Thermal characterization of materials used in rural housing constructions in Ayacucho, Peru

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Abstract. The thermal conductivity of construction materials used in rural areas of Ayacucho has been measured. For this purpose, a thermal conductivity meter for material sample plates of a size of 12 cm x 12 cm has been designed and built, based on “ASTM C177 - Standard Test Method for Steady-State Heat Flux”. The effect of the thickness of the samples and of the heating power of the central plate on the measurement results was evaluated, resulting that best results were obtained with samples less than 2 cm thick and heating powers of less than 3 W. The thermal conductivities obtained vary between 0.148± 0.005 $W.m^{-1}.K^{-1}$ for “tornillo” wood, and 0.663 ± 0.010 $W.m^{-1}.K^{-1}$ for red clay from Quinua.

1. Introduction

The thermal conductivity of materials used for housing constructions depends on many factors, such as density, temperature, humidity, crystalline structure, among others [1], physicochemical characteristics that in general vary according to the geographical area where the materials come from. Many manufacturers and researchers report the thermal properties of insulating materials, based on tabulated data and obtained under standard conditions. However, it is necessary to know the value of the thermal conductivity for each specific type of material used in a housing construction in order to be able to evaluate the thermal behavior of the construction, such as heat balances in order to establish the heating requirements at a particular location [2]. Therefore, it is necessary to characterize thermal insulating materials used in our locality, under the climatic conditions typical of the region.

There are various instruments and methods to measure the thermal conductivity of materials, but these instruments in many cases are very expensive. Having this in mind, we have designed and built an instrument (MCT) to measure the thermal conductivity of materials typical of the region and widely used in the construction of local houses, in order to identify them as bioclimatic insulating materials.

The materials selected were “tornillo”- wood (Cedrelinga cateniformis), red clay (sedimentary rock) from the town of Quinua-Ayacucho, plaster (semi-hydrated calcium sulfate), red brick, mixture of plaster and cement (proportion: one gram of cement per 3.83 grams of plaster), and adobe.

2. Design and construction of the MCT

The design of the thermal conductivity meter (MCT: “Medidor de Conductividad Térmica”) is in compliance with “ASTM C177-1997 - Standard test method to measure stationary heat flow and thermal transmission properties by means of the protected hot plate” [3]. The principle of operation of the MCT is based on a unidirectional heat transfer by conduction in a steady state, obtained with a central heated unit, of known size and heating power, surrounded by an annular heated guard, at the same temperature as the central part to prevent the sideways loss of heat and promote a uniform and unidirectional temperature gradient through two equal samples (whose heat conductivity is measured) between the central hot plate and the outer cold plates.

The MCT consists of a sandwich of two outer plates (aluminum plates with fins and cooling fans), and an inner heated plate (copper hot plate).

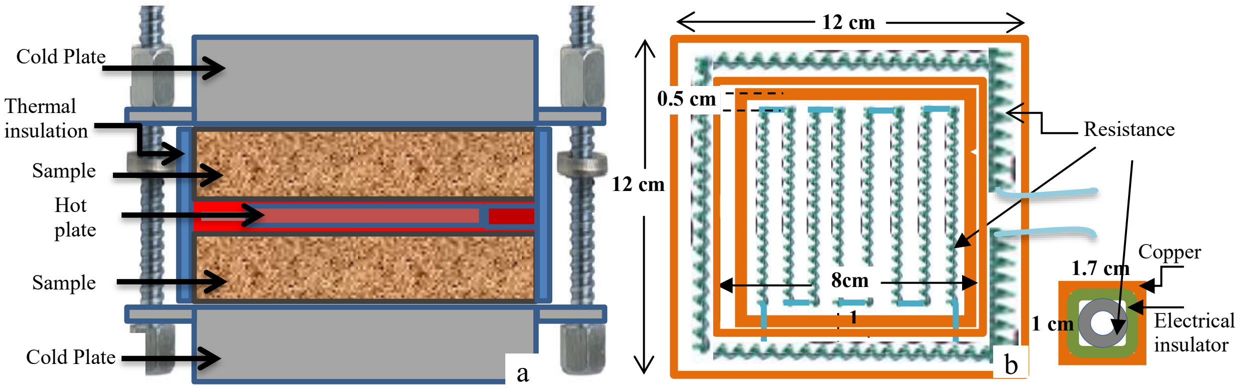

Figure 1. (a) Diagram of the designed equipment (b) Annular guard, central plate and internal resistances.

