Evaluación del coeficiente de conductividad y transmitancia térmica de elementos constructivos de tierra
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EVALUATION OF THE THERMAL CONDUCTIVITY AND TRANSMITTANCE COEFFICIENT OF EARTHEN CONSTRUCTIVE ELEMENTS

EVALUACIÓN DEL COEFICIENTE DE CONDUCTIVIDAD Y TRANSMITANCIA TÉRMICA DE ELEMENTOS CONSTRUCTIVOS DE TIERRA

VALIAÇÃO DO COEFICIENTE DE CONDUTIVIDADE E TRANSMITÂNCIA TÉRMICA DE ELEMENTOS CONSTRUTIVOS DE TERRA

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RESUMEN

En este trabajo se pretende determinar la conductividad térmica de diferentes elementos constructivos de tierra producidos con materiales característicos del centro este de la provincia de Santa Fe (Argentina) y evaluar su aptitud para ser empleados en la construcción de envolventes que cumplan con los requerimientos de aislación térmica solicitados por la normativa nacional correspondiente. Para ello se confeccionaron probetas siguiendo las diferentes técnicas de construcción con tierra empleadas en la región (bloque de tierra comprimida, adobe, tapia, quincha y revoques) y se midió su coeficiente de conductividad térmica, con el cual se calculó la transmitancia térmica de diferentes paquetes constructivos de tierra. Los resultados obtenidos indican que las técnicas de construcción con tierra evaluadas presentan, en todos los casos, un mejor desempeño térmico que los tradicionales muros de ladrillo cerámico macizo o bloques de hormigón, siendo la quincha la técnica con mayor capacidad de aislamiento térmico.

Palabras clave
aislamiento térmico, muros, materiales de construcción

ABSTRACT

The aim of this work is to determine the thermal conductivity of different earthen constructive elements produced with materials typical of the central-eastern part of the Province of Santa Fe (Argentina), and to evaluate their suitability to be used in the construction of envelopes that comply with the thermal insulation requirements of the corresponding National Regulations. For this purpose, test specimens were made following the different earth construction techniques used in the region (compressed earth block, adobe, rammed earth (*tapia)*, wattle and daub (*quincha*), and plaster), and their thermal conductivity coefficient was measured, with which the thermal transmittance of different earth construction packages was calculated. The results obtained indicate that the earth construction techniques evaluated show, in all cases, a better thermal performance than traditional solid ceramic brick or concrete block walls, with wattle and daub being the technique with the highest thermal insulation capacity.

Keywords
climate change, housing, sustainable development, resilience

RESUMO

O objetivo deste trabalho é determinar a condutividade térmica de diferentes elementos construtivos de terra produzidos com materiais característicos do centro-leste da província de Santa Fé (Argentina) e avaliar sua adequação para uso na construção de envelopes de edifícios que atendam aos requisitos de isolamento térmico dos regulamentos nacionais correspondentes. Para isso, foram feitos corpos de prova de acordo com as diferentes técnicas de construção com terra utilizadas na região (bloco de terra comprimida, adobe, tapia, quincha e gesso) e foi medido seu coeficiente de condutividade térmica, com o qual foi calculada a transmitância térmica de diferentes pacotes construtivos de terra. Os resultados obtidos indicam que as técnicas de construção com terra avaliadas apresentam, em todos os casos, melhor desempenho térmico do que as tradicionais paredes sólidas de tijolos cerâmicos ou blocos de concreto, sendo a quincha a técnica com maior capacidade de isolamento térmico.

Palavras-chave:
isolamento térmico, paredes, materiais de construção.

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INTRODUCTION

The use of context-appropriate envelopes, when faced with a continuous rise in international energy prices and the need to support global efforts to mitigate global warming, becomes a strategy to improve the energy efficiency of buildings. The choice of suitable envelopes has benefits, not only in terms of obtaining energy savings for spaces, improving the indoor microclimate, and reducing polluting emissions, but also regarding the project's technical and economic viability (Balter et al., 2020).

In this context, the potentialities of earthen-built enclosure walls can be highlighted, whose historical continuity is largely due to the abundance of its raw material, the economy of its construction processes, its bioclimatic qualities, and the harmony of its interrelation with its natural environment (Pacheco-Torgal & Jalali, 2012). This is known, sustained, and defended by the peoples with their local traditions, especially those linked to the ancestral worship of Mother Earth, who with popular wisdom produce architecture adapting it to the climate and customs of each site and society (Fernandes et al., 2019).

There are numerous construction techniques and systems that use earth as the predominant raw material (Rotondaro, 2018). However, these can be simply classified within the following categories:

- <u>Mixed techniques</u>: The earth is used as a filling and covering material, using an independent load-bearing structure, usually built with wood. The most commonly used techniques in Argentina are wattle and daub (*quincha*), which is characterized by its secondary structure of reeds or wooden slats equally spaced between 10 and 15 cm apart and arranged horizontally or diagonally; the lightened earth or formwork straw and the elongated mass (*enchorizado*) (Esteves & Cuitiño, 2020).
- <u>Monolithic techniques</u>: Monolithic walls with load-bearing capacity are built using direct molding by hand or mobile formworks filled with compacted or poured mortars. The greatest exponent of these techniques is the rammed earth (*tapia*) (Tepale Gamboa, 2016).
- <u>Masonry techniques</u>: Those that use prefabricated small-sized components, produced before building the house. These components attach to each other using earthen mortars. The walls built with compressed earth blocks (CEB) or adobe are examples of these techniques (Dorado et al., 2022).

