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THERMAL ANALYSIS OF LIGHTWEIGHT WATTLE AND DAUB WALLS FOR DIFFERENT DESIGN TEMPERATURES IN ARGENTINA

ANÁLISIS TÉRMICO DE MUROS DE QUINCHA ALIVIANADA PARA DIFERENTES TEMPERATURAS DE DISEÑO EN ARGENTINA

ANÁLISE TÉRMICA DE PAREDES DE PAU A PIQUE LEVE PARA DIFERENTES TEMPERATURAS DE PROJETO NA ARGENTINA

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RESUMEN

Se analiza el comportamiento térmico de los muros de quincha liviana en distintas zonas bioclimáticas de Argentina, que surgen como una alternativa sustentable frente a otros materiales de construcción. Se determinaron experimentalmente las conductividades térmicas del relleno de quincha (0.07 W/mK) y del revoque (0.34 W/mK), obteniendo una transmitancia térmica global de 0.79 W/m²K para muros de 15.6 cm de espesor. A partir de mediciones in situ en una vivienda, se demostró la capacidad de los muros de quincha liviana para mantener estabilidad térmica interior, con amplitudes térmicas significativamente menores respecto del exterior. El análisis comparativo con ladrillos macizos y ladrillos huecos concluyó que los muros de quincha requieren menores espesores para alcanzar niveles de aislamiento óptimos, adaptándose a diversas zonas bioclimáticas. Esta técnica constructiva permite la replicabilidad en el contexto argentino, destacándose por su eficiencia térmica, sostenibilidad y confort interior, con oportunidades futuras para explorar su resistencia al fuego.

Palabras clave
quincha, conductividad térmica, confort interior.

ABSTRACT

The thermal performance of lightweight wattle and daub walls is analyzed in different bioclimatic zones of Argentina, presenting them as a sustainable alternative to other construction materials. The thermal conductivities of the wattle and daub (0.07 W/mK) and plaster (0.34 W/mK) infill were experimentally determined, yielding an overall thermal transmittance of 0.79 W/m²K for walls with a thickness of 15.6 cm. In situ measurements conducted in a dwelling demonstrated the ability of lightweight wattle and daub walls to maintain interior thermal stability with significantly lower thermal amplitude than outside. A comparative analysis with solid and hollow bricks concluded that wattle and daub walls require less thickness to achieve optimal insulation levels, making them suitable for different bioclimatic zones. This construction technique is replicable within the Argentinian context, with its thermal efficiency, sustainability, and indoor comfort standing out, with future opportunities to explore its fire resistance.

Keywords
wattle-and-daub, thermal conductivity, indoor comfort.

RESUMO

Analisou-se o desempenho térmico de paredes de pau a pique leve (em espanhol quincha alivianada) em diferentes zonas bioclimáticas da Argentina, que surgem como uma alternativa sustentável a outros materiais de construção. As condutividades térmicas do enchimento de pau a pique (0,07 W/mK) e do reboco (0,34 W/mK) foram determinadas experimentalmente, obtendo-se uma transmitância térmica geral de 0,79 W/m²K para paredes de 15,6 cm de espessura. Com base em medições in situ em uma casa, foi demonstrada a capacidade das paredes de pau a pique leve para manter a estabilidade térmica interna, com amplitudes térmicas significativamente menores em comparação com o exterior. A análise comparativa com tijolos maciços e tijolos ocos concluiu que as paredes de pau a pique exigem menos espessura para atingir níveis ideais de isolamento, adaptando-se a diversas zonas bioclimáticas. Esta técnica de construção permite a replicabilidade no contexto argentino, destacando-se por sua eficiência térmica, sustentabilidade e conforto interior, com oportunidades futuras para explorar sua resistência ao fogo.

Palavras-chave:
pau a pique, condutividade térmica, conforto interno.

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INTRODUCTION

Thermal insulation in a house's perimeter walls has become increasingly important for sustainable and energy-efficient construction (Zhao et al., 2020; Sánchez Azócar, 2011). As Argentina covers regions with climates as diverse as the cold Patagonian ones and the hot ones of the Chaco region (Matteucci, 2012; IRAM 11603, 2012), the implementation of thermal insulation solutions becomes fundamental for occupant comfort and the energy efficiency[1]of the construction. The insulating capacity of opaque envelopes directly impacts the indoor thermal comfort[2] of the dwellings by retaining heat in winter and keeping them cool in summer. This behavior impacts energy consumption for heating and cooling, operating costs, and the carbon footprint of buildings (Muñoz et al., 2012). Therefore, analyzing the thermal conductivity[3] (λ) of materials is essential to reduce the environmental impact and improve the energy efficiency of buildings (Castillo et al., 2019). The thermal transmission coefficient (K) measures a material or a structure's ability to transfer heat (García León, Flórez-Solano. & Espinel Blanco, 2017). This is crucial in the context of walls because it determines how much heat is lost or gained through the envelopes. A low K value indicates that the wall is a good insulator with lower heat flow.

Numerous studies have investigated different strategies to improve the energy efficiency of buildings. Rey and Velasco (2006) in their work proposed practical strategies to improve this behavior through detailed audits and regulatory certifications, highlighting the importance of consumption analysis, optimization of systems and materials, and the implementation of sustainable technologies, which promote more efficient and environmentally responsible buildings (Rey Martínez & Velasco Gómez, 2006). Asdrubali et al. (2015) examined unconventional materials that promote energy efficiency in buildings, which underline their importance for climatically diverse areas (Asdrubali et al., 2015). In their work, Zhao et al. (2020) proposed using natural fibers as viable alternatives to plastics in insulation systems (Zhao et al.,2020). In contrast, Lakatos (2022) highlighted the potential of materials such as aerogels and vacuum panels for their high thermal performance. Zhovkva (2020) presented international experience in the design of sustainable multifunctional complexes, which highlights the fundamental principles of design aimed at achieving energy efficiency and respect for the environment (Zhovkva, 2020). These works show the importance of comprehensively addressing the different types of materials available on the market, which shows the importance of conducting research that compares the thermal conductivity of a wide range of construction materials and their combined impact on comfort and energy consumption.