The hot plate consists of two parts: a copper central plate with dimensions 7.8 cm x 7.8 cm x1 cm, and an annular guard, surrounding the central plate, 1.3 cm wide and with external perimeters of 12 cm x 12 cm. For the construction of the central heated plate and the annular heated guard, 2 mm thick copper plates were used, with imbedded wires for the electrical heating and with Bakelite as electrical insulation. The central plate has inside a resistance of Nichrome N° 24 folded into spirals of 0.3 cm in diameter, arranged in 8 columns connected and separated 1 cm from each other, with a resistance of 22.6 Ω. The annular guard has an electrical resistance of Nichrome wire N° 24 in turns of 0.4 cm of external diameter with a spacing of 0.15 cm between them and a resistance of 19.3 Ω.

The two cold aluminum plates, with fins, are 18 cm x 18 cm in size. On the top of each plate is a fan (220 V AC) that generates a constant cooling flow on the plates.

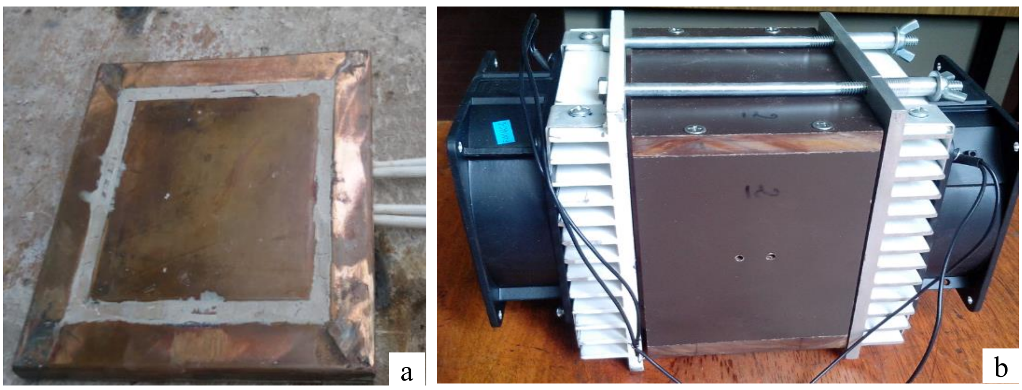

Figure 2. (a) Central hot plate and copper annular guard (b) Finished thermal conductivity meter (MCT).

3. Characterization of the MCT

For the measurements with the MCT the following instruments were used: a multichannel data logger, with thermocouple temperature sensors type K, model EBI 40-TC, from Ebro Electronic, and with a resolution of 0.1 °C. The voltage and currents of the electric power supply for the central hot plate and the heated guard (the same voltage is supplied to the central measuring hot plate and the heated guard), were measured with a Fluke 179 digital multimeter, with a resolution of 0.1 mV-AC, and 0.01 mA-AC.

The measured thermal conductivities obtained with the MCT were compared with the data got with the instrument "KD2 Pro -Thermal Properties Analyzer", with a TR-1 sensor needle (10 cm long), from Decagon Devices. This instrument measures thermal conductivity of building materials in the range of 0.1 to 4.0 W.m^{-1}.K^{-1}.

3.1. Stationary heat flow through samples

The temperatures in six points symmetrically located on the central plate were measured, with the results shown in Figure 3-a: The heating curves of all points practically overlap. The temperatures on each side of the samples, placed in the MTC, are continuously increasing until they stay stationary. In this condition the temperature difference between the hot plate and the cold plates remains constant, which allows us to have a steady heat flow (Figure 3b).