One of the most important characteristics of earth as a building material is related to its thermal properties, in particular its ability to transmit heat. This capacity can be defined based on one of its fundamental physical properties: the thermal conductivity coefficient (λ), whereby the thermal transmittance of an envelope (K), directly linked to its thermal insulation, can be determined (Cuitiño et al., 2020).

Despite extensive literature on the thermal properties of materials, research on the thermal conductivity coefficient of earthen building elements produced with materials from the Province of Santa Fe (Argentina) has not been published in academic texts, which makes it impossible to accurately calculate the thermal transmittance of enclosure walls built with these elements.

With regard to the regulatory framework in Argentina, several standards define guidelines for the thermal conditioning of buildings. For example, the IRAM 11601:2010 Standard establishes the apparent density and thermal conductivity of the country's most widely used construction materials and the calculation procedure to determine the thermal resistance and its inverse. It also determines the thermal transmittance (K) of walls and enclosures, whose values should be lower than the maximum permissible values established by the IRAM 11605:2010 and IRAM 11900:2017 Standards for each region of the country, defined in IRAM 11603:2012. However, for the thermal properties of earthen building elements, this set of standards only indicates the thermal conductivity value of CEB with a density of 1800 kg/m^3. In this way, the determination of the thermal conductivity coefficient for different earthen building elements produced with local materials is crucial for regulatory development in Argentina. Therefore, the objective of this work is to determine the thermal conductivity coefficient of different earthen building elements produced with typical materials from the central-eastern sector of the Province of Santa Fe (Argentina), and evaluate their suitability to be used in building walls that meet the thermal insulation requirements requested by the national regulations.

BACKGROUND

The measurement of the thermal conductivity coefficient (λ) of different earthen building elements has been widely studied internationally, with the articles published by Laborel-Préneron et al. (2018), Saidi et al. (2018), and El Fgaier et al. (2016), where the thermal conductivity coefficient of adobe was determined, standing out. On the other hand, there are also the determinations made by Millard and Aubert (2014) on extruded earth blocks; and those performed by Cagnon et al. (2014) and Ouedraogo et al. (2020) on CEB. In addition, the research conducted by Mosquera Arancibia (2013) for his doctoral thesis on the effectiveness of using the "hot needle" method to determine the λ in adobe and CEB; the study conducted by Wieser et al. (2018), where the thermal conductivity was evaluated on samples of wattle and daub, lightened earth, and earth mortars; and, finally, the thesis of Cabrera Córdova (2019) where, among other parameters, the thermal conductivity of adobe, earth plasters, and palm matting was determined.

Despite the aforementioned studies, there are few lines of research in Argentina to quantify the thermal properties of earthen materials. In this regard, the works by Costantini Romero et al. (2021) and Costantini Romero and Francisca (2022) are mentioned, where the thermal conductivity coefficient of CEBs produced in the city of Córdoba (Arg.) was determined, and the one by Cuitiño et al. (2015), where the thermal transmittance (K) of different wattle and daub panels was determined.

It should also be mentioned that the results published in the referenced research, despite being within similar ranges, have significant differences, mainly caused by the type of soil used to prepare the test specimen, their molding methodology, and the test equipment used. With regard to the equipment and methodologies used to determine λ, the so-called hot-box[1], thermal needle[2], and hot plate[3] methods have been used.

Finally, it is important to highlight the work carried out by the RILEM Committee (Fabbri et al., 2022), Volhard (2016), Cuitiño et al. (2020), and Minke (2005) who, despite not making direct thermal conductivity determinations of the earthen constructive elements, make an in-depth analysis of the variation of this coefficient considering variables such as the construction technique and the density of constructive elements.

METHODOLOGY

MATERIALS

The earth used to manufacture the different samples was obtained from a quarry in the municipality of Monte Vera (Santa Fe, Arg.). In previous work (Cabrera et al., 2022), the soil used was identified as a "CL low plasticity clay" with 54% silt, 32% clay, and 14% fine sand. Likewise, the semi-quantifications carried out by DRX confirm that, from the mineralogical point of view, the predominant mineral is quartz (65%), followed by phyllosilicates (clays) (25%), and feldspars (9%). The diffractograms of oriented aggregates of the earth's clay fraction indicate that the phyllosilicates present are illite, kaolinite, and smectite.

The fine sand used in the granulometric correction has a uniform size distribution, in that more than 90% of its particles are between 0.5 and 0.1 mm in size. In addition, there are no edges or angular shapes in its grains, with all of them presenting a rounded shape. From the mineralogical point of view, its grains consist mainly of quartz (95% by weight), with only 1% of clays.

The coarse sand, also made of silica and with a size distribution of between 2 and 3 mm, was purchased from the company Gravafilt in the city of Paraná (Arg.), which extracts it by dredging the upper Paraná River basin, classifying it, and commercializing it with different granulometry. This sand was used only in the preparation of the rammed earth samples.