A well-insulated house minimizes the heat flow between the inside and outside (Vanhoutteghem & Svendsen, 2014), which means that energy expenditure is significantly affected by the insulating capacity of the materials used in the construction. In cold climates, a good performance of the envelopes reduces the need for heating, while in hot climates, the need for cooling decreases. This translates into a reduction in the demand for resources. Buratti et al. (2021) highlight the relevance of integrating sustainable solutions in extreme climate contexts.

An indoor environment with good thermal regulation contributes to the physical and psychological well-being of the inhabitants (González Couret & Véliz Párraga, 2016). Thermal fluctuations can cause stress and health problems; in particular, well-insulated housing helps protect residents from extreme temperatures, which is crucial for vulnerable groups such as children, older adults, and people with pre-existing health conditions. A study in New Zealand (Howden-Chapman et al., 2007) showed that improving indoor air conditioning reduced respiratory problems and hospitalizations, especially in people with pre-existing conditions such as asthma or recurrent respiratory infections. Insulated dwellings also showed an improvement in residents' perception of general well-being. Research in South

1 Energy Efficiency: is the ability of a system, material or building to minimize heat losses and optimize energy use. It is related to thermal insulation, thermal transmittance and efficient design, reducing the energy consumption required for heating or cooling, and promoting thermal comfort and environmental sustainability (Kreith and Goswami, 2007).

2 Indoor Thermal Comfort: This is the perception of thermal well-being in a closed space, where people do not feel excessive cold or heat. A poorly insulated house can have extreme indoor temperatures, both cold in winter and hot in summer. This depends on factors such as air temperature, humidity, wind speed, thermal radiation, physical activity, and clothing, which are crucial for health, productivity, and well-being. (Forgiarini Rupp, Giraldo Vásquez & Lamberts, 2015)

3 Thermal conductivity: It is a physical, intrinsic property of materials, which measures the heat conduction capacity. (IRAM 11601, 2002)

Korea (Ham, Lee, & Kim, 2024) highlighted that building insulation standards significantly affect indoor temperatures and the risks of heat-related diseases; poorly insulated homes are more likely to exceed critical temperature thresholds, especially in rural areas and old buildings without maintenance controls. The World Health Organization WHO (World Health Organization [WHO], 2018) stresses that good thermal insulation not only improves indoor comfort but also reduces respiratory and cardiovascular diseases associated with extreme temperatures.

Research and development in the field of building materials are constantly advancing to find more durable and sustainable solutions. Natural materials are being rediscovered and adapted with new processing techniques to improve their insulating properties without compromising sustainability.

In Argentina, there are currently 60 Municipal ordinances that allow construction with earth using different techniques (Protierra Argentina Network, 2024). One of the most commonly used in envelopes is wattle and daub[4] in its diverse variants: prefabricated wattle and daub walls, filled with a mixture of a plastic consistency clayey slurry and vegetable fibers with a higher density than wet lightweight wattle and daub[5] (Cuitiño Rosales, Maldonado & Esteves Miramont, 2014), moist lightweight wattle and daub walls, where the filling comprises vegetable fiber immersed in a clayey earth slurry, commonly called slip slurry (Acevedo Oliva et al., 2017). The proposal to study the lightweight wattle and daub technique originated within the Alto Valle sustainable habitat participatory cycle in the north of the Patagonian region of Argentina. An inter-institutional collaboration and outreach agreement was signed between seven entities: Municipality of Allen (Río Negro), National Institute of Industrial Technology (INTI), National Institute of Agricultural Technology (INTA), National Council of Scientific and Technical Research (CONICET), National University of Río Negro, College of Architects of the Province of Neuquén, and the College of Architects of Río Negro.

Using natural materials when building walls has different advantages, especially thermal performance. The thermal conductivity of test cells built with the lightweight wattle and daub technique was determined using standardized tests. This data is relevant for conducting construction studies with this technique and thermally comparing lightweight wattle and daub enclosures with other industrialized materials commonly used in traditional construction.

OBJECTIVE

This work evaluates the thermal performance of lightweight wattle and daub walls as a sustainable alternative in house construction. It analyzes their thermal insulation capacity and compares them with solid bricks and hollow ceramic bricks. The thermal properties of the filler and plaster are also determined through standardized tests and on-site measurements in a house. The thicknesses of lightweight wattle and daub walls needed to comply with the thermal transmittance regulatory values are also defined[6] in several bioclimatic zones of Argentina to validate their viability.

METHODOLOGY

The methodology used in this work focuses on the thermal characterization of the components of the lightweight wattle and daub wall and its comparative analysis against conventional materials. First of all, standardized tests were carried out using the hot plate method to determine the thermal conductivity of the filler and the plaster. The test cells were manufactured with clay soil, vegetable fibers, and water mixtures, following controlled drying and hygrothermal conditioning processes. Subsequently, the wall's global thermal transmittance was evaluated theoretically following domestic regulations. A house built with this technique was also analyzed in Belén de Escobar, located 50 km north of the Federal Capital, Buenos Aires, Argentina, where hygrothermal measurements were recorded onsite. Finally, the wall thicknesses needed to comply with IRAM Standards in different bioclimatic zones were established to validate the system's thermal efficiency.

4 Wattle and daub: A construction system where the walls comprise a wooden structure, which, in turn, contains a reed fabric that is finally coated with mud (Cuitiño et al., 2015).

5 Moist lightweight wattle and daub: This is a wattle and daub with vegetable fibers immersed in a clayey earth slurry as a filler (slip), also known as lightened earth with straw or light mud-straw. (Acevedo Oliva et al., 2017)

6 Thermal transmittance: heat flow that passes per unit surface area of the element and per degree of temperature difference between the two environments separated by said element. It is expressed in W/(m2 x K). It is the thermal conductivity ratio of all the materials that the system comprises and their thicknesses. (Acevedo Oliva et al., 2017)

Figure 1: Test cell for the thermal test: a) Lightweight filler, b) Earth plaster. Source: Preparation by the authors.

