

Influence of *Stipa ichu* on the thermal and mechanical properties of adobe as a biocomposite material

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Abstract. A millenary building material that has been used in many cultures is “adobe”. In the Peruvian Andean regions during the winter, the temperature decreases drastically (+5 to -15°C), affecting the health of people of vulnerable age, agriculture and bovine livestock. Bioclimatic techniques must be considered to provide a comfortable thermal environment in the interior of housing. Furthermore, knowing the thermal conductivity of the elements that compose the houses allows us to perform thermal exchange simulations before construction is developed. Specifically, in this investigation, the thermal conductivity of adobe with and without *Stipa ichu* was measured as 0.371 W/m K and 0.349 W/m K, respectively, considering the norm ASTM C177 for that purpose. The mechanical behavior is as important as the thermal properties, and a value of 2.41 N/mm² was obtained for unit compression. Additionally, scanning electron microscopy (SEM) images of adobe samples were evaluated to investigate the internal composition, and X-ray diffraction (XRD) was used to determine the type of clay present. According to these results, our adobe has favorable thermal and mechanical performance.

1. Introduction

In the highlands of Peru, especially in regions where temperatures decrease drastically, the principal wall construction material is adobe [1]. Adobe is a biocomposite material reinforced with discontinuous and aleatory fibers [2]. Additionally, it is one of the ancient materials used for construction, for example, in cities such as Chan Chan, located in Trujillo, Peru.

Adobe bricks are handmade from clay, silt and sand. A mass of crude earth is mixed with water and additives and finally dried in open air in the shade. There are four groups of additives: mineral, synthetic, vegetable and animal sources [3].

Good workability and plasticity are mandatory for well-made adobe bricks, in addition to enough water to promote the bond strength, which involves a complex hydration process between clay and water.

The present paper analyzes the thermal and mechanical properties of adobe bricks made in the laboratory; whose experimental measures were part of the topic of one undergrad thesis [4]. Calatan *et al.* studied and analyzed the thermal and mechanical properties of this material by varying the constituent vegetable fibers; as a result, for both properties, they determined an optimal straw addition in the range of 30-40% percentage by volume [5]. In this research, for the different sizes of adobe bricks prepared in the laboratory, 33% by volume of *S. ichu* was considered. *S. ichu* is a vegetal fiber.



In terms of thermal conductivity, the measurements were performed by a device called guarded hot plate apparatus (APCG-305) located in the Conductivity Laboratory at the National Center of Metrology (CENAM). This apparatus was constructed considering the norm ASTM C177 [6] and several experimental and theoretical studies concerning different aspects of the device, such as the study of edge effects, radial heat convection and radiation through the gap, thermal conductivity results due to the material used in the guard [7-12] and some previous master theses in the development of prototypes of this apparatus [13-15]. Furthermore, the APCG-305 has been evaluated in an international comparison among national laboratories, showing good agreement with the determined thermal conductivity values [16].

In terms of mechanical strength, adobe bricks lead to a frequent maintenance problem associated with rural house wall construction due to their very poor performance when subjected to seismic actions. In many cases, these houses must be repaired; in this way, certain properties were measured at the Laboratory of Material Essays of Civil Faculty, such as unity and pile compression and flexural essays.

To improve the durability and impermeability of adobe, a low percentage of cement (2-5% by weight) and vegetable fiber (1-2.5% by weight) have been considered in some international studies, such as the vegetable fibers of *Pinus roxburghii* and *Grewia optiva*, obtaining positive results [17].

Furthermore, X-ray diffraction (XRD) was performed to determine which type of clay is present in the soil used for the fabrication of adobe bricks. Finally, scanning electron microscopy (SEM) was used to understand the macroscopic internal structure of adobe.

2. Materials and Methods

In this section, the materials, as well as the methods used for the preparations of the bricks and their characterization, are presented.

2.1. Materials

First, it is necessary to characterize the soil used for the fabrication of adobe bricks according to ASTM norms for classification of soils. Then, the type of clay is determined, and finally, the process of fabrication of adobe will be presented.

The soil used in this investigation was taken for a quarry located in Lima, Peru. Atterberg's limits were obtained according to the norm ASTM D4318, and the physical properties of soil humidity were determined according to ASTM D2216, and the granulometry by sieving and hydrometric properties were made according to ASTM D422 [18]. These results are presented in table 1.

Table 1. Soil characteristics.

