International Journal of Membrane Science and Technology, 2023, Vol. 10, No. 2, pp. 679-690

Mechanical Resistance and Thermal Conductivity of Adobes for the Walls of Rural Dwellings in Extreme Minimum Climatic Conditions

Germán Belizario-Quispe[1], Alfredo Pelayo Calatayud-Mendoza[2], Edilberto Huaquisto-Ramos[3], Heber Nehemías Chui-Betancur[4], Eliseo Pelagio Fernández-Ruelas[5], Ángel Canales-Gutiérrez[6*]

[1,3]Facultad de Ingeniería Agrícola, Universidad Nacional del Altiplano, Av. Floral 1153, Puno, Perú.
[2]Facultad de Ingeniería Económica, Universidad Nacional del Altiplano, Av. Floral 1153, Puno, Perú.
[4]Facultad de Ciencias de la Educación, Universidad Nacional del Altiplano, Av. Floral 1153, Puno, Perú.
[5]Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional del Altiplano, Av. Floral 1153, Puno, Perú.
[6]Facultad de Ciencias Biológicas, Universidad Nacional del Altiplano, Av. Floral 1153, Puno, Perú.
Email: acanales@unap.edu.pe.

Abstracts: The aim was to determine the mechanical resistance and thermal conductivity of adobe bricks in extreme minimum weather conditions, which serve two physical functions: greater compression strength and lower thermal conductivity for the construction of rural housing walls in the Peruvian highlands. The study was experimental, where the soil texture class was determined using the Bouyoucos hydrometer. An experiment was designed with 58 adobe bricks with different composition percentages: clay soil, sand, sheep manure, and chilligua. The compression strength was measured with a hydraulic press and the thermal property was measured using a thermal conductivity meter for construction materials. Then, a polynomial regression model was estimated for the behavior of the compression strength and thermal conductivity of each adobe brick, and finally, classical optimization techniques were employed. The optimal adobe brick mixture resulted from the combination of inputs in the following proportions: 83.0% clay soil, 7.1% sand, 7.5% sheep manure, and 2.4% chilligua. This mixture generates greater compression strength of 31.85 kg/cm2 per unit of thermal conductivity in W/m•°K.

Keywords: Sand, Manure, Chilligua, Thermal conductivity, Soil mixture.

1. INTRODUCTION

Approximately 50% of the population in developing countries and 30% of the world's population live in houses with adobe walls [1]. Adobe is a traditional building material used in rural housing construction [2] and mainly in developing countries [3] due to its ease of construction and low cost [4].

The primary function of a home is to ensure the safety and thermal comfort of its occupants in order to improve their living conditions [5]. However, in rural areas, there is little information about the properties of vernacular architecture construction materials [6], although it has been demonstrated that adobe with appropriate dosing can achieve satisfactory thermal comfort [7].

In rural areas, the use of soil mixture in adobe wall construction for housing is common and attractive as it contributes to sustainable development [8,9] by using minimal energy in its production and having hygrothermal properties. Adobe with a mixture of clay soil combined with natural fibers has various uses and dosages to take advantage of its hygrothermal behavior [2]. There is growing interest in the use of this mixture with natural fibers as a building material, as it offers energy efficiency, ecological sustainability, and compression resistance [10].

Improperly made adobe has low compression resistance [11] and requires permanent maintenance to prevent premature deterioration of walls and a decrease in the lifespan of homes [12]. Additionally, it can be vulnerable to seismic events [3,4,13] and prone to cracking due to excessive deformation during adobe drying caused by its high content of fine particles [14].

In the Peruvian highlands, particularly at night when temperatures drop, rural houses lack thermal comfort inside their spaces [15], thus requiring better dosed construction materials [5,16]. Adobe constructions are also an affordable alternative to the rising costs of industrialized building materials [17].

Furthermore, this region of the highland's experiences high solar radiation throughout the year [18] which can be utilized as a source of heat to achieve thermal comfort in houses [19]. One of the benefits of well-dosed adobe walls is that they can absorb heat during the day and release it gradually at night, thereby saving energy and achieving desirable thermal comfort with less temperature oscillation inside the house [20]. In this way, the thermal inertia of the house can dampen the influence of external temperatures on indoor thermal conditions [7].

To create adobe, it is necessary to conduct a study of the textural class to define the soil's physical characteristics [21]. This is to determine an appropriate mixture of clay, silt, and sand. Adding chilligua can improve compression strength [14], provided that the sand and silt undergo a stabilization process [22]. In fact, chilligua contributes to compression strength [23], as the biocomposites made from a mixture of clay and sand with the addition of chilligua can enhance both mechanical and thermal properties [24], ultimately improving the habitability conditions for its occupants [25].

In the Peruvian highlands, low temperatures, especially at night, make rural homes lack thermal comfort indoors [15]. Therefore, it is necessary to develop better dosed building materials [5,16] Adobe constructions are an economical alternative to the rising costs of industrialized construction materials [17].

Additionally, this area of the highlands experiences high solar radiation throughout the year [18], which can be used as a heat source to achieve thermal comfort in homes [19]. One advantage of well-dosed adobe walls is that they absorb heat during the day and release it gradually at night, allowing for energy savings and achieving desirable thermal comfort with less temperature fluctuation inside the house [20]. In this way, the thermal inertia of the house dampens the influence of the outside temperature on the interior thermal conditions [7].

To make adobe, a study of the textural class must be conducted beforehand to define the physical characteristics of the soil [21], in order to determine an adequate mix of clay, silt, and sand. The addition of chilligua could improve compression strength [14], as long as the sand and silt are stabilized [22]. In fact, chilligua contributes to compression strength [23], as the biocomposites made from the mixture of clay and sand, with the addition of chilligua, increase both mechanical and thermal properties [24], contributing to improving the habitability conditions of occupants [25].