Table 1. Thermal conditioning of the test cells. Source: Preparation by the authors.

Denomination	Drying time [Hs]	Test cell mass [Kg]			Relative change of the test cell mass [%]		
		M1	M2	M3	mr	mc	md
Lightweight filler test cell 1	216	9.20	7.25	7.31	26.90	25.85	0.83
Lightweight filler test cell 2		9.00	7.11	7.13	26.58	26.23	0.28
Plaster test cell 1	288	43.00	41.89	41.95	2.65	2.50	0.14
Plaster test cell 2		41.92	41.15	41.20	1.87	1.75	0.12

THERMAL CONDUCTIVITY ANALYSIS

To experimentally obtain the thermal conductivity values of the low-density straw filler and the heavier and higher-density earthen plaster, standardized tests were carried out in INTI (ISO 8302,1991); American Society for Testing and Materials [ASTM] C177 (2013); IRAM 11559 (1995). Two lightweight filler test cells and two plaster test cells were built, all 60 cm x 60 cm x 8 cm thick.

Both mixtures were prepared with a soil previously characterized in the laboratory, obtaining a composition of 17% sand, 40% silt, and 43% clay, a clay-silt soil. 50% of the characterized clay soil was mixed with 50% water to prepare the filler test cells. It was then allowed to hydrate for three days and mixed with an electric mixer until the lumps dissolved. This soil in a liquid state is called slip. Next, 72 liters of slip were mixed with a 13.16 kg bale of wheat stubble fibers, *Triticum aestivum*, until all the fibers were moistened and covered with the slip. However, when squeezed, the liquid should not run out, and it cannot contain clods of mud. Two wooden molds were filled with this mixture, and a little pressure was applied to compact them. The wooden mold was removed once the test cells were dry (Figure 1a).

The second part of the construction system uses earth plaster, the mixture responsible for covering the lightweight wheat straw filler as the wooden structure on both sides of the wall. The plaster comprises one part soil, one part water, two parts cut wheat stubble (maximum 5cm long), and two parts sand. With this slurry mixture, the mold was filled to 7.5 cm; then, it was filled up to an 8 cm thickness with a fine plaster finish to make the surfaces flat and parallel on both sides of the test cell so that the test plates could be supported correctly on the entire surface. To complete the fine finish, one part soil sieved by a 1mm x 1mm mesh, two parts sieved sand, and one part water was used, Figure 1b.

The four test cells were left to dry in the open for 20 days and then taken to the laboratory to run the test. They were placed in a temperature and humidity-controlled environment for hygrothermal conditioning. The initial weight of the test cell was taken (M1). The drying process was started at 60 °C until the constancy in the mass was confirmed (M2). Then, it was allowed to acclimatize at 23°C in the oven (M3) until a hygrothermal balance was reached.

CHANGE OF MASS

The relative mass change of the test cell after the drying process was calculated (m_r) (Equation 1). After this, a more complex conditioning treatment was applied (m_c) (Equation 2), and finally, the relative mass change was due solely to thermal conditioning (m_d) (Equation 3). The results of Table 1 were obtained according to the following expressions.

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$$m_r = \frac{M_1 - M_2}{M_2}$$ (Equation 1)

$$m_c = \frac{M_1 - M_3}{M_3}$$ (Equation 2)

$$m_d = \frac{M_3 - M_2}{M_2}$$ (Equation 3)

It was seen that, in the case of the filler test cells, 216hr were required to achieve the hygrothermal conditioning. The variation of the mass is around 26%. This variation is because, in the drying process, the test cells remove the remaining moisture from the slip incorporated into the straw mixture at the beginning of the process. For the plaster test cells, variations in the masses were smaller because a higher-density material was used with less moisture incorporation. So, during the conditioning stages in the drying oven, there was less moisture loss compared to the initial mass. Then, during the conditioning at room temperature, they did not absorb that much moisture to achieve the hygrothermal balance.

The test cell's thermal conductivity was determined under the steady-state heat transfer method using a thermal flow meter, following the guidelines established in the ISO 8302 (1991), ASTM C177 (2013), and IRAM 11559 (1995) standards. The hot plate system was used to measure the thermal resistance of the lightweight filler and plaster test cells. This consists of horizontally placing the two test cells with a hot plate in the middle, a cold plate above the upper sample, and another cold plate below the lower sample, leaving the entire perimeter of the panel insulated to avoid heat losses through the periphery. For the thermal conductivity analysis, an average hot plate temperature of 32°C and cold plate temperature of 8°C was used. The results are shown in Table 2

With the data obtained from the test, Fourier's Law for heat conduction was applied (Equation 4), obtaining the material's conductivity:

$$\frac{\Delta q}{\Delta t} = k * A * \frac{T_f - T_c}{e}$$ (Equation 4)

From this approach, and since the test involves two panels, the following calculation was made to obtain the conductivity value of the tested materials (Equation 5), (Equation 6), (Equation 7), (Equation 8):

$$\Delta Q = \left[k * A * \frac{T_{f1} - T_{c1}}{e_1}\right] + \left[-k * A * \frac{T_{f2} - T_{c2}}{e_2}\right]$$ (Equation 5)

Factoring:

$$\Delta Q = k * A * \left(\frac{\Delta T_1 * e_2 + \Delta T_2 * e_1}{e_1 * e_2}\right)$$ (Equation 6)

$$Q = k * A * \left(\frac{\Delta T_1 * e_2 + \Delta T_2 * e_1}{e_1 * e_2}\right)$$ (Equation 7)

Table 2. Test temperatures and test cell dimensions. Source: Preparation by the authors.

