Thermophysical characterization of vernacular wall materials: measurements of specific heat and density

J O Molina, H F Ríos, M M Gómez and M J Horn*

Facultad de Ciencias, Universidad Nacional de Ingeniería, Av. Túpac Amaru 210
Rímac, Lima 25, Peru

*E-mail: mhorn@uni.edu.pe

Abstract. This study presents locally implemented measurement arrangements to determine thermophysical properties, such as the density and specific heat of adobe and sillar (ignimbrite), materials widely used in the walls of high Andean houses in Peru. The values of these properties are unknown, but they are crucial as input variables of dynamic simulation programs to determine the thermal behavior and demand of the heating energy of houses. The experimental setup was referenced to international standards, such as ASTM D7263 and ASTM D4611, and used an open-source Arduino microcontroller. The evaluations were also conducted with the transient conditions of heat flow, with adobe and sillar obtaining densities of 1570 ± 62 kg.m⁻³ and 1338 ± 20 kg.m⁻³ and specific heats of 1209 ± 93 J.kg⁻¹.K⁻¹ and 1800 ± 96 J.kg⁻¹.K⁻¹, respectively. The results suggest to carry out more measurements, especially of specific heat given the scarce local and international information on vernacular building materials.

1. Introduction

The thermophysical properties of house-building materials are fundamental for the analysis of the thermal behavior of houses, which involves thermal well-being and energy demand for heating, ventilation, and air conditioning [1]. Likewise, within this analysis, a study on thermal inertia (the ability of a material to store energy and dampen the fluctuations of outside temperature) is also essential.

Despite the importance of quantifying the values of the thermophysical properties of housing construction materials that are employed in different areas, oftentimes, these values are unknown, and their routine measurement is not foreseen although they can be measured using methodologies on the basis of international standards, such as the American Society for Testing and Materials (ASTM). Particularly, there exists limited information in the literature regarding the specific heat and density of construction materials, specially of vernacular origin such as adobe and ashlar (ignimbrite), used in the construction of housing walls mainly in the highlands of Peru. These materials have good thermal behavior, which is appropriate for the climate of these regions.

In this context, this study presents the measurement of the density and specific heat of adobe and sillar using the displaced volume of the water method to obtain the density according to Archimedes’ principle and utilizing the calorimetric method of mixtures to acquire the specific heat of the material. The latter is widely employed by the scientific community for being practical and quick in obtaining results. In the case of the specific heat of adobe, a metal container is used in which the sample is placed and then introduced into a calorimeter. For the measurement of the density, the specimens are covered with paraffin to avoid water absorption. Similar studies to determine the specific heat of adobe have been presented in [2, 3], claiming to have procured results with acceptable reliability in comparison with the data found in tables.
In Peru, in recent years and especially in the Faculty of Sciences of the National University of Engineering, the measurement of the thermophysical properties of construction materials has been realized. Particularly, the thermal conductivity of materials, such as adobe, is measured using a device with a guarded hot plate [4]. The present study expands the characterization of vernacular materials, including their density and specific heat, currently unknown and not referenced in the Peruvian Technical Standard EM.110 “Thermal and Light Comfort with Energy Efficiency” [5].

The thermophysical properties of the building envelope have been identified as key parameters in the analysis of the thermal and energy behavior of buildings utilizing dynamic thermal simulation software [6–8]. Given the lack of values of these properties required as input variables by the software, data from tables from the literature or material libraries from the software itself are generally employed, which can lead to the significant uncertainties of the output variables of the simulation. It must be considered that the materials, according to the place where they are found, present divergent physical, chemical, and morphological characteristics and that the techniques of the elaboration of the materials are sometimes dissimilar. Moreover, the instrumentation used in different laboratories to determine the properties of these materials varies in terms of its precision and measurement accuracy, and the obtained measured value also depends on the expertise of the researcher as mentioned in international standards. In this sense, the characteristics of construction materials, especially those of vernacular origin for which little or no information is available, must be determined locally.

An important factor for experimentation is the automation of the data recording that saves time and brings improvements in the accuracy of the measurements. In the present study, an open-source Arduino microcontroller board is used as a temperature measurement and control system in the determination of specific heat. This system performs a temperature mapping indicating the most accurate values in time and space.

2. Materials and methods
The basic characteristics of adobe and sillar were presented. For the measurements of the density and specific heat, the details of the preparation of the specimens, as well as the control, monitoring, and data recording system that uses an Arduino microcontroller board, were also presented.

