Constants.
For 0°C ≤ T_i ≤ 30°C (a = 288.68 Pa - b = 1.098 - n = 8.02)
For -20°C ≤ T_i ≤ 0°C (a = 4.689 Pa - b = 1.486 - n = 12.30)

In Figures 14 to 16, both outdoor and indoor temperature data recorded can be distinguished, to study the Experimental Workshop, Malargüe Eco Hostel, and Multipurpose Room.

Figure 14 shows the hygrothermal response of the Experimental Workshop, whose behavior is associated with its specific exclusively daytime use, and related to the assembly tasks of solar ovens, biodigesters, solar distillers, and others typical of a workshop. During the morning, there is an almost permanent opening of the door, which favors indoor air renewal; as a consequence, at noon, the temperatures inside the workshop resemble the temperatures outside. From 4 pm, the activities are concluded and the workshop is closed, to remain empty until the next working day, and it is here that the thermal insulation capacity of the wattle and daub walls can be seen.

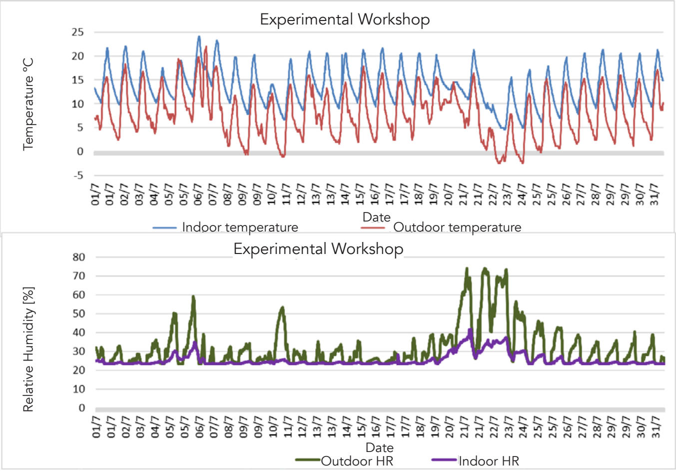


Figure 14. Measurement in situ of temperature and relative humidity inside and outside the Experimental Workshop. Source: Preparation by the authors.

The study of the hygrothermal response of the workshop showed that the datalogger used in the measurement had a starting base value of 25%. For the thermal amplitudes, it could be seen that the daily variation was between 0.3% and 15.5%, where the maximum relative humidity recorded indoors was 42% while for the same instant outdoors, it was 74%. Thus, it could be appreciated, that the relative humidity inside is within the optimal humidity range. In the indoor temperature analysis, the maximum daily thermal amplitude was 12.8°C, while the outdoor thermal amplitude, taken at the same time, was 15°C. A minimum and maximum temperature of 4.5°C and 24°C were measured inside the workshop for the recorded period, while, the values outside were -1.9°C and 19°C, respectively.

The Eco Hostel of Malargüe is located in a region of very low temperatures where wall thermal inertia must be counted on to improve its behavior. The indoor sensor was located in the living room, a shared-use area, located within the architectural distribution in a middle zone. Figure 15 shows the indoor and outdoor temperature and relative humidity curves, from which it is inferred that temperatures with low thermal amplitude are reached indoors, with variations of between 2.5 and 5°C, compared to outdoor thermal amplitudes that vary in a daily range between 19°C and 30°C. The indoor minimum recorded in the entire period was 12°C, while outdoors, at that same moment, was -5.8°C approximately, while the maximum recorded in the entire period was 22°C when it was 33°C outdoors; this is probably caused by an

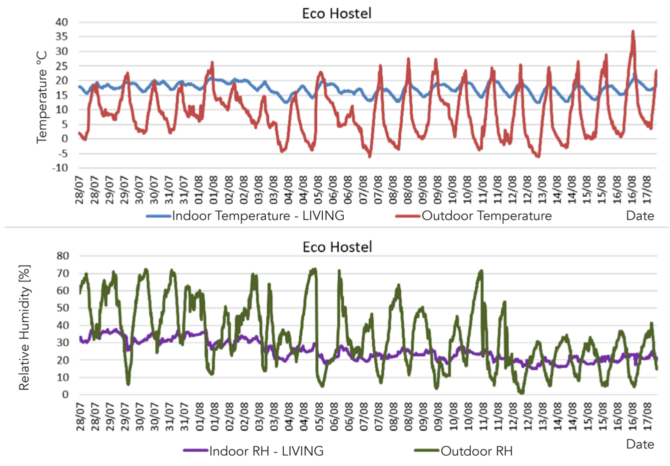


Figure 15. Measurement *in situ* of temperature and relative humidity inside and outside the Malargüe Eco Hostel. Source: Preparation by the authors.