The thermal conductivity is determined by the Fourier equation, in which any eventual edge effect is not taken into account. (The measured temperature of the guard is slightly higher than of the central plate, about 0.9 °C). It is assumed that in a stationary state, by symmetry conditions, the heat flow through each of the two samples is unidirectional and is equal to half the electrical power dissipated in the central zone.

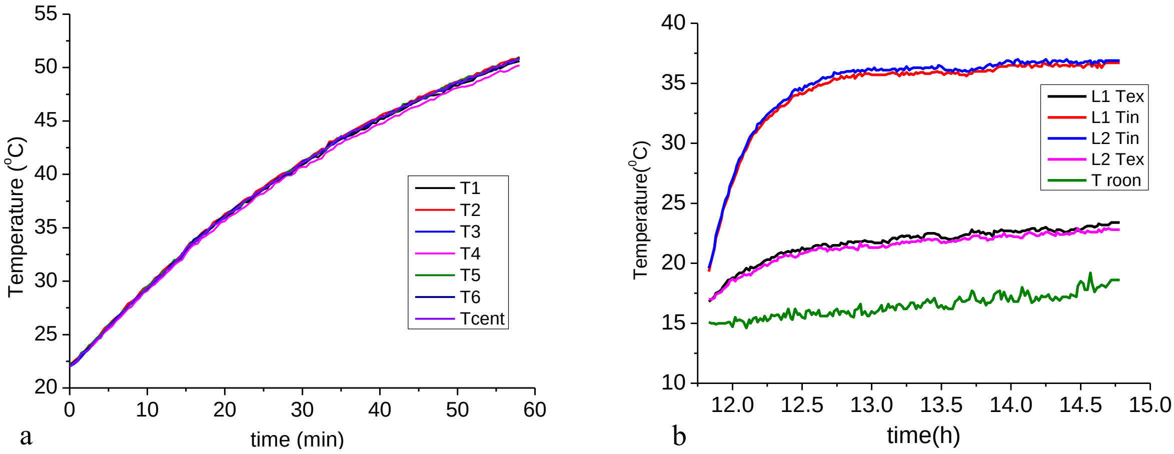

Figure 3. (a) Distribution of the heating temperature at six points on the surface of the central plate. (b). Stabilization of temperatures at the two sides of the samples.

The thermal conductivity is determined according to the expression $k = \frac{P}{A\left(\frac{\Delta T_1}{L_1} + \frac{\Delta T_2}{L_2}\right)}$

Where: P is the thermal flow though the samples, in watt, equal to the electrical power dissipated in the central part of the hot plate [3]; L is the thickness, in meters, of each sample; A is the area of the central part of the hot plate; ΔT is the average of the temperature difference between the two sides of the samples in the stationary thermal flow condition.

To obtain the optimal operation criteria of the MCT, the thermal conductivity of "tornillo" wood was evaluated under different conditions. The wood samples had been plates that were obtained by cross cutting the fibers of the wood, so that the flow direction is parallel to the fibers. The results were compared with the values measured with the KD2 Pro thermal conductivity meter. The tests were carried: a) varying the thickness of the samples from 0.5 cm to 3.0 cm (with a constant voltage at the hot plate), and b) varying the voltage supplied to the hot plate from 2.92 V to 8.76 V (with samples of constant thickness).

3.2. Thermal conductivity in wood samples of different thicknesses

To establish the influence of the thickness of the samples on the measure of the thermal conductivity with the MCT, a constant voltage of 4 V was used, with which a heating of 0.7 W of the central plate was obtained.

The sizes of the tornillo wood samples are given in Table 1 and Figure 4. The thermal conductivity of the tornillo wood, measured with the TR1 sensor of the KD2 Pro in the direction parallel to the fibers of the wood, was $k = 0.141 \pm 0.02\ W.m^{-1}.K^{-1}$. The average temperature of the measurement was 18.0 °C. All tests were performed at room temperature. The results are shown in table 2.

Table 1. Sizes of tornillo wood samples (572.3 kg. m^{-3}).