To manufacture the adobe, wattle and daub, and coarse plaster test specimens, wheat straw purchased near the city of Santa Fe (Arg) was used as vegetable fiber. Although the straw used in making the different types of test specimens was the same, it was cut into different lengths: 2 cm for coarse plasters, 3 cm for adobe, and between 10 and 12 cm for the wattle and daub filling. The materials used in the manufacture of the different types of specimens can be seen in Figure 1.

1 Determines the λ coefficient and the conductivity, K, of an enclosure in a stationary regime and on a real scale, with the test specimen being a wall that separates two environments with different temperatures.

2 Determines the λ coefficient in a non-stationary regime by introducing a metal needle with a heater and thermocouple inside the material being evaluated, measuring its temperature variation over time.

3 Determines the λ coefficient under a stationary regime on a 10 to 90 mm thick plate-shaped test specimen, which is placed between 2 plates at different temperatures. The plates are confined inside a parallelepiped box with high thermal insulation.

Figure 1. Materials used in the manufacture of the specimens: (a) earth, (b) mud (mixture of earth and water), (c) fine sand, and (d) wheat straw, 3 cm in length. Source: Preparation by the authors.

Table 1. Dosage used in the preparation of the test specimens. Source: Preparation by the authors.

Material	Dry weight proportion in %				Water* (%)	Water/earth ratio
	Earth	Fine sand	Coarse sand	Straw		
(a) CEB	70.0	30.0	-	-	11.7	0.17
(b) Adobe	96.5	-	-	3.5	32.6	0.34
(c) Wattle and daub	93.8	-	-	6.2	60.1	0.64
(d) Rammed earth	60.0	20.0	20.0	-	11.0	0.18
(e) Coarse plaster	67.5	29.1	-	3.4	23.3	0.34
(f) Fine plaster	35.0	65.0	-	-	16.3	0.47

* % determined based on the dry weight of the earth.

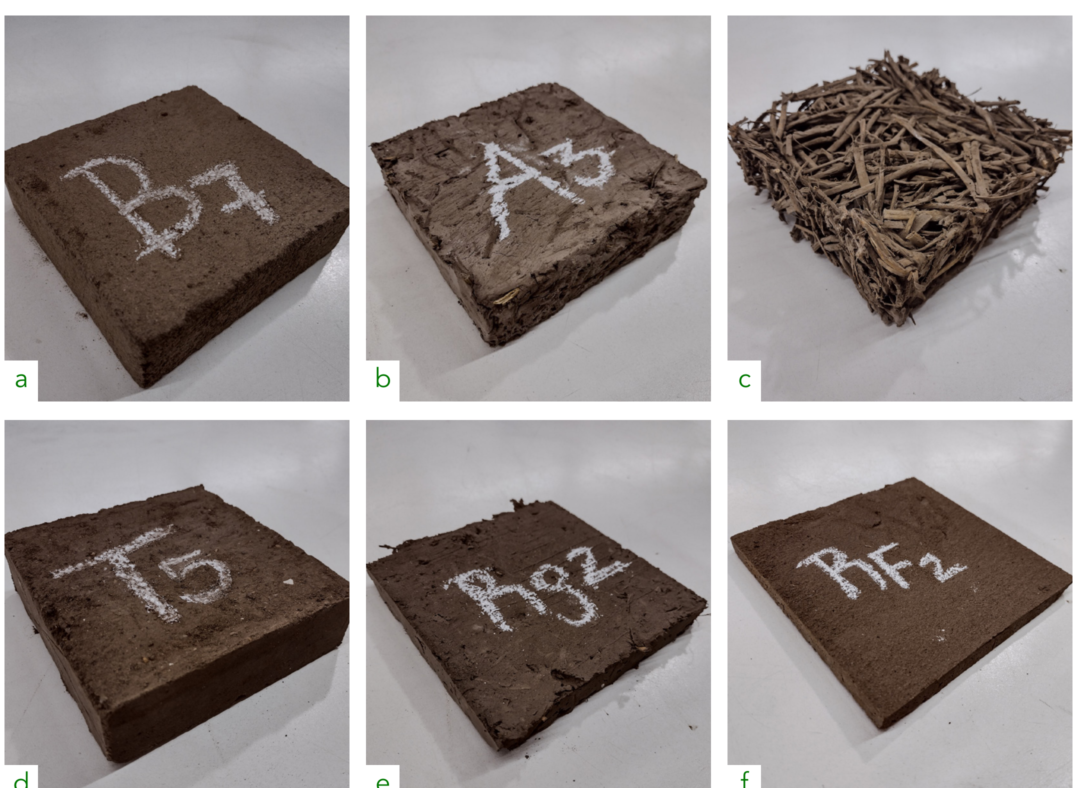

Figure 2. Representative specimens of the different earth construction techniques: (a) CEB, (b) adobe, (c) wattle and daub, (d) rammed earth, (e) coarse plaster, and (f) fine plaster. Source: Preparation by the authors.