		Filler test cell	Plaster test cell
Top/bottom hot plate temperature		32.0°C / 32.0°C	32.0°C / 31.9°C
Top/bottom cold plate temperature		8.0°C / 8.0°C	8.3°C / 7.8°C
Difference between plates		24°C	23.7°C / 24.1°C
Test average		20°C	20.1°C / 19.9°C
Average power supplied to the heating element	Voltage	6.97V	14.37V
	Current	0.62A	1.29A
Top panel thickness		0.074 m	0.0853
Bottom panel thickness		0.074 m	0.0852
Heat flow		4.273 W	18.125 W
Mean density		276.7 Kg/m^3	1354.7kg/m^2
Room temperature		22.5°C	24.4°C
Relative Humidity		50%	63%

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Finally:

$$k = \frac{Q}{A} * \frac{e_1 * e_2}{(\Delta T_1 * e_2 + \Delta T_2 * e_1)}$$ (Equation 8)

Where:
Q: Thermal power; V*I*N [W]
V: Voltage supplied [V].
I: Current supplied [A].
N: Hot plate equipment calibration factor: 0.985
k_{1-2}: Thermal conductivity of the top and bottom panels, respectively [W/m^2°C]
A: Hot plate area: 0.3078 m x 0.3078 m = 0.0948 m^2.
ΔT_{1-2}: Temperature delta for the top and bottom panels, respectively [°C].
e_{1-2}: Thickness of the top and bottom panels, respectively [m].

To analyze the thermal behavior of the wattle and daub wall as an enclosure wall, it was necessary to verify the maximum admissible thermal transmittance values for the winter season, following the provisions of IRAM 11601 (2002); IRAM 11603 (2012); IRAM 11605 (1996). The global thermal transmittance values were obtained (Equation 10) using the thermal resistance values obtained, the external 0.13 m^{2}K/W and internal 0.04 m^{2}K/W surface thermal resistance values provided in IRAM 11601 (2002), and using Equation 9. With these data from the experimental tests and based on the winter design guidelines established in IRAM 11603 (2012) and IRAM 11605 (1996), a comparative analysis was made about the wall thicknesses needed to obtain the same thermal transmittance in walls with different construction materials, such as fired brick and hollow ceramic brick, compared to the lightweight wattle and daub wall.

$$R_{Total} = \frac{e_{rev1}}{\lambda} + \frac{e_{rell}}{\lambda} + R_{Sext} + R_{Sint} + \frac{e_{rev2}}{\lambda}$$ (Equation 9)

$$K_{global} = \frac{1}{R_{Total}}$$ (Equation 10)

Where:
$e_{rev1\text{-}2}$ = Thickness of the inner and outer plaster of the wattle and daub wall [m]
e_{rell} = Thickness of the lightweight filling of the wattle and daub wall [m]
λ = Thermal conductivity of the wattle and daub wall [W/m K]
R_{Sext} =External surface thermal resistance, IRAM 11.601 [0.13 m^2 K/W]
R_{Sint} =Internal surface thermal resistance, IRAM 11.601 [0.04 m^2 K/W]

CASE STUDY

With the global thermal transmittance data, a house in a wetland area of Escobar, Buenos Aires Province, belonging to the warm temperate bioclimatic zone IIIa of the IRAM 11603 Standard (1996), was measured on-site. The records were made during July. For this purpose, dataloggers were arranged at a height of 2.20 m from the finished floor level, taking readings every 15 minutes on the temperature of the indoor and outdoor environments. The criterion for choosing the environments (main room, office, and games room) was that they did not use auxiliary heating systems during the

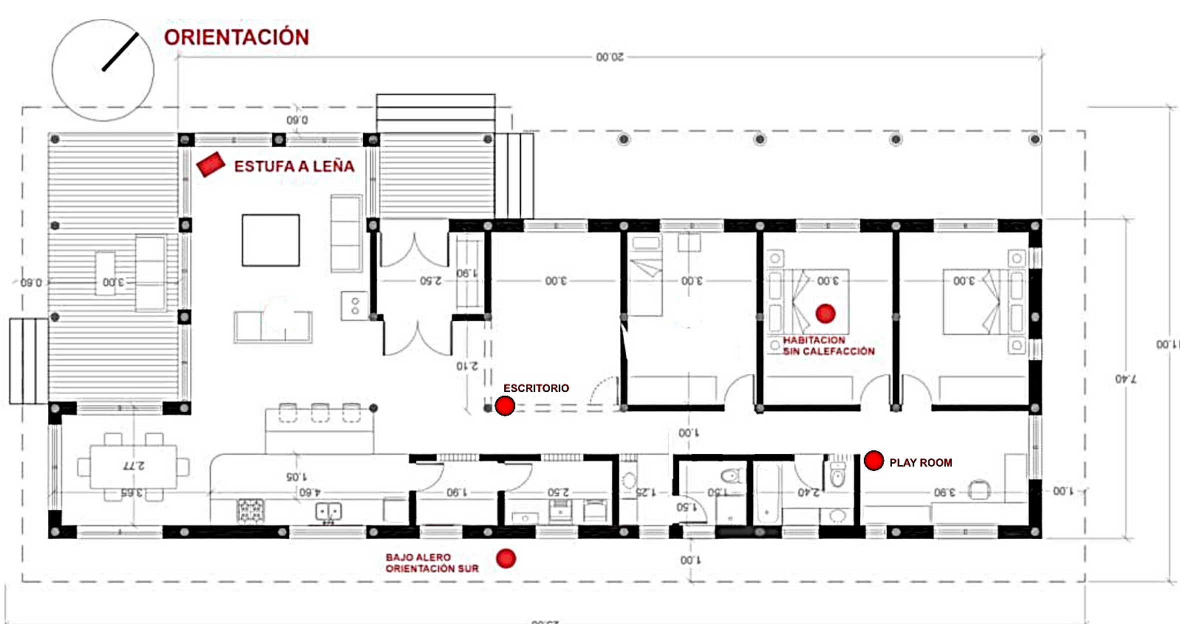

Figure 2: Architecture plan of the dwelling being measured. Source: Preparation by the Authors.