Samples	**Thickness (mm)**	**Area (m^2)**
1	5.6	0.0104
2	10.0	0.0105
3	13.8	0.0105
4	19.7	0.0106
5	25.5	0.0105
6	31.4	0.0106

Figure 4. Samples of wood, red brick and mix of plaster and cement.

Table 2. Thermal conductivity for different wood thicknesses at a constant power of 0.7 W.

Stabilizing time (min)	Thickness (m)	Average temperature between the two sides of the samples ΔT (ºC)	Thermal conductivity *k* ($W.m^{-1}.K^{-1}$)
25	0.006	1.40	0.145±0.014
35	0.010	2.47	0.147±0.008
49	0.014	3.41	0.149±0.006
55	0.020	4.66	0.154±0.004
63	0.026	5.67	0.164±0.004

The variation of the temperature difference between the sides of the samples is shown in figure 5a**,** one side that is in contact with the hot plate and the other side with the cold plate.

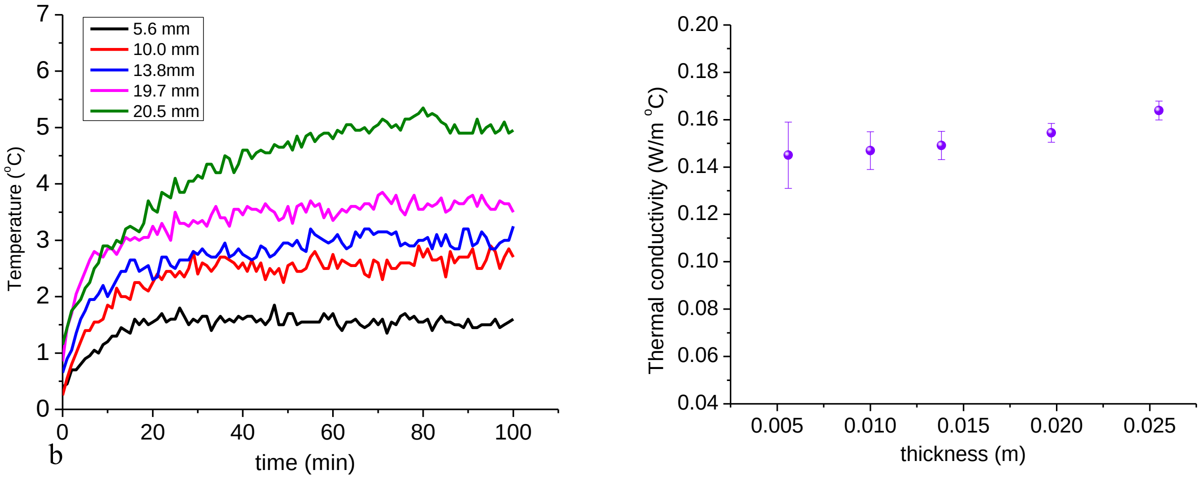

Figure 5. (a) Temperature difference between the sides of the samples for a constant voltage at the central hot plate of 4 V (0.7 W). (b) Thermal conductivity of the tornillo wood for 4 V constant voltage at the central hot plate.

In figure 5b we observe that the measured values of the thermal conductivity increases with the thickness of the samples, but stabilizes at 0.145 – 0.147 $W.m^{-1}.K^{-1}$ for lower thicknesses, a value also obtained with KD2 Pro.

3.3. Thermal conductivity in the samples with different voltages at the hot plate

The values obtained for the thermal conductivity of the tornillo wood samples, with 2 cm thickness, measured with the d MTC, for different voltages at the central hot plate are shown in Table 3.

Figure 6-a indicates the variation of the temperature between the sides of the samples in relation to the change of voltage at the hot plate: at higher voltage or power, there is a greater temperature difference across the samples. From the results shown in Figure 6-b, indicating the values obtained for the thermal conductivity of the tornillo wood for different voltages at the central hot plate, we can see that these values increase with increasing heating power. The best coincidence with the values obtained in the previous measurements with different thicknesses of the samples, we get for lower heating powers.