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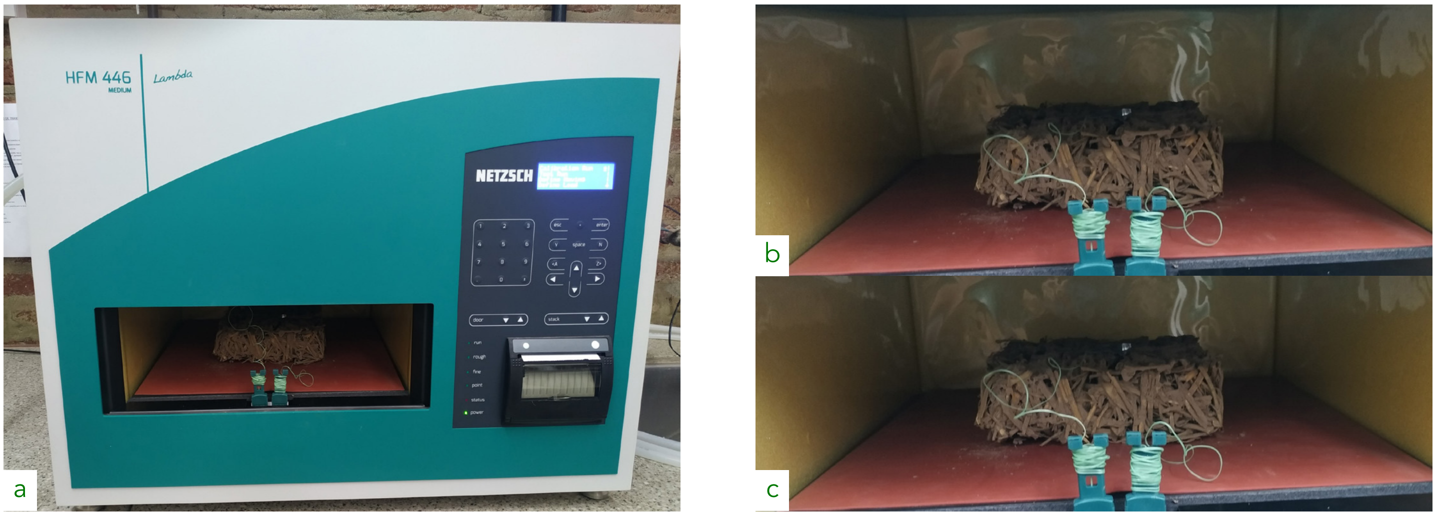

Figure 3. (a) HFM 446 equipment, (b) additional thermocouples, and (c) silicone film used to determine the thermal conductivity coefficient. Source: Preparation by the authors.

MANUFACTURE OF TEST SPECIMENS

For each construction technique, three 13 x 13 x 4 cm test specimens were made (except for the thin plaster ones, which were 2 cm thick), thus generating a total of 18 test specimens, whose dosages are presented in Table 1. The CEB test specimens were made by cutting, with a circular bench saw, whole blocks produced in the laboratory with an Altech Geo 50 manually operated press. These, because they were not stabilized with Portland cement, were not cured, and were left to dry for 7 days sheltered from the weather.

The adobe, coarse plaster, and fine plaster specimens were made by pouring the wet mixture into each mold, accommodating it to not generate vacuums or voids. After 24 hours, the specimens were removed from the mold, allowing them to dry for 7 days under laboratory temperature and humidity conditions (24 °C < t < 27 °C and 35% < RH < 45%). The molding of the rammed earth specimens was done in 3 layers, introducing third parts of the wet material into the mold and compacting each layer with 25 strokes of a 550 g block ramming machine, before sanding the upper surface with sandpaper. These specimens were immediately removed from their molds, being allowed to dry, like the rest, for 7 days inside the laboratory.

For the molding of the wattle and daub specimens, the straw was submerged in slip (mud of liquid consistency) and, after a few seconds, it was extracted. The excess liquid was then drained and the straw covered with the slip was introduced into the mold, thus intertwining the fibers embedded in the slip (Figure 2.c). Then, they were left to dry for 7 days and removed from the mold.

DETERMINATION OF THERMAL CONDUCTIVITY AND TRANSMITTANCE

For each of the specimens made, the dry apparent density and then the thermal conductivity coefficient were determined first, using an HFM 446 Lambda Medium heat flow meter model from the German firm Netzsch (Figure 3.a), adopting an average test temperature of 17 °C and a variation of ± 10 °C, following the procedure stipulated by the IRAM 1860:2002 Standard. Before the tests, all the test specimens were dried in an oven at 100 °C until mass consistency was achieved. Given the irregularity of the specimens' surface, they were tested using a complementary kit, provided by the equipment supplier, consisting of a silicone film and additional thermocouples (Figure 3.b and Figure 3.c), whose purpose is to improve the contact interface between the thermal plates and the rough surface faces of the specimens.