Property	Value
Classification ASTM D2216	CL
Specific gravity of soil, G	2.635
Liquid limit %	24.76
Plastic limit %	17.69
Plasticity index, PI	7.07
Water content %	3.13

The granulometry of the soil must first be measured to determine if it is necessary to modify the percentage of certain components. According to the Peruvian Technical Edification Standard of Adobe, the soil must contain between 10 and 20% of clay [19]. However, in this case, the percentage of clay in the soil is 9.33%, and the grain-size distribution of soil is presented in figure 1.

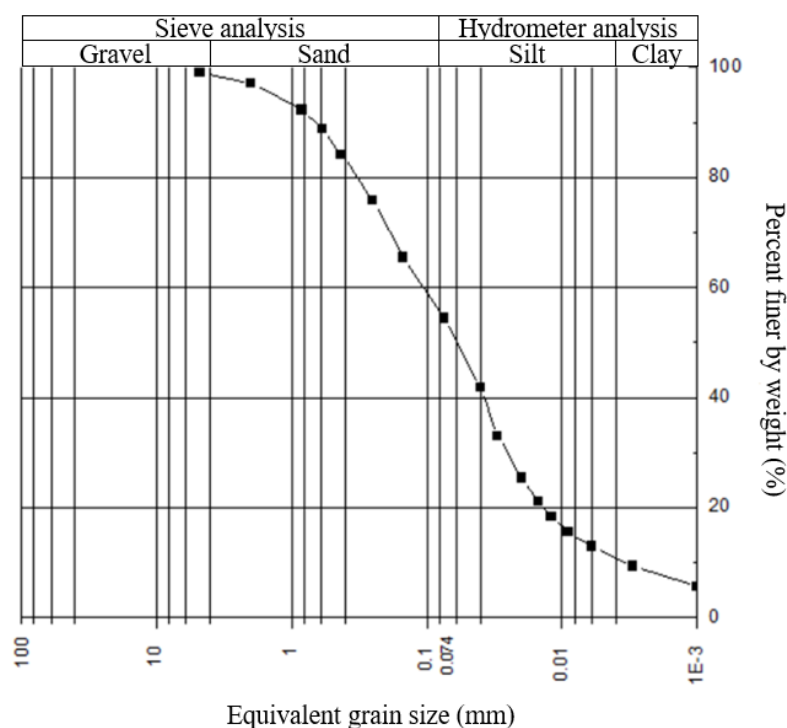


Figure 1. Grain-size distribution of soil.

2.2. Methods

In this section, the preparation, characterization methods used for determining the thermal conductivity and unit compression, morphological, and structural properties of adobe are presented.

2.2.1. Adobe preparation. The preparation of adobe is a well-known and practical procedure. There are many types of adobe, depending on the type of additives used: mineral, synthetic, vegetal and animal [3]. In this case, *S. ichu*, a plant that only grows in the highlands, was considered as an additive because of its apparent thermal conductivity of 0.05 W/m K [20]. One of the purposes of this investigation is to thermally characterize the adobe fabricated in the laboratory with dimensions of 16.0 cm x 16.0 cm x 2.5 cm.

For the fabrication of adobe, the first step is to make a correct selection of soil and immediately classify it according to the norms ASTM D422, ASTM D2216, and ASTM D4318 or to the unified soil classification system ASTM D2487. Then, a selection of the soil is made using sieves; in this case, an aperture of 2.0 mm was considered to eliminate particles larger than the minimum thickness of the adobe bricks (2.5 cm). Next, the selected soil is mixed with a sufficient amount of water to obtain good plasticity, and *S. ichu* is added, which was previously cut according to the small dimension of the brick to be prepared (2.5 cm). This mix is then placed in a wood mold, and finally, the bricks must be dried in the shade at ambient temperature. For the different adobe tests, the surface must be plated, so a prior polishing treatment is necessary. The detailed fabrication procedure is presented in figure 2.