In the adobe-making process, chilligua is used as an input to improve thermal conductivity and compression strength [20,23,26]. However, excessive use of chilligua can reduce compression strength and the weight of the adobe [14,24]. The use of soil mixture with chilligua has generated interest due to its thermal properties for heat storage and temperature regulation [9].

Furthermore, adobes with clay and chilligua mortars contribute to improving the mechanical strength of walls [13], both in tension and simple compression [27]. On the other hand, non-stabilized adobes have lower compression strength than required by structural standards [28]. Therefore, it is important to establish appropriate dosages of clay, silt, sand, and chilligua to achieve the desired compression strength [29].

Another input used in adobe-making is domestic animal manure, such as that of llamas, cows, and sheep, which could improve energy efficiency due to its high organic matter content [30, 31].

In particular, sheep manure stands out for improving thermal inertia and promoting environmental sustainability [32]. It is important to improve the thermal comfort and energy efficiency of buildings. To achieve this, it is recommended to use an appropriate dosage of adobe as a biocomposite material [33]. Adobe is a material with lower thermal conductivity [34], which allows for comfortable rooms at night [35]. This is because adobe has the ability to store heat during the day [11]. In addition, adobe constructions offer greater thermal stability [36], which helps mitigate low temperatures [37] and cushion the drop in outdoor temperature [9].

In particular, sheep manure stands out for improving thermal inertia and promoting environmental sustainability [32]. It is a priority to carry out studies on the mechanical and thermal properties of adobe wall construction materials through testing [38, 39]. It is necessary to understand the influence of inputs on the thermal properties of adobe [40]. Simple compression tests define the mechanical strength [41], and thermal conductivity tests determine the heat transfer capacity [42, 43]. Therefore, the objective of this study is to determine the mechanical strength and thermal conductivity of adobe in extreme minimum climatic conditions. The purpose is to achieve two physical functions: greater compression strength and lower thermal conductivity for the construction of rural housing walls in the Peruvian highlands.

2. MATERIALS AND METHODS

2.1. Assessment of Soil Texture Class of Soil Mixture

Firstly, it is important to study the soil texture class composition to make adobe. In the Peruvian highlands, soil materials are available. For this study, a soil sample was obtained in February 2020 from the community of Llachón, Capachica, Puno (15º43'5" S and 69º47'28" W). To determine the texture class using the Bouyoucos method (1962), soil samples were dried in an oven at a temperature of 105°C to remove moisture. They were then crushed and sieved through a 2 mm sieve. 50 grams of the sample were used to perform a chemical dispersion with sodium hexametaphosphate and distilled water in a beaker. An electric mixer was used for soil dispersion (Figure.**1a**).

Subsequently, the suspension was placed in a one-liter graduated cylinder, leveled with the aid of a pipette, and manually agitated for 5 to 10 seconds before introducing the hydrometer for reading (Figure.**1b**). The temperature and density of the sedimentation solution of the sample were recorded at forty seconds and two hours established by the Bouyoucos hydrometer method [44]. Then, the necessary calculations were performed to determine the different fractions of sand, silt, and clay, allowing for the determination of the texture class using the United States Department of Agriculture (USDA) soil classification triangle.

Figure 1. (a) Electric Mixer, (b) Soil Texture Class Test.

2.2. Mix Design for Adobe Manufacturing

Once the soil texture class was defined, experimentation was carried out. The objective was to create 58 mixtures with different proportions to achieve the optimal mixture with higher compression strength and lower thermal conductivity. To achieve this, inputs were considered in different percentages: mixture of clayey soil, sand, sheep manure, and chilligua (*Festuca dolichophylla*). The dosing was done independently, and water was added for kneading until reaching a plastic state. Finally, circular specimens of 15x10 cm and adobes in rectangular molds of 30x40x10 cm were made (Figure **2**).

Figure 2. Samples of Rectangular Adobes with Different Combinations of Clay, Sand, Sheep Dung, and Chilligua.

2.3. Measurement of Mechanical Strength and Thermal Conductivity

In the Soil and Concrete Materials Technology laboratory of the Faculty of Agricultural Engineering at the National University of the Altiplano-Puno, tests were conducted to determine the resistance to simple compression and thermal conductivity. Standardized mechanical strength tests were carried out on 58 circular specimens measuring 15x10 cm, which had been air-dried for 28 days. A digital hydraulic press manufactured by RICELI, based on Pascal's principle (Figure **3**), was used for this purpose. The determination of compressive strength was achieved by applying an axial load until the circular specimen broke. Finally, compressive strength was calculated by dividing the maximum load reached during the test by the contact section area.

Figure 3. Hydraulic press for compressive strength testing**.**

On the other hand, the measurement of the heat transmission capacity of the rectangular adobes with dimensions of 30x40x10 cm was carried out. For this purpose, a thermal conductivity measuring equipment for construction materials patented by the National University of the Altiplano was used, which is registered as a utility model in the Directorate of Inventions and New Technologies of the National Institute for the Defense of Competition and Protection of Intellectual Property, with Directorial Resolution No. 000716-2022/DIN-INDECOPI (Figure **4**). This meter features sensors for temperature reading, which have an accuracy of +/- 0.5°C and a measurement range of -40°C to 125°C. Once the readings were taken, they were converted to ºK. Finally, to determine thermal conductivity (k), the Fourier's Law equation (Equation **1**) was applied.

$$\frac{\Delta Q}{\Delta t} = \frac{ks(T_2 - T_1)}{x} \quad (1)$$

ΔQ : Heat transfer (W)

Δt : Measurement time (h)

K : Thermal conductivity (W/m·ºK)

S : Sample area of adobe in contact with the container (m^2)

T_2 : Temperature on the outer surface of the container (ºK)

T_1 : Temperature on the surface of the adobe sample (ºK)

X : Thickness of the adobe sample (m)