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Figure 3: Housing construction process - Escobar. Source: Preparation by the authors.

measurement stage. The results generated a curve for each environment, which allowed seeing the insulating capacity of the lightweight wattle and daub walls and the daily thermal amplitudes (Figure 2).

The house in Figure 3 has a covered surface area of 157m^2. It has reinforced concrete pilots for the foundations on which a wooden platform was supported and raised 0.50m from the natural terrain. The main structure is a portico system of round *eucalyptus grandis* posts, approximately 0.18m in diameter. The walls have a framework of 1"x1/2" eucalyptus slats to contain the filling, comprising a wheat straw and slip mixture with an average dry density of 400 kg/m^3 (in situ). To mix the 0.05m thick plaster, 2 parts wheat stubble with 2 parts sand and 1 part earth were used. For the pre-fine plaster, 2 parts sand were used with 1 part earth, and the fine plaster was made with 2 parts sand, 1 part Kaolin clay AF200 + ¼ part cooked paste. The experimentally tested mixture compositions described in the first part of this work were used for both the filling and the plaster. This way, the tested thermal properties obtained 0.28 m thick finished walls. The joinery comprised PVC with hermetic double glazing. Like the floor, the roof is a lightweight 2" x 8" slash pine frame with an 18mm phenolic plate on the top, an 18mm phenolic plate on the bottom, a 200µm nylon vapor barrier, and 100mm glass wool thermal insulation. The inverted roof comprises 10 cm polyethylene foam, 750 µm plastic membrane, 150g geotextile mantle, and an 8cm thick wood chip and vegetation-lightened substrate.

COMPARATIVE ANALYSIS BETWEEN BIOCLIMATIC ZONES

The lightweight wattle and daub construction system can be adapted to build the opaque envelopes of houses in any of the six bioclimatic zones of Argentina (IRAM 11603,1996). For this, the thicknesses of the lightweight filler needed for the lightweight wattle and daub wall for each design temperature for winter and the associated maximum permissible transmittance were calculated from Equation 11. The solid brick and hollow ceramic brick wall thicknesses, which would be needed for each of the localities in Argentina, were obtained similarly using Equation 13. The plaster thicknesses remained constant data for both the lightweight wattle and daub (e_{rell-Q}) and the different brick walls (e_L). In the case of the earth plasters, a 0.05 m thickness was defined for both sides of the wall ($e_{rev\ ext}$, $e_{rev\ int}$), and in the case of walls with cementitious plasters ($e_{r.int}$, and$_{r.ext}$), 0.02 m of plaster was contemplated for each face, and the joints (e_j) between 0.015m bricks, where N_{L-1} is the number of joints needed to join the N_L bricks for the entire wall, with the surface resistances (R_{yes}, R_{it}) provided in IRAM 11601 (2002). The total wall thicknesses were obtained using Equations 12 and 14, and the conductivity and thermal resistance values are shown in Table 3.

$$e_{rell-Q} = \left(\frac{1}{K_{\max adm}} - \frac{e_{rev\,ext}}{\lambda_{rev\,ext}} - \frac{e_{rev\,int}}{\lambda_{rev\,int}} - R_{si} - R_s\right.$$

(Equation 11)

$$e_{muro\ Q} = e_{rev\,int} + e_{rell-nec} + e_{rev}$$

(Equation 12)

$$e_L = \left(\frac{1}{K_{\max adm}} - \frac{e_{r.int}}{\lambda_{r.int}} - \frac{N_{L-1*}e_j}{\lambda_j} - \frac{e_{r.ext}}{\lambda_{r.ext}} - R_{si} - R_{se}\right.$$

(Equation 13)

$$e_{muro\ L} = e_{rev.int} + N_{L-1} * e_j + N_L * e_L + e_r$$

(Equation 14)

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Table 3. Conductivity and surface resistance values of the materials used. Source: Preparation by the authors.

Conductivity (W/mK)							Surface resistance (m^2K/W)	
$\lambda_{ext\ plas}$	$\lambda_{int\ plas}$	$\lambda_{ext\ r}$	$\lambda_{int\ r}$	λ_{fill-Q}	$\lambda_{Solid\ Brick}$	$\lambda_{Hollow\ Brick}$	R_{si}	R_{se}
0.34	0.34	1.16	0.91	0.07	0.91	0.42	0.13	0.04

Table 4. Thermal response of the lightweight wattle and daub panels. Source: Preparation by the authors.

Designation	Characteristics		Thermal response	
	Thickness [m]	Density [kg/m3]	Thermal Resistance [mK/W]	Thermal Conductivity [W/mK]
Filler	0.074	276.7	14.29	0.07
Plaster	0.0852	1354.7	2.94	0.34

Table 5. Comparative analysis of wall thicknesses and thermal transmittance. Source: Preparation by the authors.

Author	Thickness [m]	Global Thermal Transmittance [W/m2K]
INTI	0.156	0.79
Acevedo Oliva et al.	0.156	1.03 0.73
Cuitiño Rosales, Maldonado & Esteves Miramont.	0.10	1.82
Adec	0.145	1.14

RESULTS AND DISCUSSION

EXPERIMENTAL TEST IN TEST TUBES

Using the equations of Fourier's Law for heat transmission (Equation 8), the value of thermal conductivity for the lightweight filler is k1= 0.07W/mK (Equation 15), and for earth plaster, it is k_2= 0.34W/mK (Equation 16), which can be seen in Table 4.

$$k_1 = \frac{6.97V * 0.62A * 0.985}{0.0948\ m^2} * \frac{0.074m * 0.074m}{(24\ K * 0.074m + 24K * 0.024m)} = 0.07\ \frac{W}{mK}$$