Table 3. Thermal conductivity of the 2 cm wood samples at different voltages.

Voltage (V)	Electric current intensity (A)	Power (W)	Stabilizing time (min)	Average temperature between the sides of the samples ΔT (°C)	Thermal conductivity *k* ($W.m^{-1}.K^{-1}$)
2.92	0.13	0.37	30	2.59	0.148±0.005
4.32	0.19	0.81	40	5.42	0.155±0.004
5.84	0.26	1.49	45	9.29	0.165±0.004
7.30	0.32	2.33	57	14.12	0.170±0.005
8.76	0.38	3.35	80	19.41	0.178±0.005

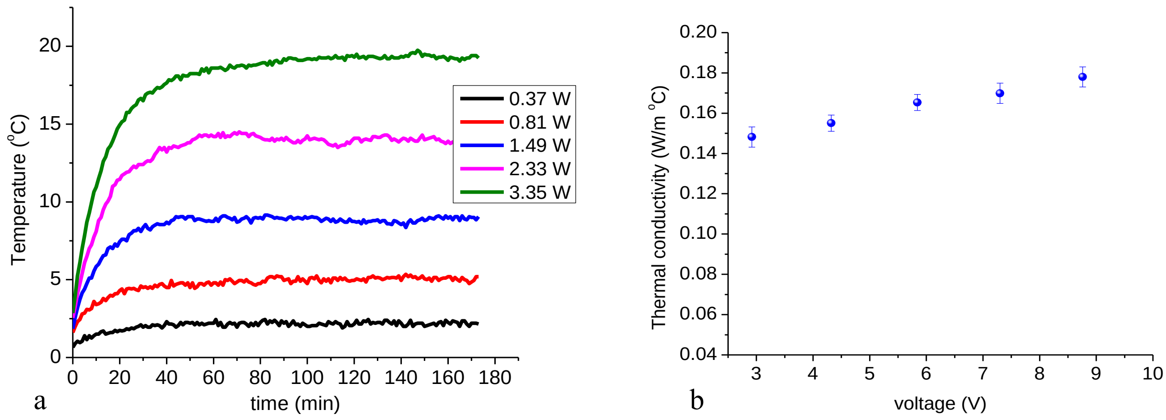

Figure 6. (a) Variation of the temperature difference between the sides of the wood sample of 2 cm thickness for different voltages (power). (b) Thermal conductivity of the tornillo wood for different voltages at the central hot plate.

4. **Measured thermal conductivity of samples of building materials of the Ayacucho region**.

The above results establish that the MCT obtains more accurate results in the case that the samples have lower thicknesses, and no greater temperature difference between the sides of the sample are generated. Taking into account these criteria, the samples of the materials of the Ayacucho region were prepared. With samples of 12 cm x12 cm x 2 cm the following results were obtained:

Table 4. Thermal conductivity of materials from the Ayacucho region.

Material	Average temperature difference between plates (°C)	Average test temperature (°C)	Average thickness (cm)	Density* ($kg.m^{-3}$)	Medium power (W)	Thermal conductivity *k* ($W.m^{-1}.K^{-1}$)
“Tornillo“ wood	2.59	21.6	2.0	570	0.37	0.148±0.005
Cement-plaster	7.60	26.6	2.0	1210	2.79	0.380±0.006
Adobe	10.40	28.9	2.0	1350	2.80	0.386±0.011
Red brick	9.90	28.8	2.0	1180	2.98	0.297±0.008
Gypsum	19.90	31.9	4,0	990	2.58	0.290±0.006
Red clay	4.30	25.4	2,0	1780	2.79	0.663±0.010

* Density was measured in order to classify the degree of compaction of the materials.