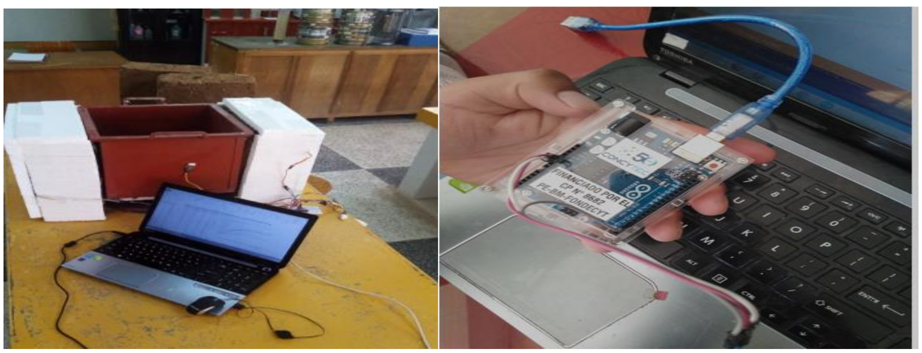

Figure 4. Thermal Conductivity Meter for Building Materials.

Estimation of the polynomial regression function and determination of the optimal adobe, after determining the mechanical strength and thermal conductivity, the polynomial regression was estimated, considering the dependent variable as the relationship between compressive strength (R*i*) and thermal conductivity (k*i*) of adobe "*i*", that is:

$$Y_i = \frac{R_i}{k_i} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_1^2 + \beta_6 X_2^2 + \beta_7 X_3^2 + \beta_8 X_4^2 + \beta_9 X_1 X_2 + \beta_{10} X_1 X_3 + \beta_{11} X_1 X_4 + \beta_{12} X_2 X_3 + \beta_{13} X_2 X_4 + \beta_{14} X_3 X_4 + \varepsilon_i$$

Where i is the number of inputs (X_i), that is: clay soil (X_1), sand (X_2), sheep manure (X_3), and chilligua (X_4), β are the coefficients of the model; ε_i is the random disturbance that is distributed as a normal function with zero mean and unit variance, the model was estimated using the ordinary least squares estimation technique. After estimating the coefficients of the model, the polynomial function was maximized by applying the first-order conditions, and solving the equations yields the following expression:

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} 2\beta_5 & \beta_9 & \beta_{10} & \beta_{11} \\ \beta_9 & 2\beta_6 & \beta_{12} & \beta_{13} \\ \beta_{10} & \beta_{12} & 2\beta_7 & \beta_{14} \\ \beta_{11} & \beta_{13} & \beta_{14} & 2\beta_8 \end{bmatrix}^{-1} \begin{bmatrix} -\beta_1 \\ -\beta_2 \\ -\beta_3 \\ -\beta_4 \end{bmatrix}$$

Where: X_1 = clay soil; X_2 = sand; X_3 = sheep manure; X_4=chilligua (*Festuca dolichophylla*).

3. RESULTS AND DISCUSSION

3.1. Textural Composition Of Clay Soil Mixture

The results of the soil textural composition revealed the following proportions: 5.75 ± 3.54% sand, 6.41 ± 5.38% silt, and 87.84 ± 8.62% clay, which classifies it as a clayey soil texture. These values are similar to those obtained by. Calatan *et al.* who used a soil with a sandy clay content of 97% for adobe production [26]. On the other hand, Vasić *et al.* recommend a clay content between 20.4% and 40.6% [21]; however, clays with high organic matter content are not suitable for construction [45].

3.2. Resultados De La Medición De Resistencia a La Compresión Y Conductividad Térmica

In Table **1**, the results of the mechanical compressive strength tests in kg/cm^2 and thermal conductivity tests in W/m-°K of rectangular adobe blocks are presented. The report on the relationship between the mechanical compressive strength (R*i*) and thermal conductivity (k*i*) is also included.

Table 1. Compressive strength and thermal conductivity of adobe at different dosages.