2.1 Adobe
Adobe is defined as a solid block of uncooked earth, which may contain straw or other materials that improve its stability against external agents. Soil gradation should be close to 10%–20% clay, 15%–25% silt, and 55%–70% sand, and organic soils should not be employed [9]. In Peru, as shown on the map (figure 1a), the use of adobe for wall construction extends over the entire mountain range with 72.6% compared with other materials (figure 1b) according to the National Institute of Statistics and Computer Science (INEI), and its use is limited to one or two floor houses according to the seismic zone. Generally, economic advantages and traditions have a great influence on the adoption of adobe as a building material around the world, especially in rural and remote areas [10].

2.2. Manufacture of adobe specimens
Five specimens of adobe composed of natural earth and previously sifted sand (figure 2a) were made to remove the stones and organic stubbles. Furthermore, 40% by the mass of water and 33% by the volume of vegetable fiber were considered for the mixture (figure 2b). The mixing of the components was performed manually on simple polyethylene plastic, and then they were wrapped with the same plastic and allowed to “sleep” for 48 hours so that the clay was hydrated and thus would not suffer cracks. The molding was conducted in small wooden trays previously hydrated and bathed inside with fine sand to facilitate the sliding of the specimens and maintain the block shape. Finally, the specimens were dried in open air on a wooden board (figure 2c) and under shade exposed to environmental conditions for 5 days. For the density measurement, the finished specimens were coated with paraffin to prevent them from absorbing water when determining the volume. This step comprises melting paraffin and immersing the specimens in it for a few seconds to prevent the specimens from absorbing paraffin as it is desired that it be impregnated only on its surface. This process is repeated twice or thrice to ensure that the paraffin homogeneously covers the surface of the specimens.
2.3. Sillar or ignimbrite (volcanic rock)
Voluminous neogenic and quaternary ignimbrites are produced in the Arequipa region, the central volcanic zone of the Andes in southern Peru. At the local level, the ignimbrites of Arequipa are called “sillar” [11]. Fenner (1948) introduced this term for the first time in the volcanological literature when describing the well-known whitish ignimbrite used for the construction of colonial buildings in Arequipa [12].

Igimbrite is an igneous rock, a product of the volcanic deposit, which consists of hard tuff composed of rock fragments and phenocrysts in a matrix of dust-like glass fragments, along with pieces of pumice stones and dense lava blocks.

The south of Peru represents the second ignimbritic field of the Andes with an area that exceeds 25000 km² and volumes of almost 5000 km³ and outcrops in the area of the deep canyons of the Ocoña–Cotahuasi–Marán and Colca rivers with approximately 12 types of ignimbrites [13]. In the present study, the Arequipa Airport type of ignimbrite was used.
2.4. Manufacture of sillar specimens
In the case of sillar, which was extracted directly from the quarry in large cuts, the specimens had to be prepared in smaller sizes and in different measures and masses. After being cut, the specimens were covered, like the adobe, with molten paraffin (figures 3a and 3b) to determine their density. For this case, four specimens, numbered from 6 to 9, were made as shown in the lower part of figure 3c, and those numbered 1 to 5 correspond to adobe.

![Figure 3](image)

**Figure 3.** Covering the specimens with paraffin, (a) melting the paraffin, (b) layer of the paraffin on the specimen, and (c) specimens with paraffin, adobe from 1 to 5 and sillar from 6 to 9.

2.5. Temperature measurement system
For the control and measurement of the temperature in the specific heat test, a measurement system was used (figure 4), which performs a temperature mapping indicating accurate values in space and time. K-type sensors were utilized that were connected to thermocouple amplifiers (MAX6675K) that digitize the voltage difference ($\Delta V$) versus the temperature difference ($\Delta T$), and these are connected to an open-source Arduino microcontroller board. The data obtained by this system were stored every 10 s in an Excel program through an interface made in Java.

3. Thermophysical characterization methodology: density and specific heat
The test methodology used to determine the density and specific heat of adobe and sillar is presented, taking as references the methodologies of international standards, such as the ASTM D7263 [14] standard for density, which infers two test methods: method A, a procedure to measure the volume of samples covered with wax by determining the amount of water displaced, and method B, a procedure to measure directly the dimensions of the sample, preferably cylindrical, and the mass with a balance. For the measurement of the specific heat, ASTM 4611 [15] was taken as a reference, which infers the use of the classical method of calorimetric mixtures and provides simpler procedures and apparatus than those generally employed in scientific calorimetry, but with adequate precision for most rocks and soils.