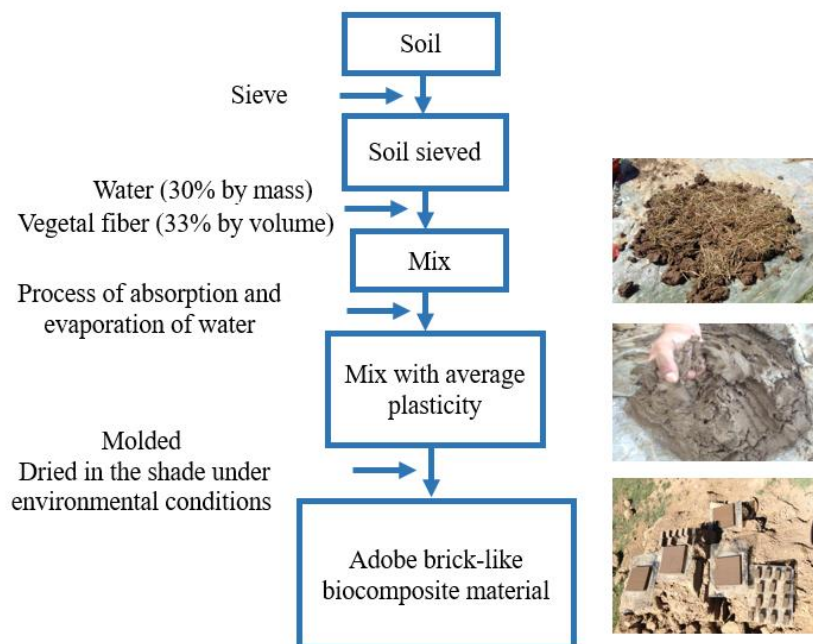


Figure 2. Diagram of adobe fabrication.

2.2.2. Thermal conductivity measurements. For the thermal properties, the thermal conductivity was measured using the ACPG-305 constructed following the norm ASTM C177 and the previous research in this field in Mexico. Some characteristics of this apparatus are indicated in table 2. This apparatus is composed of a central plate, two cold plates, a refrigeration system, two heat sources, and a data acquisition system.

The central plate is composed of two parts: one central plate called the “measurement zone” and a ring surrounding it called the “guard”, made of the same material; in each of these parts, an electrical resistance is incorporated at their interior, and each resistance is heated by an independent external source. For the use of this apparatus, two identical samples are required. The complete system has the following representation (transversal cut) as shown in figure 3.

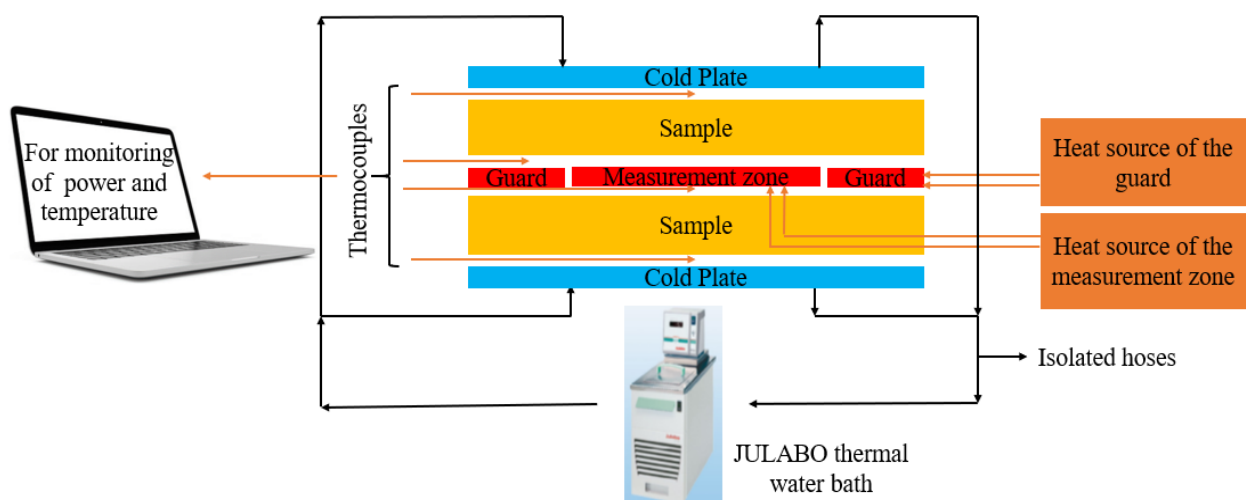


Figure 3. Transversal cut of the guarded hot plate apparatus.