Nº of mixture	Essays with different input compositions (% by weight)				Measurement results			Nº of mixture	Essays with different input compositions (% by weight)				Measurement results		
	X_1 Clay soil	X_2 Sand	X_3 Sheep manure	X_4 chilligua (*Festuca dolichophylla*)	R_i Compressive strength (kg/cm^2)	k_i Thermal conductivity (W/m·ºK)	Ratio= $Y_i = \frac{R_i}{k_i}$		X_1 Clay soil	X_2 Sand	X_3 Sheep manure	X_4 chilligua (*Festuca dolichophylla*)	R_i Compressive strength (kg/cm^2)	k_i Thermal conductivity (W/m·ºK)	Ratio= $Y_i = \frac{R_i}{k_i}$
1	92.50	1.00	6.00	0.50	11.00	0.40	27.50	30	81.00	8.40	7.44	3.25	23.50	0.70	33.57
2	92.50	1.20	5.60	0.75	11.20	0.42	26.99	31	80.70	8.50	7.50	3.35	23.80	0.71	33.52
3	91.80	1.50	6.10	0.77	13.10	0.43	30.59	32	80.00	8.70	7.52	3.78	23.70	0.72	33.15
4	91.00	1.73	6.20	1.10	13.84	0.46	30.38	33	79.65	9.00	7.60	3.75	23.90	0.72	33.19
5	91.10	2.00	6.20	0.70	14.47	0.48	30.00	34	79.00	9.30	7.62	4.08	22.00	0.69	32.12
6	91.00	2.05	6.10	1.70	13.98	0.50	28.17	35	78.65	9.50	7.70	4.15	21.00	0.64	32.81
7	90.40	2.50	6.30	0.80	13.49	0.51	26.44	36	78.10	9.70	7.70	4.50	20.00	0.62	32.26
8	89.90	2.75	6.40	1.00	13.98	0.52	26.88	37	77.75	10.00	7.80	4.45	19.00	0.63	30.16
9	89.70	3.00	6.40	0.90	14.47	0.53	27.31	38	77.00	10.30	7.82	4.90	18.00	0.59	30.77
10	89.00	3.30	6.50	1.20	14.97	0.51	29.37	39	76.65	10.50	7.90	4.95	17.00	0.54	31.48
11	89.00	3.50	6.50	1.00	15.46	0.49	31.61	40	76.00	10.79	8.00	5.20	16.00	0.53	30.19
12	89.80	3.65	6.60	0.70	15.84	0.53	29.99	41	75.65	11.00	8.20	5.25	15.00	0.52	28.85
13	88.30	4.00	6.60	1.10	16.23	0.57	28.59	42	74.80	11.30	8.01	5.80	14.00	0.49	28.63
14	87.95	4.20	6.60	1.25	17.16	0.56	30.76	43	74.45	11.50	8.10	5.95	13.50	0.46	29.49
15	87.60	4.50	6.70	1.20	18.09	0.55	33.00	44	74.10	11.70	8.08	6.12	12.80	0.44	29.09
16	87.10	4.60	6.80	1.50	18.01	0.54	33.44	45	73.75	11.90	8.20	6.20	12.50	0.43	29.07
17	86.90	5.00	6.80	1.30	17.93	0.53	33.90	46	72.50	12.30	8.30	6.80	11.70	0.42	27.86
18	86.50	5.45	6.89	1.20	18.40	0.55	33.74	47	72.50	12.50	8.40	6.90	11.25	0.41	27.44
19	86.20	5.50	6.90	1.40	19.30	0.57	33.85	48	72.00	12.80	8.32	6.90	10.80	0.41	26.67
20	86.00	5.70	6.93	1.37	19.25	0.57	33.85	49	71.65	13.00	8.40	6.95	10.40	0.40	26.13
21	85.50	6.00	7.00	1.50	19.20	0.58	33.37	50	70.18	13.30	8.70	7.30	10.00	0.39	25.97
22	85.10	6.30	7.15	1.60	19.41	0.58	33.47	51	69.83	13.50	8.50	8.17	9.80	0.38	25.79
23	84.75	6.50	7.10	1.65	19.63	0.59	33.26	52	69.70	14.00	8.70	8.25	9.20	0.37	24.86
24	84.00	6.70	7.15	2.15	19.80	0.62	32.08	53	68.90	14.20	8.60	8.30	8.90	0.37	24.05
25	83.65	7.00	7.20	2.15	20.00	0.64	31.05	54	68.50	14.40	8.68	8.55	8.60	0.35	24.57
26	83.00	7.35	7.15	2.50	21.30	0.65	32.77	55	68.00	14.60	8.70	8.90	8.10	0.33	24.92
27	82.65	7.50	7.30	2.55	21.90	0.66	33.18	56	67.97	14.70	8.73	9.00	8.00	0.31	25.60
28	82.00	7.70	7.30	3.00	22.00	0.68	32.35	57	67.20	14.90	8.80	9.15	7.50	0.31	24.59
29	81.65	8.00	7.40	2.95	22.40	0.69	32.46	58	67.00	15.00	9.00	9.25	7.00	0.30	23.35

According to the initial results, it is reported that mixtures containing a higher percentage of chilligua and sand improve the mechanical strength up to a certain proportion. It is also observed that as the percentage of clay soil and chilligua increases, the heat storage capacity improves (Figure **6**). These results partly coincide with the study of Calatan *et al.* who found that adding chilligua to clay soil adobes improves their strength and heat storage capacity [26]. It is important to highlight that houses built with adobe are usually cool during the day and warm at night [35], making them a good option for the high solar radiation areas of the Peruvian altiplano (between 4.70 and 7.78 kW/hour·m^2 according to Yancachajlla *et al.* [18]) and extreme minimum temperatures below zero during the months of May to August [46].

The measured adobes presented different levels of compressive strength and thermal conductivity, suggesting that walls can be constructed to regulate indoor thermal comfort based on external climate conditions. Similar studies conducted by Balaji *et al.* found similar results, although they did not apply optimization models [5]. In addition, the appropriate use of adobe in wall construction increases the comfort and energy efficiency of homes as a biocomposite material [33,47] and contributes to sustainable development due to its low embodied energy and hygrothermal behavior [48].

It is reported that the signs of the coefficients of the polynomial regression were as expected and that the coefficient of determination of the model is good, explaining 87.88% of the variation in the dependent variable through the independent variables (inputs). Furthermore, applying the F-test, the estimated coefficients jointly were statistically significant at a significance level of 1% (Table **2**).

Table 2. Results of the Polynomial Regression Estimation.

Variables	**Coeficiente** (β_S)	**EE** (β)	**T**
X_1	963.448	910.03	1.06
X_2	3.151	788.68	0.004
X_3	4419.307	2.902.98	1.52
X_4	1332.294	987.40	1.35
X_1^2	-3.845	4.13	-0.93
X_2^2	6.403	5.21	1.23
X_3^2	-42.281	39.05	-1.08
X_4^2	-6.417	5.26	-1.22
X_1X_2	1.940	7.60	0.26
X_1X_3	-41.703	27.47	-1.52
X_1X_4	-11.569	8.98	-1.29
X_2X_3	-32.604	27.46	-1.19
X_2X_4	-4.353	6.79	-0.64
X_3X_4	-41.687	27.60	-1.51
_const	-58035.43	50043.35	-1.16
R^2	0.8788		
F(14.43)	22.27		
Probability	0.0		
N	58		

3.3. Optimal Adobe Dosage Determination

Replacing the values of the obtained βs in the polynomial regression, the optimal adobe dosage was obtained with the combination of inputs in the following proportions: 83.0% clayey soil, 7.1% sand, 7.5% sheep manure, and 2.4% chilligua. This mixture generates a greater mechanical compression resistance and a lower thermal conductivity, that is, 31.85 kg/cm^2 of mechanical compression resistance per unit of thermal conductivity in W/m·°K within its properties

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} -7.69 & 1.94 & -41.70 & -11.57 \\ 1.94 & 12.81 & -32.60 & -4.35 \\ -41.70 & -32.60 & -84.56 & -41.69 \\ -11.57 & -4.35 & -41.69 & -12.83 \end{bmatrix}^{-1} \begin{bmatrix} -963.448 \\ -3.151 \\ -4419.31 \\ -1332.29 \end{bmatrix} = \begin{bmatrix} 83.0 \\ 7.1 \\ 7.5 \\ 2.4 \end{bmatrix}$$

Figure **5,** shows the relationship between mechanical compressive strength in kg/cm^2 per unit of thermal conductivity in W/m·°K and each input, whose behavior is nonlinear. An excessive increase in any of the inputs could decrease the mechanical strength and increase the thermal conductivity of the adobe.