Once the thermal conductivity coefficient of each type of sample tested had been determined, the thermal transmittance coefficient (K) of different earthen building packages was calculated following the procedure indicated by the IRAM 11601:2010 Standard; adopting the interior and exterior surface thermal resistance values proposed by it. The formulas used to calculate K were those indicated in Equation 1, Equation 2, and Equation 3:

$$R_i = e_i \;/\; \lambda_i \qquad \text{(Equation 1)}$$

$$R_t = R_{ext} + R_i + R_{int} \qquad \text{(Equation 2)}$$

$$K = 1/R_t \qquad \text{(Equation 3)}$$

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Where:

- R_i: thermal resistance of each constituent layer of the wall, in m²K/W
- λ_i: thermal conductivity coefficient of each material, in W/mK
- e_i thickness of each material the wall comprises, in m
- R_t: total thermal resistance of the wall, in m²K/W
- R_{ext}: external surface thermal resistance, adopting a value of 0.04 m²K/W
- $R_{int:}$ internal surface thermal resistance, adopting a value of 0.13 m²K/W
- K: total thermal transmittance of the wall, in W/m²K

RESULTS

The apparent density (ϱ) and thermal conductivity coefficient (λ) values obtained for each specimen tested are shown in Table 2, together with the corresponding average value, the standard deviation (S_d), and the variation coefficient (V_c).

On the other hand, Table 3 presents the thermal transmittance coefficient (K) values calculated for different wall construction packages using the earth components analyzed in this work, proposed based on local construction practices. In this table, the column called "main element" refers to the thickness of the adobe, CEB, rammed earth, or wattle and daub, as applies.

DISCUSSION

ON THE DETERMINATION OF THE THERMAL CONDUCTIVITY COEFFICIENT

As can be seen in Table 2, there is a correlation between the density of the construction elements

Table 2. Apparent density and thermal conductivity coefficient of the test specimens. Source: Preparation by the authors.

Material	Density				Thermal conductivity			
	ρ_i (kg/m3)	ρ_{prom} (kg/m3)	S_d (kg/m3)	C_v (%)	λ_i (W/mK)	λ_{prom} (W/mK)	S_d (W/mK)	C_v (%)
CEB	1587	1595	13.4	0.8	0.59	0.60	0.01	1.7
	1588				0.61			
	1611				0.59			
Adobe	1353	1352	12.2	0.9	0.46	0.43	0.05	11.4
	1364				0.45			
	1340				0.37			
Wattle and Daub	341	429	76.4	17.8	0.11	0.13	0.02	15.3
	478				0.14			
	468				0.15			
Rammed Earth	1634	1687	48.9	2.9	0.58	0.67	0.10	15.0
	1697				0.64			
	1730				0.78			
Coarse plaster	1348	1329	22.8	1.7	0.49	0.48	0.08	16.0
	1303				0.41			
	1334				0.56			
Fine plaster*	1233	1260	37.6	3.0	0.23	0.25	0.04	15.8
	1286				0.28			

* Only 2 measurements could be made on this series.

Table 3: Calculation of the thermal transmittance coefficients of different earth construction packages. Source: Preparation by the authors.

Constructive package	Thickness of each layer (m)						K (W/m²K)
	External fine plaster	External coarse plaster	Main element	Internal coarse plaster	Internal fine plaster	Total	
CEB (12 cm)	-	-	0.12	-	0.01	0.13	2.443
CEB (25 cm)	0.01	0.02	0.25	0.02	0.01	0.31	1,337
CEB with air chamber (4 cm)	0.01	0.02	0.25 + 0.12	-	-	0.44	0.969
Adobe	0.01	0.02	0.30	0.02	0.01	0.36	0.972
Plastered rammed earth (30 cm)	0.01	0.02	0.30	0.02	0.01	0.36	1,282
Visible rammed earth	-	-	0.55	-	0.01	0.56	0.969
Wattle and Daub	0.01	0.02	0.15	0.02	0.01	0.21	0.675