This is a primary apparatus in which the operational principal is in stationary state to provide a constant temperature and power; the thermal conductivity is calculated according to equation (1),

$$\lambda = \frac{Q \cdot e}{S \cdot (\Delta T_1 + \Delta T_2)} \quad (1)$$

where λ is the thermal conductivity of the specimen (W/ m K), Q is the heat flux through the specimens (W), $\Delta T_1 = T_h - T_{c1}$ and $\Delta T_2 = T_h - T_{c2}$ represents the differences in temperature in the stationary state between the central plate (T_h) and the top and bottom cold plates (T_{c1} , T_{c2}) (K), e is the average thickness of the specimens (m), and S is the area of the measurement zone (m²).

Table 2. Characteristics of APCG-305.

Parameters	Value
Orientation	Horizontal
Maximum thickness of the specimen (mm)	47
Maximum temperature of the hot plate (°C)	60
Temperature range in the cold plates (°C)	-10 to 60
Estimated uncertainty (%)	2
Maximum conductance of the specimen (W/m ² K)	1.5

Figure 4 presents the frontal view of the central plate and its two components: the measurement zone and the guard.

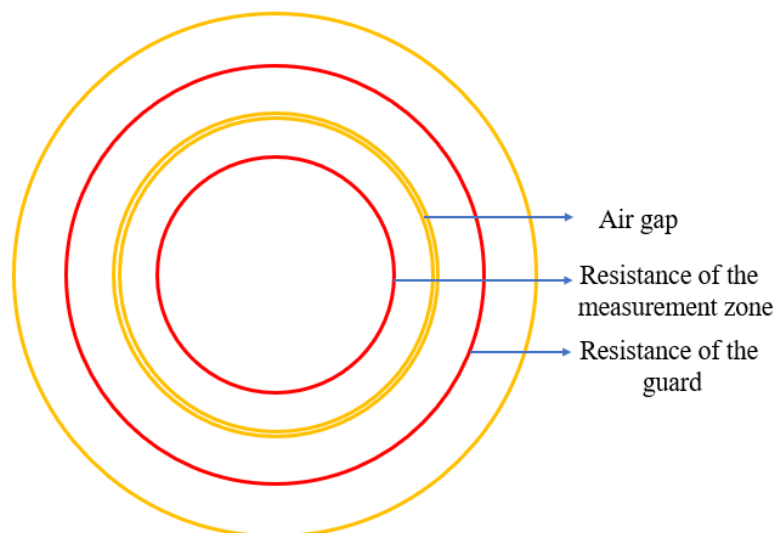


Figure 4. The measurement zone has a diameter of 150 mm and a guard external diameter of 305 mm. The air gap that separates the two is 0.8 mm.

2.2.3. Mechanical properties. In buildings, the walls and roofs are subjected to forces and charges. In the case of a dwelling made of adobe, it is necessary to know the characteristics of the material and then determine the ability of each component to withstand possible rupture or fracture. The mechanical behavior of a material reflects the relationship between its response or deformation when a force is applied to it. In Peru, there have been some studies on adobe, especially regarding its mechanical

behavior in terms of its seismic vulnerability [21]. Likewise, it must be highlighted that the predominant material of the external walls of housing in rural areas is adobe, with a percentage of 72.5% [1].

The mechanical property considered in this investigation was the compression resistance to unity. This assay was developed for the two types of adobes: without and with *S. ichu*. The dimensions of adobe were 7.0 cm x 14.0 cm x 28.0 cm according to the Edification Technical Norm E.080 Adobes [19].

The tested adobe is placed between two plates, such that the pressure is distributed homogeneously in the exposed areas and the force at break is registered when adobe breaks. Equation (2) describes the calculus for unit compression.

$$f_0 = \frac{P}{A_p} \quad (2)$$

where f_0 is the bending load of the specimen (N/mm²), P is the load (N), and A_p is the average area between the top and bottom surface (mm²).

2.2.4. Structure and morphology characteristics. The crystal structure of the adobe brick was characterized by X-ray diffraction using a diffractometer Bruker, model D8 Advance Eco operated with Cu K α radiation.

In addition, the surface morphology of very small bricks of the adobe was determined by SEM using a ZEISS model EVO MA 10 instrument operated at 30 kV.

3. Results and analysis

In brief, the different results of the measured properties are shown. Additionally, scanning electronic microscopy images of the transversal cut of adobe samples are presented.

3.1. Thermal conductivity

The thermal conductivity values of adobe with and without *S. ichu* were obtained. The results are presented in table 3. It is important to mention that these measurements were made after a thermal treatment for one day at 80°C.

Table 3. Thermal conductivity of adobe with the APCG-305.