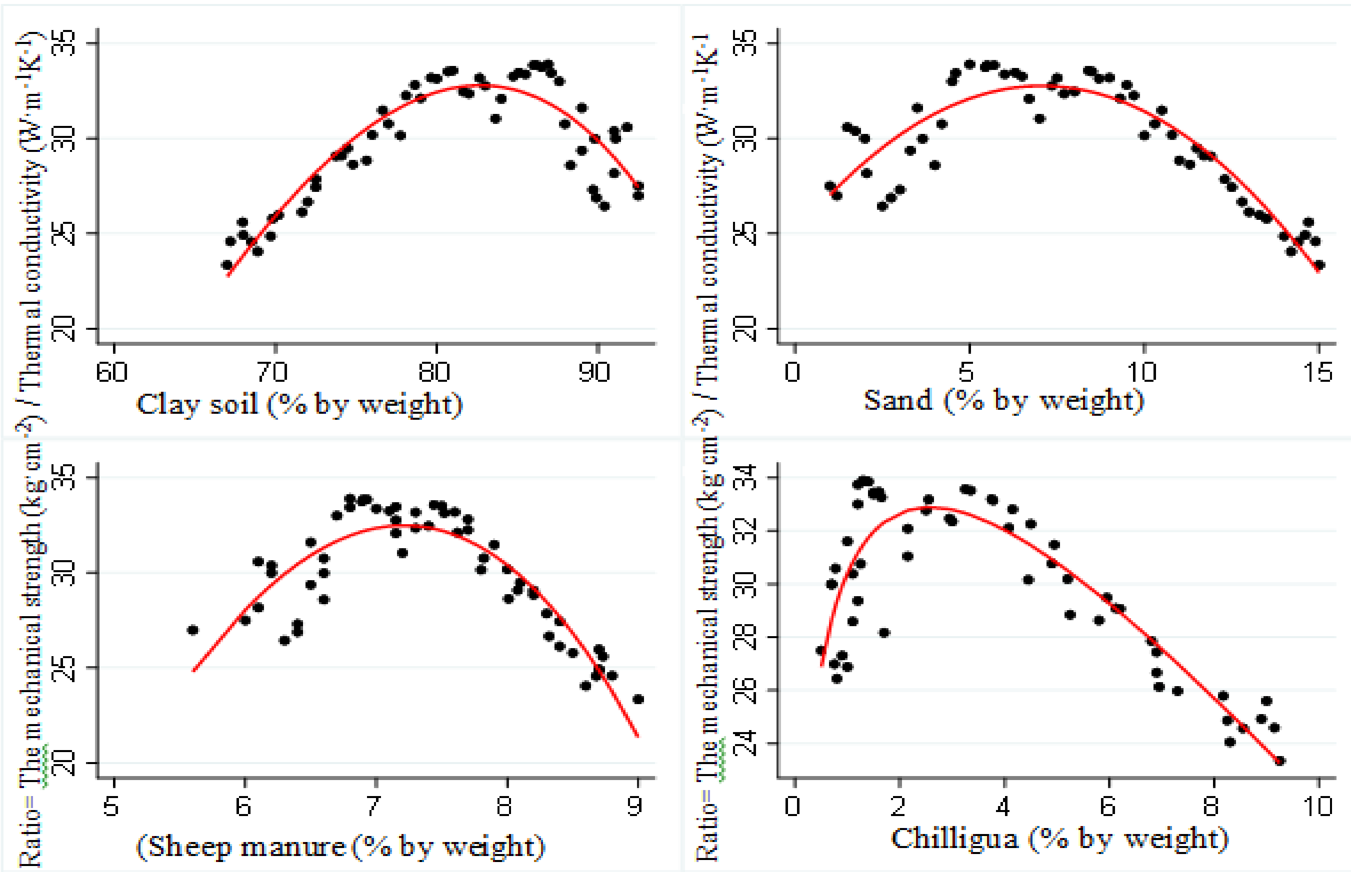

Figure 5. Behaviour of the Relationship between Compressive Strength in Kg/Cm^2 per Unit of Thermal Conductivity in W/M·°K.

The optimal dosing of inputs for the production of adobe, expressed as a percentage of weight, is as follows: 83.0% clayey soil, 7.1% sand, 7.5% sheep manure, and 2.4% chilligua. This mixture achieves a maximum compressive strength of 31.85 kg/cm^2 per unit of thermal conductivity. However, it is important to note that if the inputs are not properly dosed, the resulting adobes may be vulnerable to extreme natural events, such as earthquakes, which can cause serious damage or even the collapse of structures [4].

On the other hand, it has been found that adobes reinforced with natural fibers and mud mortar have good mechanical behavior in masonry walls [19,49]. The addition of fibrous materials, as well as an adequate proportion of clay and sand in the clayey soil, allows reducing the formation of cracks and improving compressive strength, significantly reducing the degree of cracking due to contraction [9,49].

Likewise, it has been found that adobes containing a mixture of clay and straw contribute to thermal comfort, as they store heat during the day to release it at night, thanks to their thermal properties as an insulating material [9].