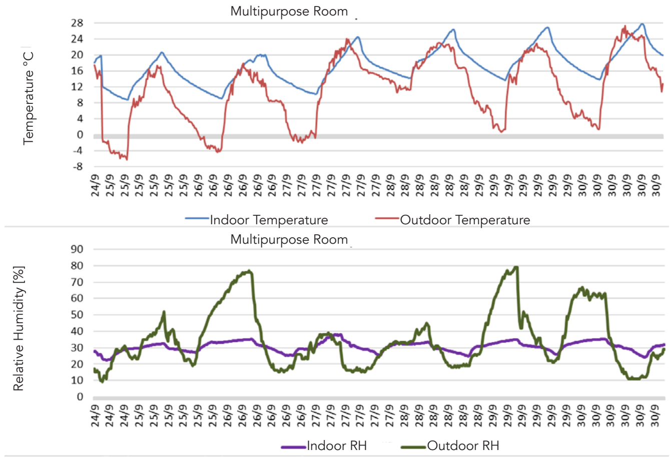


Figure 16. Measurement *in situ* of temperature and relative humidity inside and outside the Multipurpose Room. Source: Preparation by the authors.

occasional southerly wind. Regarding relative humidity, hygroscopic stability is also appreciated. Thus, the average daily amplitude of relative humidity has a variation between 4.5% and 13.2%, while outdoors shows a daily amplitude variation between 28% and 56%, respectively. Indoor maximum and minimum values are observed at 37.9% and 14.8%, respectively, and for the same instant, 66.8% and 24% were recorded outside.

In the last case, the Multipurpose Room, sensors were placed in the common use area, which is used to hold meetings, yoga, and all daytime activities. As for the outdoor temperature (Figure 16), a minimum of -6.3°C and a maximum of 17.3°C were recorded, resulting in a daily thermal amplitude of 23.6°C, while inside, simultaneously, a minimum and maximum temperature of 8.8°C and 19°C, respectively, and a daily amplitude of 10.2°C were recorded (said daily amplitude is stable at 13°C during the measurement period). It should be clarified that, during the measurement, the place was not being used and it did not have any heating system. Regarding outdoor relative humidity, a daily minimum and maximum value of 19% and 60% were recorded, respectively, and at the same time values of 27.4% and 33.2% were recorded inside the Living Room, with oscillations of between 6.7% and 12.7%, when outside the oscillations were between 24% and 62%.

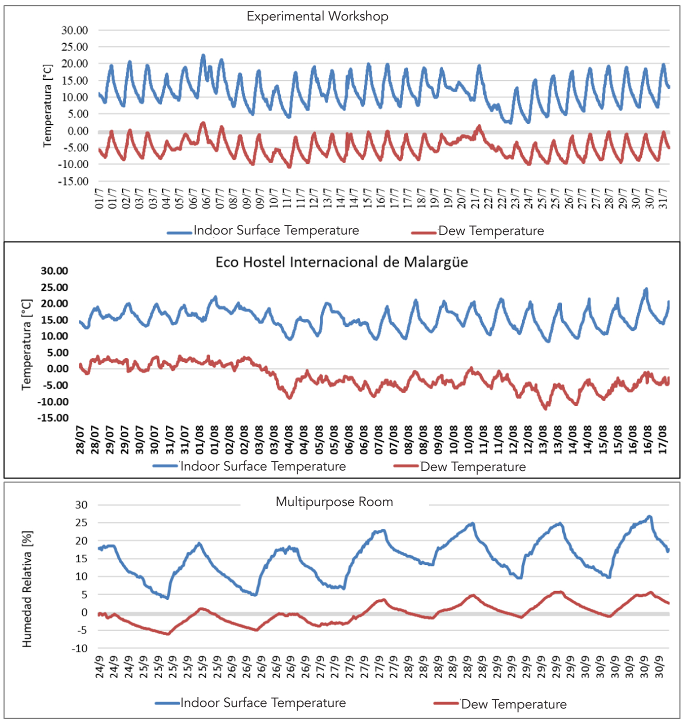


Figure 17. Indoor surface temperature and dew temperature of the Experimental Workshop, Eco Hostel, and Multipurpose Room. Source: Preparation by the authors.