(Equation 15)

$$k_2 = \frac{14.37V * 1.29A * 0.985}{0.0948\ m^2} * \frac{0.0853m * 0.0852m}{(23.7\ K * 0.0853m + 24.1K * 0.0852m)} = 0.34\ \frac{W}{mK}$$

(Equation 16)

The global thermal transmittance of a lightweight wattle and daub wall is determined by Equations 9 and 10. The value obtained for a 0.156m thick wall (equivalent to the one used in the tests by the Protierra Chile team) consisting of 0.05m thick plaster and 0.05m thick filler is 0.79W/m²K. In the tests carried out by the Protierra Chile Team (Acevedo Oliva et al., 2017)) for a 0.156 m thick wet lightweight wattle and daub wall, a thermal transmittance of 1.03W/m²K was obtained. The same study was made for a lightweight dry[7] wattle and daub wall where the thermal transmittance was 0.73W/m²K. In the work of Cuitiño Rosales, Maldonado, and Esteves Miramont (2014), in the experimental test in 0.10 m thick wet wattle and daub test cells[8], thermal transmittance of 1.82 W/m²K was obtained. Finally, in the work of the Agency for the Economic Development of the City of Córdoba (Adec, 2019), for a 0.145m thick wall, a thermal transmittance value of 1.14W/m²K was

7 Dry Lightweight Wattle and Dab: This is a wattle and daub that only uses dry vegetable fibers as its filler, without any soil, clay, or water content (Acevedo Oliva et al., 2017).
8 Wet wattle and daub: This is wattle and daub with a filling of a mixture of clay in a plastic state (clayey earth plus water) with vegetable fibers of a higher density than lightweight wet wattle and daub (Acevedo Oliva et al., 2017).

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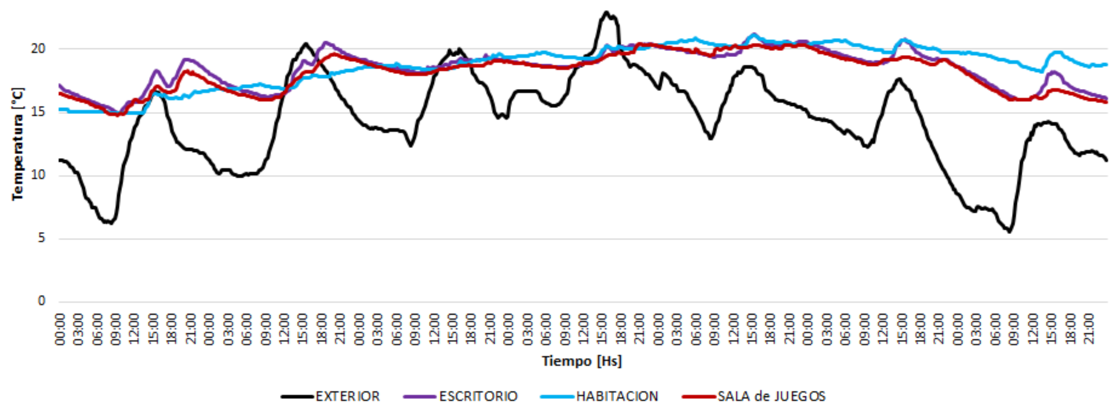
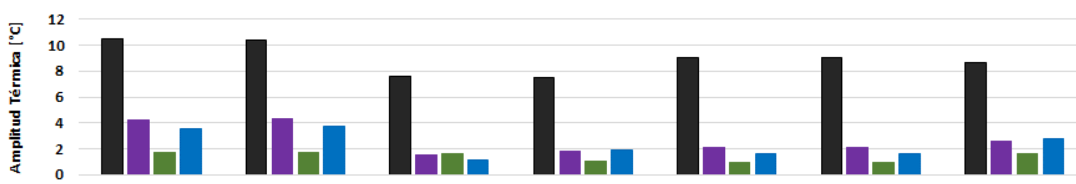


Figure 4: Thermal behavior curves of the house under study. Source: Preparation by the authors.



	1-07	2-07	3-07	4-07	5-07	6-07	7-07
EXTERIOR	10.5	10.4	7.6	7.5	9	9	8.7
ESCRITORIO	4.2	4.3	1.5	1.8	2.1	2.1	2.6
HABITACION	1.7	1.7	1.6	1	0.9	0.9	1.6
SALA DE JUEGOS	3.5	3.7	1.1	1.9	1.6	1.6	2.8

Figure 5: Daily thermal amplitude for the case study. Source: Preparation by the authors.

obtained. It can be seen that the lightweight fiber wall tested by the INTI has a better insulating response than the other walls. These data can be seen in Table 5.

MEASUREMENTS INSIDE THE HOUSE

Argentina has six bioclimatic zones: zone I: very warm, zone II: warm, zone III: warm temperate, zone IV: cold temperate, zone V: cold, and zone VI: very cold. In the cold bioclimatic zones of Argentina, it was necessary to use wattle and daub walls with thicknesses between 0.25m and 0.30 m to verify the conditions of the maximum permissible thermal transmittance level A given in Table 1 of IRAM 11605 (1996), which follows the winter design temperature established in IRAM 11603 (2012). This study has a thermal transmittance of 0.30W/m^{2}K for a lightweight straw wall comprising 0.05 m thick plaster for each side of the wall plus 0.20 m thick lightweight straw filling mixed with slip.

Figures 4 and 5 show the temperature data obtained in July. The external measurement curve is taken as a reference, where the daily thermal amplitude is observed[9], with values between 7.6°C and 10.5 °C. Despite this outdoor thermal variability, inside, there is less variation between the daily thermal amplitudes, where the maximum values recorded in the case of the desk are 4.3°C, in the bedroom, it is 1.7°C, and in the games room, it is 3.7°C, which shows a stable thermal behavior, which favors housing comfort. The house has a wood-burning stove in the living room if a higher comfort temperature is needed. However, no auxiliary heating system was used during this data recording stage.