3.1. Determination of density
The determination of the density is conducted taking the ASTM D7263 standard as a reference. For specimens covered with paraffin, method A is used and method B for paraffin. The density of the paraffin influences the calculations of the adobe density; therefore, its determination is advisable. It should also be considered that the volume varies with temperature; hence, the water in the container for method B should be at a temperature of approximately 20 °C. It is also recommended to place the specimens in distilled water, which reduces the effects of surface tension [16]. Finally, the density is calculated using the relationship between mass and volume, including open and closed pores.
3.1.1. Determination of paraffin density

Method B, direct method, is used with cylindrical samples to determine the density of the paraffin (ρ_p). Four tests are executed with samples with the same diameter but with different heights. Applying the relation of equation (1), an average of 899 kg.m\(^{-3}\) was obtained (table 1).

\[ \rho_p = \frac{m_p}{V_p} \]  

(1)

Where:

\( \rho_p \): density (899 kg.m\(^{-3}\))
\( m_p \): paraffin mass (g)
\( V_p \): paraffin volume (cm\(^3\))

| Diameter (cm) | Height (cm) | \( V_p \) (cm\(^{3}\)) | \( m_p \) (g) | \( \rho_p \) (kg.m\(^{-3}\)) |
|---------------|-------------|--------------------------|---------------|-----------------------------|
| 6.53          | 5.38        | 180.18                   | 162           | 899                         |
| 6.53          | 6.16        | 206.30                   | 186           | 902                         |
| 6.53          | 7.25        | 242.80                   | 218           | 898                         |
| 6.53          | 8.20        | 274.62                   | 247           | 899                         |

3.1.2. Determination of the volume of the paraffin adhered to the specimens

To determine the density of the specimens, the volume of the paraffin adhered to their surfaces (\( V_p \)), whose masses are equal to the difference (\( \Delta m \)) between the final masses (\( m_f \): specimen + paraffin) and the initial masses (\( m_o \): specimen), from equation (2):

\[ m_f - m_o = \Delta m = V_p \rho_p \]

\[ V_p = \frac{\Delta m}{\rho_p} \]  

(2)

Where:

\( m_o \): initial mass of the specimen (g)
\( m_f \): final mass of the specimen coated with paraffin (g)
\( \Delta m \): mass variation of the paraffin in the specimen (g)
\( V_p \): paraffin volume (cm\(^3\))
3.1.3. Calculation of the volume and density of the specimens

The volume of the specimens is calculated using Archimedes’ principle of the displaced volume of water from the diagram of forces in equilibrium acting on the vertical axis (equation (3)). In the case of figure 5a, the balance only records the weight of the liquid ($P_o$), while in figure 5b, it records the weight of the liquid and the specimen ($P_f$). The difference in weights is the volume of the displaced liquid ($V_s$) by the submerged object and equal to the thrust determined by equation (4).

![Figure 5. Archimedes’ principle: (a) specimen without contact with water and (b) specimen inside the water to determine the displaced volume.](image)

$$P_f - P_o = \Delta P = \Delta M g = V_s \rho_{\text{water}} g$$  \hspace{1cm} (3)

$$V_s = \frac{\Delta M}{\rho_{\text{water}}}$$  \hspace{1cm} (4)

Where:
- $\rho_{\text{water}}$: density of distilled water at 20 °C (997 kg.m$^{-3}$)
- $V_s$: volume displaced by the specimen covered with paraffin (cm$^3$)
- $g$: gravity (9.8 m.s$^{-2}$)
- $\Delta M$: variation of the mass marked by the balance (g)

Finally, from the known volumes, equation (5), and the masses, the density of the specimens is determined by means of equation (6).

$$V_{\text{specimen}} = V_s - V_p$$  \hspace{1cm} (5)

Where:
- $V_{\text{specimen}}$: volume of the specimen (cm$^3$)

The values of the densities are obtained from the mass and volume relationship:

$$\rho_{\text{specimen}} = \frac{m_o}{V_{\text{specimen}}}$$  \hspace{1cm} (6)

Where $m_o$ is the initial mass or mass of the specimen (g).

3.2. Determination of specific heat

Specific heat ($C_e$) is the amount of heat needed per unit mass to raise the temperature by one Kelvin. For the estimation of this parameter, a calorimetric system was implemented, and the classic mixing method was used according to the ASTM D4611 methodology.