In particular, the addition of chilligua at a percentage of 2.4% not only generates the required thermal comfort but also the highest compressive strength, reducing the probability of cracks and reducing the risk of collapse of housing. These results are consistent with the study by Sharma *et al*. which indicates that adding fiber in a proportion of 0.5 to 2.0% shows an increase in soil compressive strength [8], thus providing greater safety in homes built with a mixture of clayey soil and fibers [50]. Additionally, another study by Ige and Danso recommends including chilligua in a proportion of between 0.5 and 0.75% in adobe production [17]. Indeed, the use of natural fibers is important in the construction of housing walls [40].

In this study, it was found that the optimal dosing of inputs allows for achieving a compressive strength of 31.85 kg/cm^2 per unit of thermal conductivity in W/m·ºK. The incorporation of chilligua in the dosing of reinforced adobes significantly improves their compressive strength, avoiding cracks and increasing strength by 43.34% and 79.10%, respectively [3]. In addition, the amount of clay present in the adobes shows a positive correlation with compressive strength [45], while the inclusion of natural fibers in the mixture further increases this strength, reaching values over 23.45 kg/cm^2 during experiments with adobes exposed to the outdoors for 28 days [51].

The results of various studies confirm that the use of chilligua in adobe production allows for an increase in compressive strength, which contributes to improving the thermal insulation of buildings [52] and offers the real possibility of improving both their mechanical and thermal properties [53]. Therefore, establishing the appropriate dosing of clay soil, sand, sheep manure, and chilligua to achieve adobes with greater compressive strength and low thermal conductivity is essential to ensure the safety and thermal well-being of occupants in homes.

4. CONCLUSIONS

In the case study, the optimal dosage of adobe was determined through the combination of the following inputs by weight percentage: 83.0% of clayey soil mix, 7.1% of sand, 7.5% of sheep manure, and 2.4% of chilligua. With this composition, a higher compressive strength of 31.85 kg/cm^2 per unit of thermal conductivity in W/m·°K was achieved. The recommended optimal dosage provides greater safety against seismic risks and, inside the housing, offers greater thermal comfort in low temperatures due to its higher thermal inertia

5. ACKNOWLEDGEMENT

The authors acknowledge the financial support from the Concytec - World Bank project, "Improvement and Expansion of the Services of the National System of Science, Technology and Technological Innovation" 8682-PE, through its executing unit Fondecyt [Contract number 120-2018-FONDECYT-BM-IADT-MU]

REFERENCES

[1] Varum H, Costa A, Fonseca J, Furtado A. Behaviour characterization and rehabilitation of adobe construction. Procedia Engineering 2015; 114: 714–21. https://doi.org/10.1016/j.proeng.2015.08.015

[2] Hema CM, Moeseke GV, Evrad A, Courard L, Messan A. Vernacular housing practices in Burkina Faso: representative models of construction in Ouagadougou and walls hygrothermal efficiency Energy Procedia 2017;122:535–40. https://doi.org/10.1016/j.egypro.2017.07.398

[3] Zhang JF, Pang SY, Gao JW, Deng EF, Wang H, Zhao JJ, Zhang JF. Experimental study on seismic behaviour of adobe wall reinforced with cold–formed thin–walled steel. Thin-Walled Structures 2020;147: 106493. https://doi.org/10.1016/j.tws.2019.106493

[4] Abdulla KF, Cunningham LS, Gillie M. Out-of-plane strengthening of adobe masonry using hemp fibre ropes: An experimental investigation. *Engineering Structures*, 2021;245:112931. https://doi.org/10.1016/j.engstruct.2021.112931

[5] Balaji NC, Mani M, Venkatarama BV. Discerning heat transfer in building materials. Energy Procedia 2014;54:654–668. https://doi.org/10.1016/j.egypro.2014.07.307

[6] Daudon D, Sieffert Y, Albarracín O, Garino L, Navarta G.. Adobe construction modeling by discrete element method: first methodological steps. Procedia Economics and Finance. 2014;18:247–254. https://doi.org/10.1016/s2212-5671(14)00937-x

[7] Rincón L, Carrobé A, Martorell I, Medrano M. Improving thermal comfort of earthen dwellings in sub-Saharan Africa with passive design. Journal of Building Engineering 2019;24:1–11. https://doi.org/ 10.1016/j.jobe.2019.100732

[8] Sharma V, Vinayak HK, Marwaha BM. Enhancing sustainability of rural adobe houses of hills by addition of vernacular fiber reinforcement. International Journal of Sustainable Built Environment 2015;4(2):348–58. https://doi.org/10.1016/j.ijsbe.2015.07.002

[9] El Azhary K, Chihab Y, Mansour M, Laaroussi N, Garoum M.. Energy efficiency and thermal properties of the composite material clay-straw. Energy Procedia 2017;141:160–64. https://doi.org/10.1016/j.egypro.2017.11.030

[10] Türkmen İ, Ekinci E, Kantarcı F, Sarıcı T. The mechanical and physical properties of unfired earth bricks stabilized with gypsum and Elazığ Ferrochrome slag. International Journal of Sustainable Built Environment 2017;6(2):565–73. https://doi.org/10.1016/j.ijsbe.2017.12.003

[11] Widder L.. Earth eco-building: Textile-reinforced earth block construction. Energy Procedia 2017;122:757–62. https://doi.org/10.1016/j.egypro.2017.07.392

[12] Sharma V, Marwaha BM, Vinayak HK.. Enhancing durability of adobe by natural reinforcement for propagating sustainable mud housing. International Journal of Sustainable Built Environment 2016;5(1):141–55. https://doi.org/10.1016/j.ijsbe.2016.03.004

[13] Meybodian H, Eslami A, Morshed R. Sustainable lateral strengthening of traditional adobe walls using natural reinforcements. Construction and Building Materials 2020;260:119892. https://doi.org/10.1016/j.conbuildmat.2020.119892