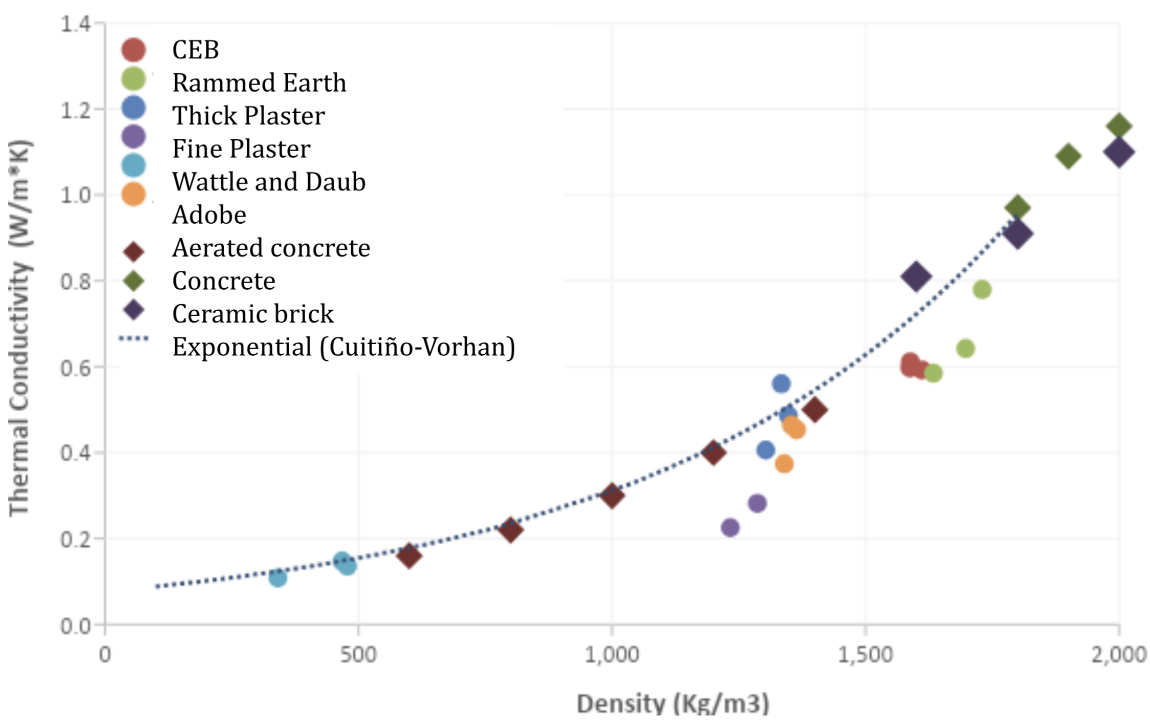

Figure 4. Correlation between the density of building elements and their thermal conductivity coefficient. Source: Preparation by the authors.

and their thermal conductivity coefficient, with the wattle and daub, whose density is around 400 kg/m³, being the one with the lowest thermal conductivity coefficient, with about 0.13 W/mK. This coefficient is comparable to that of cellular concretes of similar density (IRAM 11601:2010), but significantly higher than that of conventional insulating materials, such as glass wool, expanded polystyrene, or polyurethane foam (Navacerrada et al., 2021). After the wattle and daub, the constructive element with the lowest thermal conductivity coefficient is adobe with an $_{average}$ λ of 0.43 W/mK, followed by CEB with an $_{average}$ λ of 0.60 W/mK, and finally rammed earth with an $_{average}$ λ of 0.67 W/mK.

According to this data, the spread in the results of the wattle and daub samples becomes evident, which can be associated with greater variability in the densities of each sample, typical of the process to make these, namely manual filling with a large volume of voids due to the intertwining of straw fibers in the wattle and daub and dynamic compaction for rammed earth.

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As far as the coarse plaster samples are concerned, both their density and λ are similar to those of the adobe samples. This similarity is attributed to the fact that, regardless of the materials used (straw for adobe and sand + straw for coarse plaster), the water/earth ratio of both, the main cause of the porosity and apparent density of the earthen constructive elements (Laborel-Préneron et al., 2018), are equal, with 0.34. Similarly, the coarse plaster samples with a water/earth ratio of 0.47 - the highest after the wattle and daub - have the lowest density and average λ.

In Figure 4, the experimental results obtained in this research (colored dots) can be compared with those collected and published by Volhard (2016) and Cuitiño et al. (2020) for different earth-building elements (dotted line). In this, it can be seen how, despite the spread in the results achieved in this work, the exponential correlation between the density of the earthen constructive elements and their thermal conductivity coefficient is similar to that determined by the cited authors. This allows thinking that, regardless of the mineralogical characteristics of the earth used, the amount and type of sand, along with the vegetable fibers used in the stabilization, the main determinant of the thermal conductivity coefficient of these constructive elements is their final apparent density.

In addition, Figure 4 includes the thermal conductivity values for different traditional constructive elements, corresponding to their densities. It can be seen how aerated concrete, whose densities resemble that of the different earthen constructive elements, has thermal conductivity coefficients very similar to those determined by Cuitiño et al. (2020) and Volhard (2016) (dotted line), and that both concrete and solid ceramic brick, despite being in a range of densities higher than those studied by the aforementioned authors, follow the same trend.

ON THERMAL TRANSMITTANCE

The Argentine regulation IRAM 11605:2010 establishes three levels of hygrothermal comfort in winter and summer for the country's different bioclimatic zones, depending on the average outdoor temperatures. Thus, for the central-eastern sector of the Province of Santa Fe (bioclimatic zone IIb), the thermal transmittance values for each comfort level are as follows:

- Level A: 0.38 W/m²K
- Level B: 1.00 W/m²K
- Level C: 1.85 W/m²K

Table 4. Calculation of the thermal transmittance coefficient of different construction packages. Source: Preparation by the authors based on data from the IRAM11601:2010 Standard.

Material	Thickness (m)						K (W/ m²K)
	External fine plaster*	External coarse plaster*	Main element	Internal coarse plaster*	Internal fine plaster*	Total	
Common brick 25 cm	0.01	0.02	0.25	0.02	0.01	0.31	1.505
Common brick with air chamber	0.01	0.02	0.25+0. 25	0.02	0.01	0.56	0.924
Hollow brick 18 cm	0.01	0.02	0.18	0.02	0.01	0.24	1.390
Hollow brick with air chamber	0.01	0.02	18 + 12	0.02	0.01	0.36	0.927
Concrete block 20 cm	0.01	0.02	0.20	0.02	0.01	0.36	2.226
Concrete block with air chamber	0.01	0.02	0.20+0.20	0.02	0.01	0.36	1.540
Aerated concrete (600 kg/m3)	0.01	0.02	0.15	0.02	0.01	0.21	0.843

* Cementitious plasters

Based on the thermal transmittance coefficient values determined in Table 3 for different earthen construction packages, to meet the hygrothermal comfort level B –minimum level requested by the Ministry of Housing (Arg.)-, the most suitable alternative is the plastered wattle and daub wall, which, with a total thickness of 21 cm, has a K of 0.675 W/m²K.