Estimating $C_e$ requires a thermodynamic analysis, which is applied directly for some materials such as sillar, but for others such as adobe, additionally using a metallic material as a container (figure 6) whose shape and specific heat is known is crucial. This is due to the fact that the adobe in contact with the water undergoes fragmentation. A similar study using a container was developed by [2] to determine...
the specific heat of adobe, claiming that results were achieved with acceptable reliability in comparison with the data found in tables. Another similar study has been conducted in Mexico considering traditional materials, such as red brick, tepetate, adobe, tabicón, and concrete [3].

Figure 6. Views of the container and test material inside.

The method used to determine $C_e$ of a substance $(C_{ex})$ that does not react chemically with the rest of the system (in this case that of a solid) consists of introducing the substance $(m_x)$ into a known mass of water $(m_{water})$ that is at a different temperature $(T_{water})$ from that of the solid $(T_x)$. If heat exchanges with the environment are ignored (difficult to avoid), then the solid–water–calorimeter mixture will reach an equilibrium temperature $(T_f)$ so that the heat transferred or absorbed by the solid or sample $(Q_1)$ will be equal to the heat absorbed or transferred by the water $(Q_2)$ and by the calorimeter $(Q_3)$. Equations (7) and (8) allow the calculation of the specific heat $(C_{ex})$ of the solid if the other variables are known. Temperatures and masses can be obtained from direct measurements. However, calculating the calorific capacity of the calorimeter $(C)$, which consists of a cylindrical container with adiabatic walls and a lid that ensures good sealing and hermeticity, is essential.

\begin{equation}
Q_{1(sample)} + Q_{2(water)} + Q_{3(calorimeter)} = 0
\end{equation}

O well:

\begin{equation}
m_x C_{ex} (T_f - T_x) + m_{water} C_{water} (T_f - T_{water}) + C (T_f - T_c) = 0
\end{equation}

Where:

$m_x$: sample mass (g)

$C_{ex}$: specific heat of the sample to be calculated (cal.g$^{-1}$. °C$^{-1}$)

$T_x$: sample temperature (°C)

$m_{water}$: mass of water (g)

$C_{water}$: specific heat of water (cal.g$^{-1}$. °C$^{-1}$)

$T_{water}$: water temperature (°C)

$C$: thermal capacitance of calorimeter (cal. °C$^{-1}$)

$T_f$: final temperature or system equilibrium (°C)

The calculation of $C$ is performed under the same method of equation (8) for two quantities of water at divergent temperatures given that the specific heat of the water is known.

The steps to follow are the following (figure 7): a certain amount of water $(m_1)$ of an initial temperature $(T_1)$ is poured in the calorimeter and allowed to stand for a while so that it is in thermal equilibrium with the calorimeter. Subsequently, another quantity of water $(m_2)$ of temperature $(T_2)$ is poured in, and the calorimeter is hermetically closed. This process is controlled with the temperature measurement system (figure 4) to find the value of the final temperature $(T_f)$ in thermal equilibrium.
Equation (9) is obtained from equation (8) to determine the heat capacity of the calorimeter ($C$).

$$C = \frac{m_1 c_{water}(T_f - T_1) + m_2 c_{water}(T_f - T_2)}{T_c - T_f}$$

The calculation of the specific heat of the sillar ($C_{es}$) is performed conventionally on the basis of thermal equilibrium. The mass and temperatures of the sillar ($m_s$ and $T_s$) and of the water ($m'_2$ and $T'_2$) are measured inside the calorimeter to determine the value of the final temperature ($T_{f'}$) as shown in thermal equilibrium in figure 8.

For adobe, a metal container ($cm$) is used for the specimens, which, together with $cm$-specimen ($m_{cm}$ and $M_a$) at a certain temperature ($T_{cm}$ and $T_a$), is introduced in the calorimeter containing water (figure 9). At a defined temperature ($T''_2$) and mass ($m''_2$), the calorimeter is hermetically closed, and then later, when the system reaches equilibrium, the final temperature ($T_{f''}$) is obtained. Equation (11) is obtained from equation (8), which solving for $C_{ea}$ gives equation (12) to determine the specific heat of adobe.

$$m_{cm}c_{cm}(T_{f''} - T_{cm}) + M_a C_{ea}(T_{f''} - T_a) + m''_2 c_{water}(T_{f''} - T''_2) + C(T_{f''} - T_{cr}) = 0$$

Where:
- $m_{cm}$: mass of the metal container (g)
- $c_{cm}$: specific heat of the metal container (cal.g$^{-1}$.°C$^{-1}$)
- $T_{cm}$: metal container temperature (°C)
- $M_a$: mass of the adobe specimen (g)
- $C_{ea}$: specific heat of the adobe specimen (cal.g$^{-1}$.°C$^{-1}$)
- $T_a$: adobe specimen temperature (°C)
It has been previously necessary to measure the specific heat of the metal container material, for which tests of the constant mass metal container are performed for different initial temperatures, finding a value of 912.55 J.kg\(^{-1}\).K\(^{-1}\).