[14] Bertelsen IMG, Belmonte LJ, Fischer G, Ottosen LM. Influence of synthetic waste fibres on drying shrinkage cracking and mechanical properties of adobe materials. Construction and Building Materials 2021;286:122738. https://doi.org/10.1016/j.conbuildmat.2021.122738

[15] Canales Á, Belizario G, Calatayud AP, Chui HN, Huaquisto E. Thermal comfort and the risk of respiratory infections in older adults in the Peruvian highlands. *Revista* Espanola de Geriatria y Gerontologia 2021;56(1):24–28. https://doi.org/10.1016/j.regg.2020.07.007

[16] Ravindra K, Agarwal N, Kaur-Sidhu M, Mor S. Appraisal of thermal comfort in rural household kitchens of Punjab, India and adaptation strategies for better health. Environment International 2019;124:431–40. https://doi.org/10.1016/j.envint.2018.12.059

[17] Kulshreshtha Y, Mota NJA, Jagadish KS, Bredenoord J, Vardon PJ, Van Loosdrecht MCM, Jonkers HM. The potential and current status of earthen material for low-cost housing in rural India. Construction and Building Materials 2020;247:118615. https://doi.org/10.1016/j.conbuildmat.2020.118615

[18] Yancachajlla U, Vilca-Huayta OA, Borja-Borja MG, Belizario-Quispe G. 2021. Optimization of a Wind-Photovoltaic Hybrid System for a Rural Housing Isolated from The Network in The District of Paucarcolla - Perú. in 2021 IEEE XXVIII International Conference on Electronics, Electrical Engineering and Computing (INTERCON). IEEE, 1–4. https://doi.org/10.1109/INTERCON52678.2021.9533024

[19] Evola G, Marletta L, Natarajan S, Patane EM. Thermal inertia of heavyweight traditional buildings: experimental measurements and simulated scenarios. Energy Procedia 2017;133:42–52. https://doi.org/10.1016/j.egypro.2017.09.369

[20] Chaussinand A, Scartezzini JL, Nik V. Straw bale: A waste from agriculture, a new construction material for sustainable buildings. Energy Procedia 2015;78:297–302. https://doi.org/10.1016/j.egypro.2015.11.646

[21] Vasić MV, Pezo LL, Radojević Z.. Optimization of adobe clay bricks based on the raw material properties (mathematical analysis). Construction and Building Materials 2020:244. https://doi.org/10.1016/j.conbuildmat.2020.118342

[22] Mellaikhafi A, Tilioua A, Souli H, Garoum M, Alaoui MA. Characterization of different earthen construction materials in oasis of south-eastern Morocco (Errachidia Province). Case Studies in Construction Materials 2021;14:e00496. https://doi.org/10.1016/j.cscm.2021.e00496

[23] Serrano S, Barreneche C, Cabeza LF. Use of by-products as additives in adobe bricks: Mechanical properties characterisation. Construction and Building Materials 2016;108:105–11. https://doi.org/10.1016/j.conbuildmat.2016.01.044

[24] Ajouguim S, Talibi S, Djelal-Dantec C, Hajjou H, Waqif M, Stefanidou M, Saadi L. Effect of Alfa fibers on the mechanical and thermal properties of compacted earth bricks. Materials Today: Proceedings 2019;37:4049–57. https://doi.org/10.1016/j.matpr.2020.07.539

[25] Zhang Z, Zhang Y, Ling J.Thermal comfort in interior and semi-open spaces of rural folk houses in hot-humid areas. Building and Environment 2018;128:336–47. https://doi.org/10.1016/j.buildenv.2017.10.028

[26] Calatan G, Hegyi A, Dico C, Mircea C. Determining the optimum addition of vegetable materials in adobe bricks. Procedia Technology 2016;.22:259–65. https://doi.org/10.1016/j.protcy.2016.01.077

[27] Ige O, Danso H. Physico-mechanical and thermal gravimetric analysis of adobe masonry units reinforced with plantain pseudo-stem fibres for sustainable construction. Construction and Building Materials 2021;273:121686. https://doi.org/10.1016/j.conbuildmat.2020.121686

[28] Cárdenas-Haro X, Todisco L, León J. Database with compression and bending tests on unbaked earth specimens and comparisons with international code provisions. Construction and Building Materials 2021;276:122232. https://doi.org/10.1016/j.conbuildmat.2020.122232

[29] Calatan G, Hegyi A, Dico C, Szilagyi H. Opportunities regarding the use of adobe-bricks within contemporary architecture. Procedia Manufacturing 2020;46;150–57. https://doi.org/10.1016/j.promfg.2020.03.023

[30] Macphail RI, Bill J, Crowther J, Haită C, Linderholm J, Popovici D, Rødsrud CL. European ancient settlements – A guide to their composition and morphology based on soil micromorphology and associated geoarchaeological techniques; introducing the contrasting sites of Chalcolithic Borduşani-Popină, Borcea River, Romania and Viking Age. Quaternary International 2017;460:30–47. https://doi.org/10.1016/j.quaint.2016.08.049

[31] Martí-Herrero J, Alvarez R, Cespedes R, Rojas MR, Conde V, Aliaga L, Balboa M, Danov S. Cow, sheep and llama manure at psychrophilic anaerobic co-digestion with low cost tubular digesters in cold climate and high altitude. Bioresource Technology 2015;181:238–46. https://doi.org/10.1016/j.biortech.2015.01.063

[32] Amorim AC, Watte A, Toesca RM, Souza SV, Previdelli MA, Maciel T, Aspilcueta RR, Miranda F. Can adding liquid hatchery waste to sheep manure potentialize methane production and add value to sheep farming?. Environmental Technology & Innovation 2021;24:101866. https://doi.org/10.1016/j.eti.2021.101866

[33] Abanto GA, Karkri M, Lefebvre G, Horn M, Solis JL, Gómez MM. Thermal properties of adobe employed in Peruvian rural areas: Experimental results and numerical simulation of a traditional bio-composite material. Case Studies in Construction Materials 2017;6:177–91. https://doi.org/10.1016/j.cscm.2017.02.001