Material	Thermal Conductivity (W/m K)	Uncertainty 4% (W/m K)
Adobe without fibers	0.371	0.015
Adobe with fibers	0.349	0.014

A thermal conductivity of 0.349 W/m K with 1.66% water content was determined in the case of adobe with *S. ichu*. On the other hand, in the case of adobe without *S. ichu*, a thermal conductivity of 0.371 W/m K with 1.39% water content was obtained.

From the thermal conductivity results, there are differences between these two types of adobe. The thermal conductivity of adobe with *S. ichu* is 5.9% lower than that of with adobe without *S. ichu*. In conclusion, the addition of fibers to adobe is necessary to improve the thermal conductivity.

3.2. Unit compression

This assay was performed considering that all adobe samples have the same proportions and the same fabrication conditions.

Table 4. Results of compression resistance.

Material	Unit compression resistance (N/mm ²)
Adobe without <i>Stipa ichu</i>	2.40
Adobe with <i>Stipa ichu</i>	2.41

It was hoped that when considering an adobe sample containing *S. ichu*, the compression value must increase considerably; however, by comparing the average results as shown in table 4, the difference is almost negligible for unit compression. The addition of *S. ichu* apparently does not significantly increase the compression resistance [22].

According to the Peruvian norm E.080 Adobes, the results in terms of the compression resistance to unity test are higher than the minimum values dictated in the norm, 1.17 N/mm².

3.3. Structure and morphology

The characterization technique of XRD was used to determine the different phases present in the soil used for adobe fabrication. For this purpose, the XRD apparatus used was a BRUKER D8 ADVANCE ECO scanning in the range of 5° to 30° to identify the type of clay present. The diffractogram is presented in figure 5.

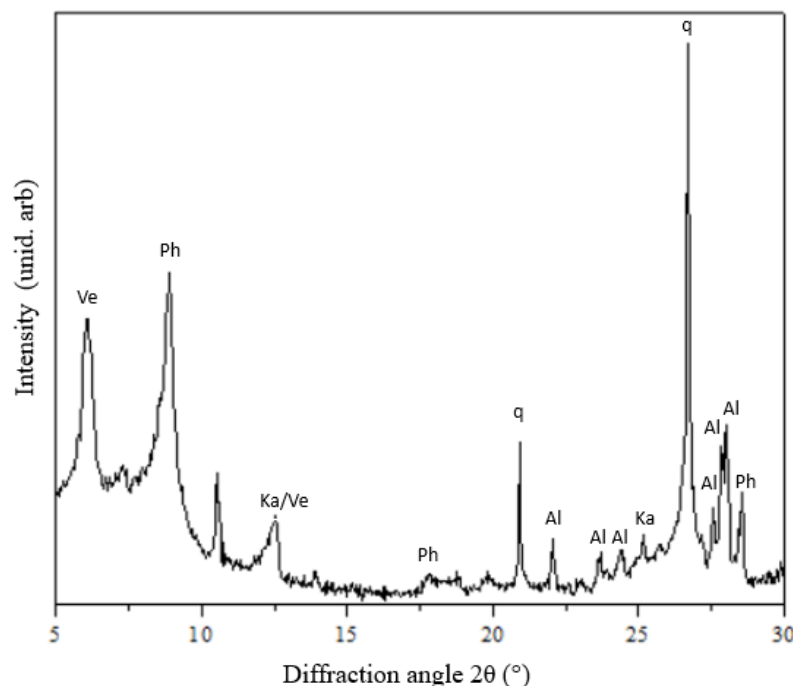


Figure 5. X-ray powder diffraction patterns for the soil used. The predominantly detected crystalline phases are albite (Al), kaolinite (Ka), phlogopite (Ph), quartz (q), and vermiculite (Ve).

The XRD study (figure 5) showed the presence of albite, kaolinite, phlogopite, quartz and vermiculite.

Small adobe specimens of 5.0 cm x 5.0 cm x 2.5 cm were fabricated and then cut into small pieces for analysis of their internal morphology with SEM.

Figure 6 shows a system consisting of a heterogeneous matrix composed of particles of different sizes and cylindrical *S. ichu*, which exhibit aleatory distributions, and their radii are from tens to

hundreds of μm . Additionally, in the system, there are zones in which the *S. ichu* is completely embedded in the matrix, while in other zones, the *S. ichu* is present in cavities.