![Adobe cylinder inside the calorimeter.](image-url)

Finally, with all the measured and calculated values, the specific heat of the adobe specimen (\(C_{ea}\)) is obtained from equation (11), where:

\[
C_{ea} = \frac{m_{cm}C_{cm}(T_{f11}-T_{cm})+m_{2}'C_{water}(T_{f11}-T_{2})'+C(T_{f11}-T_{esi})}{M_{d}(T_{a}-T_{f11})}
\] (12)

4. Results and discussions

4.1. Density test: adobe

The densities of each adobe specimen are obtained with equation 6 and presented in table 2. The average density of the adobe samples is 1.570 g.cm\(^{-3}\), equivalent to 1570 kg.m\(^{-3}\) with a standard deviation of ±62 kg.m\(^{-3}\) in the international system.

| Specimen | \(V_s\) (cm\(^3\)) | \(V_p\) (cm\(^3\)) | \(V_{\text{specimen}}\) (cm\(^3\)) | \(m_o\) (g) | \(\rho_{\text{specimen}}\) (g.cm\(^{-3}\)) |
|----------|----------------------|---------------------|-------------------------------|----------|-----------------------------|
| 1        | 241.7                | 47.8                | 193.9                         | 303      | 1.563                        |
| 2        | 106.3                | 25.6                | 80.7                          | 130      | 1.610                        |
| 3        | 96.3                 | 22.2                | 74.0                          | 117      | 1.580                        |
| 4        | 59.2                 | 15.6                | 43.6                          | 71       | 1.628                        |
| 5        | 29.1                 | 10.0                | 19.1                          | 28       | 1.468                        |

4.2. Density test: sillar

In the same way as for adobe, the densities of the sillar are obtained for the four samples (table 3), with an average density of the sillar being 1.338 g.cm\(^{-3}\), equivalent to 1338 kg.m\(^{-3}\) with a standard deviation of ±20 kg.m\(^{-3}\) in the international system.

4.3. Specific heat test: sillar

Using equation (10) for each of the four sillar specimens, their \(C_{es}\) values are obtained (table 4). Their average specific heat is 0.430 cal.g\(^{-1}\).°C\(^{-1}\), equivalent to 1800 J.kg\(^{-1}\).K\(^{-1}\) with a standard deviation of ±96 J.kg\(^{-1}\).K\(^{-1}\) in the international system.
Table 3. Density of the sillar specimen ($\rho_{\text{specimen}}$).

| Specimen | $V_s$ (cm$^3$) | $V_p$ (cm$^3$) | $V_{\text{specimen}}$ (cm$^3$) | $m_s$ (g) | $\rho_{\text{specimen}}$ (g.cm$^{-3}$) |
|----------|----------------|----------------|-------------------------------|-----------|-------------------------------------|
| 6        | 162.5          | 44.5           | 118.0                         | 161       | 1.364                               |
| 7        | 118.4          | 30.0           | 88.3                          | 118       | 1.336                               |
| 8        | 86.3           | 21.1           | 65.1                          | 87        | 1.336                               |
| 9        | 58.2           | 15.6           | 42.6                          | 56        | 1.315                               |

Table 4. Specific heat of sillar ($C_{es}$).

| $m_2'$ (g) | $C_{\text{water}}$ (cal.g$^{-1}.^\circ$C) | $T_2'$ (g) | $C$ (cal.$^\circ$C$^{-1}$) | $m_s$ (g) | $T_s$ (°C) | $T_f$ (°C) | $C_{es}$ (cal.g$^{-1}.^\circ$C) |
|------------|----------------------|-------------|-------------------------|-----------|-----------|-----------|------------------|
| 349        | 1                     | 54.00       | 36.504                  | 57        | 23.00     | 52.00     | 0.466            |
| 357        | 1                     | 77.00       | 36.504                  | 56        | 24.00     | 74.00     | 0.422            |
| 329        | 1                     | 50.75       | 36.504                  | 56        | 23.00     | 49.00     | 0.439            |
| 301        | 1                     | 65.00       | 36.504                  | 128       | 23.75     | 59.50     | 0.406            |
| 346        | 1                     | 75.50       | 36.504                  | 86        | 23.25     | 71.00     | 0.419            |

4.4. Specific heat test: adobe

Using equation (12) for each of the five adobe specimens, their $C_{ea}$ values are obtained (table 5). Their average specific heat is 0.289 cal.g$^{-1}.^\circ$C$^{-1}$, equivalent to 1209 J.kg$^{-1}.K^{-1}$ with a standard deviation of ±93 J.kg$^{-1}.K^{-1}$ in the international system.