For each of the data measured *in situ* for temperature and relative humidity and using equations 1 to 4 (Martinez *et al.*, 2005), the wattle and daub wall indoor surface and dew temperature were obtained (Aria Jiménez & Bobadilla Moreno, 2017), which is plotted in the curves of Figure 17.

In all cases, it can be seen that the dew temperature remained below the surface temperature, corroborating the lack of surface condensation (Fabbri & Morel, 2016). Although the theoretical results based on data of the IRAM 11.625 Standard are almost alike (the indoor surface temperature values and the dew temperature data are almost the same when compared with those obtained from real measurements), some differences allow confirming that wattle and daub walls have a good response to relative humidity, absorbing moisture when the ambient humidity is high, and releasing it when the environment is drier, thus achieving environmental stability (Bruno, Gallipoli, Perlot & Kallel, 2020) (Lee, Ozaki & Cho, 2018).

CONCLUSIONS

Wattle and daub walls are characterized by their internal cane or wooden slat framework and their mud filling, with variable thicknesses depending on the technique used and the location. However, their behavior considering the environmental humidity had always presented an unknown (Indekeu, Feng, Janssen & Woloszyn, 2021). From this study, it was possible to verify, both theoretically and experimentally, that the walls have a favorable response against superficial or interstitial condensation (Vereecken, Gelder, Janssen & Roels, 2015). Specifically, three case studies were addressed: the experimental Workshop for day work, the Hostel with permanent housing, and the MR measured unoccupied.

The three cases analyzed are located in the province of Mendoza, Argentina. In the capital, the climate is temperate cold, and in Malargüe and Uspallata is a cold mountain area. In the mountain area, it was necessary to work with wall thicknesses of 30cm, and in the cold temperate zone, it was possible to work with one of 7.5cm, because the use as a workshop did not require greater thicknesses. The analysis showed that indoor relative humidity is stable, with an average range of values between 15% and 40% (Hall & Allinson, 2009a), which favors hygrothermal comfort and is outside the range that favors the proliferation of mold, mites, and respiratory infections (Sedlbauer, 2002).

In terms of the walls' behavior against interstitial condensation, it is appreciated that, in all cases, the possibility of interstitial condensation occurs in the layer near the outer reed (Janssen & Roels, 2009). Commonly, in traditional construction, the solution, given the above, would be incorporating an insulating material with low thermal conductivity on the outer face of the wall (Romero Alonso, 2022; Colinart, et al., 2020; Hung Anh & Pásztory, 2021), because this removes the risk of interstitial condensation. The material used can be an expanded polystyrene plate (thermal conductivity 0.035 W/mK) fastened with a metal mesh and plastered with a cementitious mixture or the insulation can be carried out with projected polyurethane foam (thermal conductivity 0.027 W/mK) on the outdoor façade and the finish, with plasterboard. If it was chosen to arrange the insulation in the middle of the wall, it would be necessary to incorporate a vapor barrier to reduce the risk of interstitial condensation; a process that should be studied in detail to incorporate materials that were compatible with the natural and sustainable technology proposed here.

Indeed, the use of natural materials is promoted (Read *et al.*, 2018) in the construction of the walls, where earth, straw, and cane or wooden slats are the main materials for wattle and daub walls, and one of the main characteristics to be preserved is the wall's ability to absorb and "desorb" environmental humidity (Hendry, 2001), to work as the main material for the *"natural lung"* of the housing. With this premise established, to optimize the walls' enclosure, whether they are built or in the project stage, the most advisable option would be to incorporate an insulating material as close to the outer face of the wall as possible. As a solution, a layer of lightened mud was chosen on the outer face to work as a natural insulator. According to the work by Minke (2005), the lightened mud (density of 750 Kg/m^3) has a reference conductivity value of 0.20W/mK and the permeability is 0.225 g/m h kPa, which can be incorporated simply by moistening the earth base of the existing wall so that the fusion between the existing mud and the one applied occurs to improve the wall's thermal insulation. The wall's finish must be made with lime plaster.

In the future, it would be interesting to measure the ability of the different wall materials to absorb moisture from the air and then deliver it, under favorable conditions, to the indoor air.

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