In the case of using 30 cm adobe walls, with thick and thin plasters on both sides, comfort level B (0.972 W/m²K) can be reached with a total wall thickness of 36 cm. On the other hand, to achieve this level of comfort with a CEB wall, the best alternative is to use double walls (25 + 12 cm) with an inner air chamber of 4 cm and plasters only on the outer face of the wall, generating a wall whose final thickness is 44 cm, which is the common practice in the region (Dorado et al., 2022). Finally, using the exposed rammed earth technique (only with thin interior plaster), 56 cm thick walls should be used to achieve comfort level B.

Despite the high thicknesses of the adobe, CEB, and rammed earth walls required to reach comfort level B, it should be considered that, as shown in Table 4, except for walls built with hollow bricks and aerated concrete blocks, none of the so-called "traditional" construction packages reaches this level of insulation without the use of air chambers and a total wall thickness greater than 50 cm.

CONCLUSIONS

The evaluation of the results obtained in this research allows concluding the following:

- There is a direct correlation between the thermal conductivity coefficient and the apparent density of constructive elements made with earth, sand, and vegetable fiber from the central-eastern part of the Province of Santa Fe. This coincides with what is reported by different researchers from the national and international contexts.
- The earthen construction technique with the highest thermal insulation capacity is wattle and daub, complying with the requirements stipulated by current Argentine regulations, with a 21 cm thick package.
- For wall thicknesses of less than 40 cm, among the construction packages proposed in Table 3, the adobe walls (36 cm) present, after the wattle and daub (21 cm), the best thermal insulation level, followed by the rammed earth walls (36 cm), and finally the CEB ones (31 cm).
- The earth construction techniques all have better thermal performance than the traditional solid ceramic brick walls or concrete blocks, requiring lower thicknesses to achieve equal thermal insulation levels.

Finally, it can be stated that the main contribution of this research is strengthening public policies that look to encourage energy efficiency in Argentine homes, as is the case of the National Housing Labeling Program, implemented in 2023, in whose database the option of using walls built with earth elements in the envelopes is not available. This situation is mainly motivated by the shortage of reliable technical data on the thermal properties of earthen building elements produced with local materials.

BIBLIOGRAPHIC REFERENCES

Balter, J., Ganem, C., & Barea, G. (2020). Mejoras en el desempeño energético de edificios en verano mediante la integración de envolventes ventiladas en fachadas norte y cubiertas. El caso de Mendoza, Argentina. *Hábitat Sustentable*, *10*(2), 94–105. DOI: https://doi.org/10.22320/07190700.2020.10.02.07

Cabrera Córdova, C. (2019). Transmitancia Térmica de Sistemas Constructivos en Tierra [Universidad de Azuay]. In *Proyecto Final de Arquitectura*. Recuperado de: http://dspace.uazuay.edu.ec/handle/datos/9268

Cabrera, S., Elert, K., Guilarducci, A., & Margasin, A. (2022). The effect of local pozzolans and lime additions on the miner-alogical, physical and mechanical properties of compressed earth blocks in Argentina. *Revista de La Construccion*, *21*(2), 248–263. DOI: https://doi.org/10.7764/RDLC.21.2.248

Cagnon, H., Aubert, J. E., Coutand, C., & Magniont, C. (2014). Hygrothermal properties of earth bricks. *Energy and Buildings*, *80*, 208–217. DOI: https://doi.org/https://doi.org/10.1016/j.enbuild.2014.05.024

Costantini Romero, B., & Francisca, F. (2022). Construcción con bloques de suelo cemento como alternativa sostenible para envolvente edilicia. *Hábitat Sustentable*, *12*, 114–125. DOI: https://doi.org/https://doi.org/10.22320/07190700.2022.12.01.08

Costantini Romero, B., Francisca, F., & Giomi, I. (2021). Hygrothermal properties of soil–cement construction materials. *Construction and Building Materials*, *313*(October), 1–9. DOI: https://doi.org/10.1016/j.conbuildmat.2021.125518

Cuitiño, M. G., Esteves, A., Maldonado, G., & Rotondaro, R. (2015). Análisis de la transmitancia térmica y resistencia al impacto de los muros de quincha. *Informes de La Construccion*, *67*(537). DOI: https://doi.org/10.3989/ic.12.082

Cuitiño, M. G., Rotondaro, R., & Esteves, A. (2020). Análisis comparativo de aspectos térmicos y resistencias mecánicas de los materiales y los elementos de la construcción con tierra. *Revista de Arquitectura*, *22*(1), 138–151. Recuperado de: https://editorial.ucatolica.edu.co/index.php/RevArq/article/view/2348

Dorado, P., Cabrera, S., & Rolón, G. (2022). Contemporary difficulties and challenges for the implementation and development of compressed earth block building technology in Argentina. *Journal of Building Engineering*, 46, 103748. DOI: https://doi.org/10.1016/j.jobe.2021.103748

El Fgaier, F., Lafhaj, Z., Chapiseau, C., & Antczak, E. (2016). Effect of sorption capacity on thermo-mechanical properties of unfired clay bricks. *Journal of Building Engineering*, *6*, 86–92. DOI: https://doi.org/10.1016/j.jobe.2016.02.011