Table 5. Specific heat of adobe ($C_{ea}$).

| $m_2''$ (g) | $T_2''$ (°C) | $M_e$ (g) | $T_a$ (°C) | $m_{cm}$ (g) | $T_{cm}$ (°C) | $T_{fr}$ (°C) | $C_{ea}$ (cal.g$^{-1}.^\circ$C$^{-1}$) |
|-------------|--------------|-----------|------------|--------------|---------------|-------------|------------------|
| 319         | 25.0         | 180       | 46.25      | 50           | 46.25         | 28.0        | 0.264            |
| 298         | 25.0         | 180       | 34.50      | 50           | 34.50         | 26.5        | 0.288            |
| 309         | 24.0         | 180       | 42.00      | 50           | 42.00         | 27.0        | 0.323            |
| 311         | 25.5         | 180       | 39.00      | 50           | 39.00         | 27.5        | 0.275            |
| 291         | 25.0         | 180       | 43.50      | 50           | 43.50         | 28.0        | 0.293            |

As a reference, some published data of the density and specific heat of adobe and sillar are given: adobe has a density of 1600 kg.m$^{-3}$ according to the Spanish international standard NBE-CT-79. The Peruvian standard EM.110 indicates density values in the range of 1100 to 1800 kg.m$^{-3}$, data compiled from several international standards. In [17], a study realized in Argentina, adobe density values of 1200 to 1700 kg.m$^{-3}$ were reported. Regarding the density of sillar or ignimbrite, the Peruvian standard EM.110 does not present any value. Moreover, in [18], where Arequipa ignimbrite sillar was studied, a value of 1306.96 kg.m$^{-3}$ was measured in a laboratory in Mexico (a discrepancy of 2.37% with the value measured in the present study). Another study of the geotechnical characterization of ignimbrite in New Zealand infers densities in the range of 1212 to 1928 kg.m$^{-3}$ [19]. Finally, in the study developed by [20], it was estimated that the density of the samples of tuff and ignimbrite collected from different regions of Yemen are in the order of 1660 to 2250 kg.m$^{-3}$.

In the case of the specific heat of adobe and sillar, there are no values in the Peruvian EM.110 standard. The Spanish standard presents a value of 920 J.kg$^{-1}.K^{-1}$. In the study [18] for the Arequipa ignimbrite sillar, a value of 463.75 J.kg$^{-1}.K^{-1}$ was also found. Although Arequipa ignimbrite was used in this study, this value seems doubtful because for materials such as igneous rocks of volcanic lavas in the literature, values of nearly 1000 J.kg$^{-1}.K^{-1}$ are given, as exhibited in the catalog of the construction elements of the Technical Building Code of Spain or, between 840 and 1260 J.kg$^{-1}.K^{-1}$, as presented in [21]. The values of the order of 450 J.kg$^{-1}.K^{-1}$ are more representative for metallic materials and not
for stone construction materials. In the study developed by [22] regarding the characteristics and properties of Bitlis ignimbrites used as construction materials in Turkey, the specific heats of five ignimbrite specimens were obtained out of a total of 16 whose average was 1440 ± 70 J.kg⁻¹.K⁻¹. The thermal simulation program EnergyPlus considers specific heats between 800 and 2000 J.kg⁻¹.K⁻¹ [23] to be in a typical range for opaque construction materials.

5. Conclusions
This study measured the density and specific heat of the specimens of adobe and sillar, reference materials in Peru for the construction of high Andean house walls. The obtained densities are 1570 ± 62 kg.m⁻³ for adobe and 1338 ± 20 kg.m⁻³ for sillar and specific heats of 1209 ± 93 J.kg⁻¹.K⁻¹ for adobe and 1800 ± 96 J.kg⁻¹.K⁻¹ for sillar. These values differ, in some cases, quite significantly from published values, especially in the case of specific heat, where little information is available. Therefore, conducting further measurements is suggested.

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