5. **Discussion**

To validate the operation of the MTC equipment and determine the optimal criteria for the use of the meter, the measured values of the thermal conductivity of "tornillo" wood samples of different thicknesses were evaluated. The thermal conductivity of wood depends on the shape, dimension, orientation, chemical composition, moisture content, temperature, among other factors, the moisture content being the most influential factor [4]. The moisture content of the samples has been considered between 12 and 15%, taking the reference of Pacheco and Juliá [5] when the wood dries in the air at room temperature, since our samples were dried under these conditions. Figures 5-a and 6-a indicate the constant flow reached between the sides of the wood samples. It is observed that the greater the thickness of the sample, the greater the difference in temperature on its sides and, similarly, the greater the power in the central plate, the greater the difference in temperature between the sides of the sample. In relation to the results of Tables 2 and 3, and Figures 5 and 6, the thermal conductivity of the samples of smaller thickness is closer to the measurement made with the KD2 Pro. The thicker samples acquire a higher temperature, which influences the value obtained for the thermal conductivity of the material. In principle, this could mean that at higher temperatures the thermal conductivity is higher, but when measuring with the KD2 Pro the thermal conductivity of the "tornillo" wood at temperatures between 20 °C and 50 °C (in an oven) did not show any variation.

The designed meter gets best results for samples of smaller thickness, between 5 mm and 20 mm, and heating powers of the central plate of less than 3 W.

The measured value of the thermal conductivity of the "tornillo" wood was 0.148 $W.m^{-1}.K^{-1}$ with a density of 570 $kg.m^{-3}$. Holguino et al [7] reported 0.274 $W.m^{-1}.K^{-1}$. According to the Urakami and Fukayama model, referenced by Pinto et al. [6], a value of 0.20 $W.m^{-1}.K^{-1}$ is obtained, however the type of wood is not characterized. Acuña *et al* [4] reports that the thermal conductivity of wood varies between 0.18 and 0.60 $W.m^{-1}.K^{-1}$ for a moisture content between 2.5 and 15.8 % [4].

The thermal conductivity of our gypsum sample was 0.290 $W.m^{-1}.K^{-1}$ with density of 990 $kg.m^{-3}$, result that complies with Spanish Standard UNE-EN 13279-1 2006 [8], that reports 0.330 $W.m^{-1}.K^{-1}$, for a density of 1000 $kg.m^{-3}$; Holguino et al [7] reports a value of 0.149 $W.m^{-1}.K^{-1}$, without indicating the respective density.

In the case of adobe, we measured a thermal conductivity of 0.386 $W.m^{-1}.K^{-1}$, for a density of 1350 $kg.m^{-3}$. Cuitiño et al [9] mentioned a thermal conductivity of adobe, with a density of 1200 $kg.m^{-3}$, of 0.46 $W.m^{-1}.K^{-1}$, which is similar to the value obtained by us. Holguino *et al* [8] reports 0.176 $W.m^{-1}.K^{-1}$. without characterizing the density.

For the thermal conductivity of the red clay of the locality of Quinua-Ayacucho, with a density of 1780 $kg.m^{-3}$, we measured a value of 0.663 $W.m^{-1}.K^{-1}$, for which no specific reference was found.

As can be seen, the bibliography contains thermal conductivity data for many materials, with a very wide range of values.

6. Conclusion

A thermal conductivity meter, MCT, has been manufactured that is based on the hot plate method with an annular guard, in which it is possible to establish a steady unidirectional heat flow through the samples. For the most adequate measurement of the thermal conductivity of solid materials, the samples must have a thickness less than 2 cm and applied powers less than 3 W.

The measurements of the thermal conductivity of the construction materials of our region, obtained with this instrument, are in the range of values of the reviewed bibliography, however, correspond to different local conditions.

The values of the thermal conductivity obtained were: tornillo wood 0.148±0.005 $Wm^{-1}.K^{-1}$, Gypsum-cement 0.380±0.006 $Wm^{-1}.K^{-1}$, Adobe 0.386±0.01 $Wm^{-1}.K^{-1}$, brick 0.297±0.008 $Wm^{-1}.K^{-1}$, Gypsum 0.290 ± 0.006 $Wm^{-1}.K^{-1}$, Red clay from Quinua 0.663 ± 0.010 $Wm^{-1}.K^{-1}$.

Acknowledgments

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