Esteves, J. M. & Cuitiño, M. G. (2020). El sistema constructivo de la quincha en zonas rurales del Norte de Mendoza (Argentina). *Estoa*, *9*(17), 93–102. DOI: https://doi.org/10.18537/est.v009.n017.a08

Fabbri, A., Morel, J.-C., Aubert, J.-E., Bui, Q.-B., Gallipoli, D. & Reddy, B. V. V. (2022). *Testing and Characterisation of Earth-based Building Materials and Elements. State-of-the-Art Report of the RILEM TC 274-TCE*. RILEM. DOI: https://doi.org/https://doi.org/10.1007/978-3-030-83297-1

Fernandes, J., Peixoto, M., Mateus, R. & Gervásio, H. (2019). Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. *Journal of Cleaner Production*, *241*. DOI: https://doi.org/10.1016/j.jclepro.2019.118286

IRAM (2002). Norma *IRAM 1860: Materiales aislantes térmicos. Método de ensayo de las propiedades de transmisión térmica en régimen estacionario, mediante el aparato de medición del flujo de calor*.

IRAM (2010). Norma *IRAM 11601: Aislamiento térmico de edificios. Métodos de cálculo. Propiedades térmicas de los componentes y elementos de construcción en régimen estacionario*.

IRAM (2010). Norma *IRAM 11605: Acondicionamiento térmico de edificios. Condiciones de habitabilidad en edificios. Valores máximos de transmitancia térmica en cerramientos opacos*.

IRAM (2012). Norma *IRAM 11603: Acondicionamiento térmico de edificios. Clasificación bioambiental de la República Argentina*.

IRAM (2017). Norma *IRAM 11900: Prestaciones energéticas en viviendas. Método de cálculo y etiquetado de eficiencia energética*.

Laborel-Préneron, A., Magniont, C., & Aubert, J. E. (2018). Hygrothermal properties of unfired earth bricks: Effect of barley straw, hemp shiv and corn cob addition. *Energy and Buildings*, *178*, 265–278. DOI: https://doi.org/https://doi.org/10.1016/j.enbuild.2018.08.021

Millard, P., & Aubert, J. E. (2014). Effects of the anisotropy of extruded earth bricks on their hygrothermal properties. *Construction and Building Materials*, *63*, 56–61. DOI: https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.04.001

Minke, G. (2005). *Manual de construcción en tierra. La tierra como material de construcción y su aplicación en la arquitectura actual*. Fin de siglo.

Mosquera Arancibia, P. (2013). *Medida de la conductividad térmica con el método de la aguja térmica, basado en la fuente lineal de calor transitorio para su aplicación en los cerramientos de adobes y bloques de tierra comprimida*. [Tesis de doctorado inédita] Universidad Politécnica de Madrid.

Navacerrada, M. Á., De la Prida, D., Sesmero, A., Pedrero, A., Gómez, T., & Fernández-Morales, P. (2021). Comportamiento acústico y térmico de materiales basados en fibras naturales para la eficiencia energética en edificación. *Informes de La Construcción*, *73*(561), e373. DOI: https://doi.org/10.3989/ic74558

Ouedraogo, K. A. J., Aubert, J.-E. E., Tribout, C., Escadeillas, G. & Escadeilas, G. (2020). Is stabilization of earth bricks using low cement or lime contents relevant? *Construction and Building Materials*, *236*, 117578. DOI: https://doi.org/10.1016/j.conbuildmat.2019.117578

Pacheco-Torgal, F. & Jalali, S. (2012). Earth construction: Lessons from the past for future eco-efficient construction. *Construction and Building Materials*, *29*, 512–519. DOI: https://doi.org/10.1016/j.conbuildmat.2011.10.054

Rotondaro, R. (2018). Construir con tierra: Tecnología y arquitectura del siglo XX. *Notas CPAU*. Recuperado de: https://www.revistanotas.org/revistas/41/2295-construir-con-tierra-tecnologia-y-arquitectura-del-siglo-xxi

Saidi, M., Soukaina, C., Belkacem, Z., & Seidiki, E. (2018). Stabilization effects on the thermal conductivity and sorption behavior of earth bricks. *Construction and Building Materials*, *167*, 566–577. DOI: https://doi.org/https://doi.org/10.1016/j.conbuildmat.2018.02.063

Tepale Gamboa, B. A. (2016). *La tierra vertida compactada como sistema tecnificado para la autoconstrucción de vivienda en zonas rurales* [Universidad Nacionall Autónoma de México]. Recuperado de: https://repositorio.unam.mx/contenidos/76043

Volhard, F. (2016). *Construire en terre allegee*. Acte Sud - Craterre.

Wieser, M., Onnis, S., & Meli, G. (2018). Conductividad térmica de la tierra alivianada con fibras naturales en paneles de quincha. In R. PROTERRA (Ed.), *Actas del 18° Seminario Iberoamericano de Arquitectura y Construcción con Tierra* (pp. 1–10). Recuperado de: https://files.pucp.education/facultad/arquitectura/2019/11/27173426/2018-SIACOT-Wieser-Onnis-Meli.pdf