[34] El Wardi FZ, Cherki A, Mounir S, Khabbazi A, Maaloufa Y. Thermal characterization of a new multilayer building material based on clay, cork and cement mortar. Energy Procedia 2019;157:480–91. https://doi.org/10.1016/j.egypro.2018.11.212

[35] Coffman CV, Duffin RJ, Knowles GP. Are adobe walls optimal phase-shift filters? Advances in Applied Mathematics 1980;1:50–66. https://doi.org/10.1016/0196-8858(80)90006-8

[36] Miño-Rodríguez I, Naranjo-Mendoza C, Korolija I. Thermal assessment of low-cost rural housing-a case study in the ecuadorian andes. Buildings 2016;6(3):1–11. https://doi.org/10.3390/buildings6030036

[37] Gupta J, Chakraborty M, Rallapalli HS, Nivedhitha R. Climate-Responsive architecture in rural vernacular dwellings: A study in composite climate in ranchi, Jharkhand, India. AEGAEUM Journal 2020;8(7):1710–34. Available at: http://aegaeum.com/ Page No:1711.

[38] Bayode O, Daisiowa YM. Review of economic and environmental bene fi ts of earthen materials for housing in Africa. Frontiers of Architectural Research 201;76(4):519–28. https://doi.org/10.1016/j.foar.2017.08.003

[39] Cividini A. Geomechanical characterization of some adobe materials. Structural Integrity Procedia 2017;5:1072–77. https://doi.org/10.1016/j.prostr.2017.07.079

[40] Ramakrishnan S, Loganayagan S, Kowshika G, Ramprakash C, Aruneshwaran M. (2020). Adobe blocks reinforced with natural fibres: A review. Materials Today: Proceedings 2020;45:6493–99. https://doi.org/10.1016/j.matpr.2020.11.377

[41] Silveira D, Varum H, Costa A, Martins T, Pereira H, Almeida J. Mechanical properties of adobe bricks in ancient constructions. Construction and Building Materials 2012;28(1):36–44. https://doi.org/10.1016/j.conbuildmat.2011.08.046

[42] Baccoli R, Di Pilla L, Frattolillo A, Mastino CC. An adaptive neural network model for thermal characterization of building components. Energy Procedia 2017;140:374–85. https://doi.org/10.1016/j.egypro.2017.11.150

[43] Rasooli A, Itard L. In-situ rapid determination of walls' thermal conductivity, volumetric heat capacity, and thermal resistance, using response factors. Applied Energy 2019;253:1–17. https://doi.org/10.1016/j.apenergy.2019.113539

[44] Gama-Castro JE, Cruz T, Pi-Puig T, Alcalá-Martínez R, Cabadas-Báez H, Jasso-Castañeda C, Díaz-Ortega J, Sánchez-Pérez S, López-Aguilar F, Vilanova de Allende R. Arquitectura de tierra: el adobe como material de construcción en la época prehispánica. Boletín de la Sociedad Geológica Mexicana 2012;64(2):177–88. Available at: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-3322

[45] Meimaroglou N, Mouzakis C. Cation Exchange Capacity (CEC), texture, consistency and organic matter in soil assessment for earth construction: The case of earth mortars. Construction and Building Materials 2019;221:27–39. https://doi.org/10.1016/j.conbuildmat.2019.06.036

[46] Arnold TE, Hillman AL, McGrath SJ, Abbott MB, Werne JP, Hutchings J, Arkush EN. Fecal stanol ratios indicate shifts in camelid pastoralism in the highlands of Peru across a 4,000-year lacustrine sequence. Quaternary Science Reviews 2021;270:107193. https://doi.org/10.1016/j.quascirev.2021.107193

[47] Horn M, Solis JL. Thermal properties of adobe employed in Peruvian rural areas: experimental results and numerical simulation of a traditional bio-composite material. Case Studies in Construction Materials. 2017.https://doi.org/10.1016/j.cscm.2017.02.001

[48] Bui QB, Morel JC, Tran VH, Hans S, Oggero M. How to use in-situ soils as building materials. Procedia Engineering 2016;145:1119–26. https://doi.org/10.1016/j.proeng.2016.04.145

[49] Li-Piani T, Weerheijm J, Peroni M, Koene L, Krabbenborg D, Solomos G, Sluys LJ. Dynamic behaviour of adobe bricks in compression: The role of fibres and water content at various loading rates. Construction and Building Materials 2020;230:117038. https://doi.org/10.1016/j.conbuildmat.2019.117038

[50] Widera B. Comparative analysis of user comfort and thermal performance of six types of vernacular dwellings as the first step towards climate resilient, sustainable and bioclimatic architecture in western sub-Saharan Africa. Renewable and Sustainable Energy Reviews 2021;140:110736. https://doi.org/10.1016/j.rser.2021.110736

[51] Abid R, Kamoun N, Jamoussi F, El Feki H. Fabrication and properties of compressed earth brick from local Tunisian raw materials. Boletin de la Sociedad Espanola de Ceramica y Vidrio 2021;1–11. https://doi.org/10.1016/j.bsecv.2021.02.001

[52] Laborel-Préneron A, Aubert JE, Magniont C, Bertron A. Influence of straw content on the mechanical and thermal properties of bio-based earth composites. First International Conference on Bio-based Building Materials 2015;33:517–22. https://doi.org/10.26168/icbbm2015.80

[53] Laibi AB, Poullain P, Leklou N, Gomina M, Sohounhloué DKC. Influence of the kenaf fiber length on the mechanical and thermal properties of Compressed Earth Blocks (CEB). KSCE Journal of Civil Engineering 2018;22(2):785–93. https://doi.org/10.1007/s12205-017-1968-9

DOI: https://doi.org/10.15379/ijmst.v10i2.1291