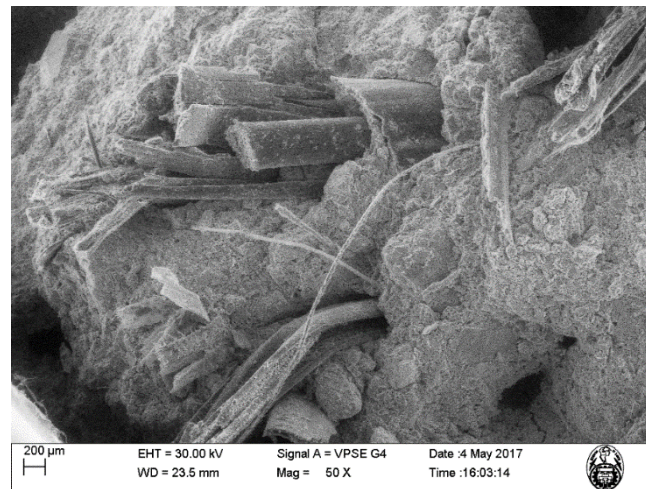


Figure 6. SEM micrograph of an adobe sample with *Stipa ichu*. Magnification 50X.

Figure 7 shows the photomicrography of one sample of adobe without *S. ichu*. This system presents cavities of diverse sizes, among which the smallest cavities are less than $50 \mu\text{m}$ and the largest are on the order of $400 \mu\text{m}$. Furthermore, the porosity of adobe is clearly shown, and it can be seen how the particles interact with each other. In this way, a material is almost compact in certain zones. In another study, scanning electronic microscopy was used to observe the porosity of *S. ichu* [20] and surface morphologies of adobe made in the laboratory from different areas of Peru [23].

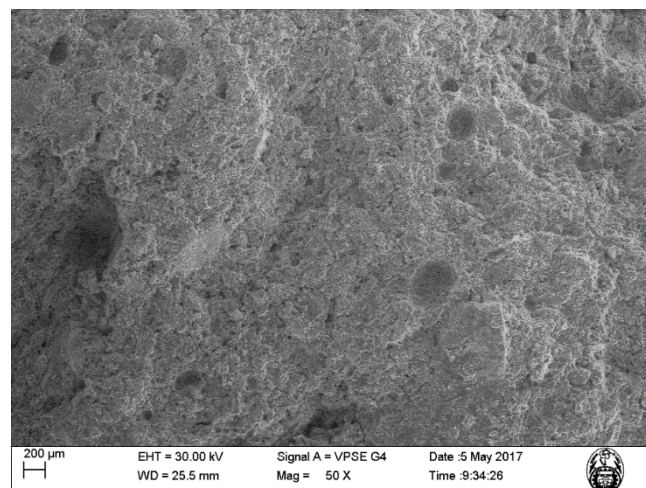


Figure 7. SEM micrograph of an adobe sample without *Stipa ichu*. Magnification 50X.

In accordance with the scanning electron microscopy images, adobe is a biocomposite material composed of different size particles and encapsulated air bubbles and reinforced, in this case, with *S. ichu*. The composition variation of soil, sand and *S. ichu* cannot be identified with this technique.

4. Conclusions

To determine the influence of *Stipa ichu* on the thermal conductivity and mechanical properties of adobe made in the laboratory, international and national procedures were considered for adobe with and without *Stipa ichu* fibers. The soil used in this study is catalogued and shown to contain inorganic fine

particles of clay of low plasticity according to the norm ASTM D4318. It essentially consists of albite, quartz, kaolinite, phlogopite and vermiculite.

The laboratory adobe samples performed well in terms of mechanical and thermal conductivity. The average compression resistance to unity of the adobe specimens satisfies the minimum value established in the norm E.080 Adobes. The average thermal conductivity of adobe without and with *Stipa ichu* is 0.371 W/m K and 0.349 W/m K, respectively. It is necessary to consider the addition of natural fibers to adobe to reduce the thermal conductivity.

Additionally, using SEM, we could see that the internal morphology of adobe is porous, containing particles of different sizes and encapsulated air bubbles, that the distribution of *Stipa ichu* is aleatory, and that the fibers adhere very well to the matrix. Finally, with the help of XRD, the predominant clay present in the soil was kaolinite.

It could be interesting to supplement this study by further comparing the thermal conductivity of adobe samples containing *Stipa ichu* by varying the percentage of silt and clays.

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