COMPARATIVE ANALYSIS BETWEEN BIOCLIMATIC ZONES

The lightweight wattle and daub construction technique, Figure 6 a, can be adapted to be built in any bioclimatic zone of Argentina. However, the wall thicknesses must be analyzed to verify the maximum admissible thermal transmittance condition stated by IRAM 11605 (1996).

9 Thermal amplitude: Difference between the maximum and minimum temperature that is recorded in a place in a given period of time (IRAM 11549, 2002).

Table 6. Required and total wall thicknesses. Source: Preparation by the authors (2024)

Data		Lightweight wattle and daub wall [m]		Solid brick wall [m]			Hollow ceramic brick wall [m]		
Ext. design temp.	Level A $K_{max\ adm}$ [W/m2K]	Required thickness	Total Thickness	Required thickness	Total Thickness	Solid brick units N_{LM}	Required thickness	Total Thickness	Hollow brick units N_{LH}
-15	0.23	0.27	0.37	3.50	3.73	19	1.68	1.78	9
-14	0.23	0.27	0.37	3.50	3.73	19	1.68	1.78	9
-13	0.24	0.26	0.36	3.33	3.73	19	1.61	1.78	9
-12	0.25	0.25	0.35	3.19	3.535	18	1.54	1.59	8
-11	0.25	0.25	0.35	3.19	3.535	18	1.54	1.59	8
-10	0.26	0.24	0.34	3.07	3.34	17	1.48	1.59	8
-9	0.27	0.23	0.33	2.95	3.15	16	1.42	1.59	8
-8	0.28	0.22	0.32	2.83	3.15	16	1.37	1.39	7
-7	0.29	0.21	0.31	2.74	2.95	15	1.32	1.39	7
-6	0.3	0.20	0.30	2.63	2.95	15	1.27	1.39	7
-5	0.31	0.19	0.29	2.55	2.76	14	1.23	1.39	7
-4	0.32	0.19	0.29	2.46	2.76	14	1.18	1.39	7
-3	0.33	0.18	0.28	2.39	2.56	13	1.15	1.20	6
-2	0.35	0.17	0.27	2.23	2.56	13	1.08	1.20	6
-1	0.36	0.16	0.26	2.17	2.37	12	1.04	1.20	6
> 0	0.38	0.15	0.25	2.05	2.17	11	0.98	1.20	6

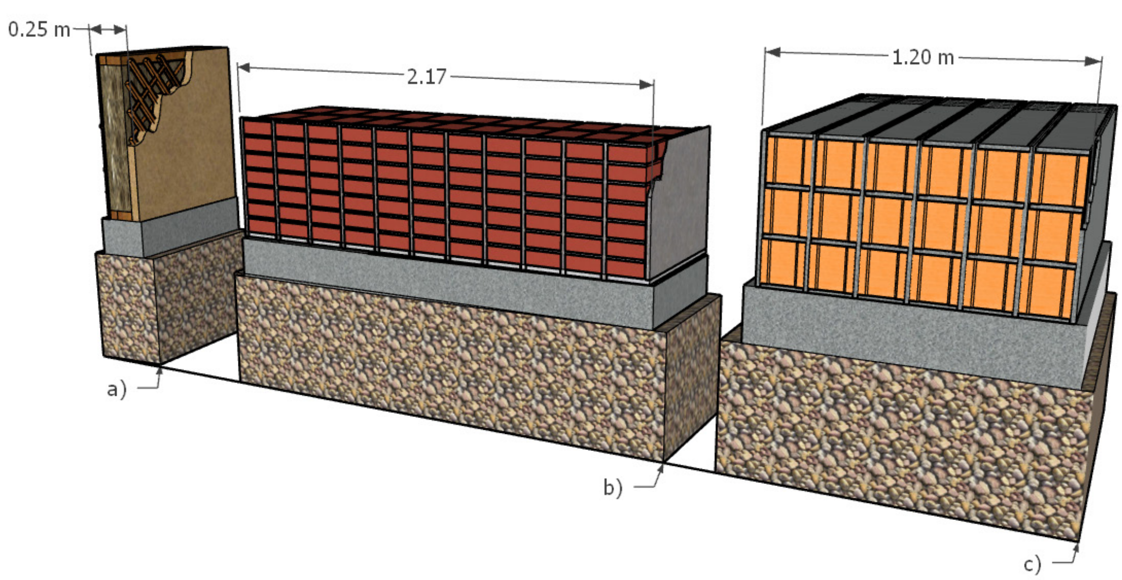


Figure 6: Details of the walls: a) Lightweight Wattle and Daub, b) Solid brick, c) Hollow brick. Source: Preparation by the authors (2024)

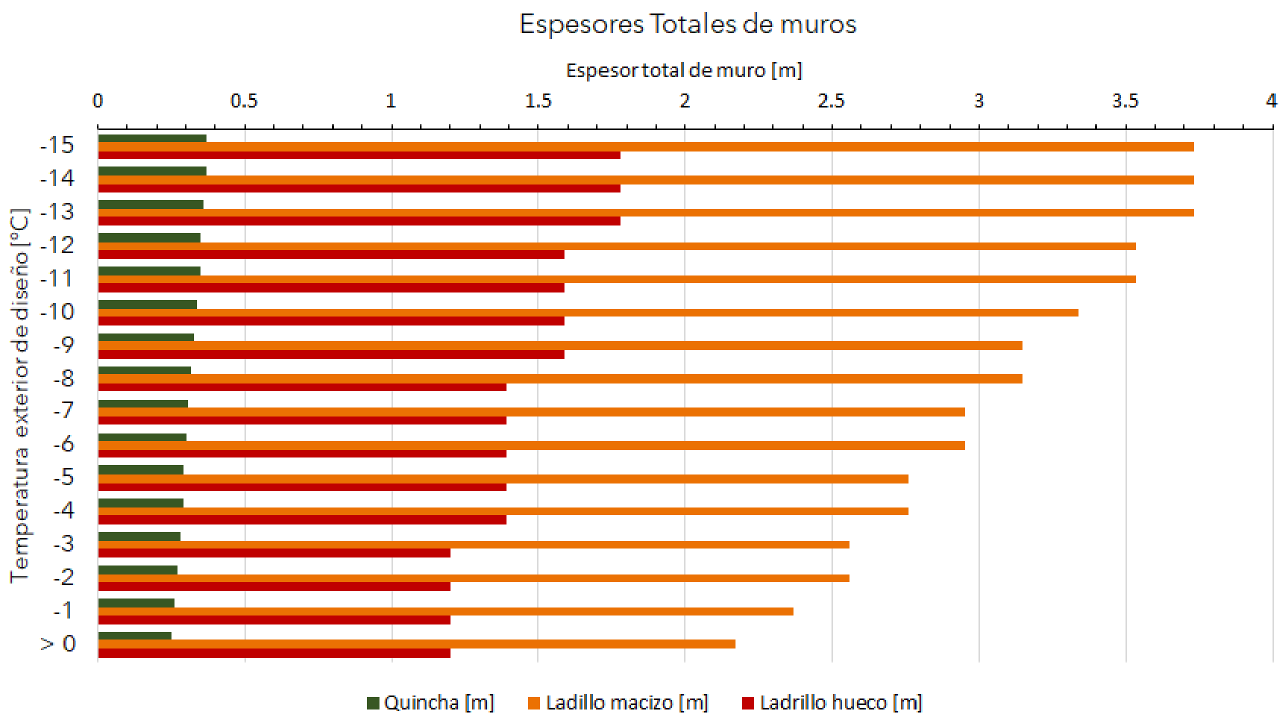


Figure 7: Comparative table of wall thicknesses of study materials for different exterior design temperatures. Source: Preparation by the authors (2024).

From what is described in the methodology (Equation 11-12-13 and 14), in Table 6, the wall thicknesses needed to comply with the maximum admissible thermal transmittance level A for each of the winter design temperatures were obtained, and then the total wall width that would comply with said regulations. In the case of wattle and daub, the data variable to be obtained was the thickness of the lightweight filler, and in the other two cases, the variable to be analyzed was the width of the brick wall. In all cases, the plaster is fixed data. Figures 6 a, b, and c show the proposed case studies.

Figure 7 shows the total wall thicknesses for each case study. In the wattle and daub walls with straw filler and plaster on both sides, the total wall thickness represents between 10% and 12% of the required wall thickness. The solid brick wall and the hollow solid brick represent between 21% and 23% of the total thickness. It can also be seen that faced with the same thermal transmittance demand, solid brick walls and hollow ceramic walls require a high amount of masonry to form the wall, as can be seen in Figure 6, where the last situation has been represented with a design temperature higher than 0°C, and a maximum permissible transmittance of 0.38W/m^{2}K, requiring a 0.15 m filler for wattle and daub and a finished wall thickness of 0.25m. 11 blocks would be needed for the solid brick wall giving a finished wall of 2.17m. In contrast, 6 were needed for the hollow ceramic brick, resulting in a 1.20 m wall. For the solid brick and hollow brick, it is not feasible to build walls with the obtained values due to the large dimensions required to reach the K_{maxadm} levels. In these cases, it is necessary to reduce the wall thicknesses and compensate for this reduction by incorporating insulating materials (Mac Donnell, 2014).

CONCLUSIONS

The parameters needed to conduct the hygrothermal study of the houses built with the lightweight wattle and daub wall plaster and filler technique were obtained with the thermal conductivity values obtained in their tests. As a result, an optimal response regarding thermal behavior was obtained, compared with similar studies in opaque envelopes for housing.

The thermal conductivity obtained from the filler was 0.07 W/m.K, and from the earth plaster, 0.34 W/m.K. The formation of a 0.156 m thick wall, with 0.05 m plaster on each side and 0.056 m thick filler, results in an overall thermal transmittance of 0.79 W/m^{2}K, compared with the wattle and daub tested in Protierra Chile (Acevedo Oliva et al., 2017), where a wall of the same thickness (0.156 m) gives a thermal transmittance of 1.03 W/m²k.

In the studied house, lightweight wattle and daub walls with thicknesses between 25 cm and 30 cm were used, and the hygrothermal behavior could be verified with a thermal transmittance of 0.30 W/m²K. From the on-site measurements in July 2023, it was obtained that, despite the external thermal amplitudes varying between 7.5°C and 10.5°C, the interior has thermal stability throughout the measurement, with amplitudes between 4.3°C and 0.9°C, which is reflected in the interior comfort, because it was not necessary to resort to auxiliary heating systems.

The data obtained in this study allowed making the theoretical calculations to determine the different thicknesses required according to Argentina's thermal transmittance needs for each bioclimatic zone. In this way, for an optimal level of thermal transmittance, it could be concluded that, for all cases, the lightweight wattle and daub wall complies with Level A with considerably lower wall thicknesses compared to a solid brick wall and a hollow ceramic brick wall.

It should be noted that the behavior of lightweight wattle and daub walls continues to be investigated for implementation in both bioclimatic and seismic areas. With this information, the fire resistance of this construction system will be studied, following IRAM 11950 (2010), "Fire resistance of construction elements—Test method."

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, M.G.C.R., A.D., G.V. and V.D.; Data curation, A.D. and G.V.; Formal analysis, M.G.C.R. and V.D.; Acquisition of A.D. and G.V. financing; Research, M.G.C.R., A. D., G.V. and V.D.; Methodology, M.G.C.R.; Project management, A.D. and G.V.; Resources, M.G.C.R., A.D., G.V. and V.D.; Software. M.G.C.R.; Supervision, A.D. and G.V.; Validation, M.G.C.R. and V.D.; Visualization, G.V. and V.D.; Writing - original draft, M.G.C.R., A.D, G.V. and V.D.; Writing - revision and editing, M.G.C.R., A.D., G.V. and V.D.

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