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Thermal conductivity of straw bales and other materials used in Ecuador's masonry by the thermal needle probe method.

Conductividad térmica de fardos de paja y otros materiales usados para realizar mampostería en Ecuador por el método de la aguja térmica.

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Abstract

The construction industry in Ecuador faces a series of challenges regarding the implementation of the energy efficiency law passed in 2019. This law stipulates that the builder informs the buyers of the projects of their energy rating. Therefore, it is necessary to study and contrast the thermal properties of traditional and new building materials in the country. The main objective of this research is, through the thermal needle probe method, to obtain thermal conductivity data of materials used in bricks. This is the first time in Ecuador that such a comprehensive study about thermal conductivity in construction materials is developed. Also, the thermal needle is constructed by using basic principles and tools which reduce its cost to a minimum. The conductivity results obtained are between 0.344 and 0.986 W / K.m. Subsequently, the wheat straw bale, made from agro-industrial waste, is analyzed, obtaining that the average conductivity of this element is 0.045 W /K.m. It is concluded that it is possible to obtain the thermal conductivity of bricks by the method of the thermal needle and, that the bale of straw, with respect to the analyzed elements, is the only one that according to the Ecuadorian Standard of Construction meets the criteria of thermal insulator, so it could be constituted as an alternative for energy efficient homes.

Resumen

La industria de la construcción en Ecuador enfrenta una serie de retos respecto a la implementación de la ley de eficiencia energética aprobada en 2019. Esta ley estipula que el constructor informe a los compradores de los proyectos sobre su calificación energética. Por lo tanto es necesario estudiar y contrastar las propiedades térmicas de los materiales de construcción tradicionales y nuevos en el país. El principal objetivo de esta investigación es, mediante el método de la aguja térmica, obtener datos de la conductividad térmica de los materiales utilizados en ladrillos. Esta es la primera vez, en Ecuador, que se lleva a cabo un estudio tan completo sobre la conductividad térmica en materiales de construcción. Además la aguja térmica ha sido construida usando herramientas y principios básicos lo cual reduce su costo al mínimo. Los resultados de conductividad obtenidos están entre 0.344 y 0.986 W/K.m Posteriormente, se analiza el fardo de paja de trigo, hecho a partir de desechos agroindustriales, obteniendo que la conductividad media de este elemento es 0.045 W/K.m Se concluye que es posible obtener la conductividad térmica de ladrillos por el método de la aguja térmica y que el fardo de paja es el único elemento que cumple con criterios de aislante térmico de acuerdo a la Norma Ecuatoriana de la Construcción, con respecto a otros elementos analizados, por lo cual puede constituir en una alternativa para viviendas energéticamente eficientes.

1. Introduction.

In March 2019, the Energy Efficiency Law, in spanish: "Ley Orgánica de Eficiencia Energética" (Asamblea Nacional, 2019) was approved by the Ecuador's National Assembly. In the Article 13 of this law, referenced to the construction sector, it is indicated that the building energy behavior should be reported. But the country does not have data in this regard. However, it is known that the residential sector is the second largest consumer of energy after the transport sector. The historical trend for the year 2020 indicates that this situation will not vary significantly. (MIDUVI, 2018)

To establish the energy efficiency of buildings, a first step is to determine the thermal properties of building materials. Note that, according to statistics obtained from the 2010 population and housing census, in Ecuador 58.7% of homes have block and brick walls (INEC, 2010). Within the design approach used on constructions on Ecuador, there are no normative considerations about thermal parameters that promote an efficient use of materials which, in addition to its minimal mechanical characteristics, reflect adequate thermal conditions, in the context of energy saving and housing comfort. Based on this reality, this study offers results of thermal conductivity obtained from the principal masonry used on Ecuador.

However, one of the difficulties in determining, for example, the thermal conductivity of these materials on-site, is the portability of the equipment. Previous studies in soft rock have shown the possibility of doing it with a thermal needle (Mosquera, 2013). Other research papers in Argentina and Ecuador have shown the possibility of using this method to evaluate thermal properties of masonry (Obando & Pachacama, 2018). The thermal needle method consists of an apparatus that injects current into the medium to be analyzed, thus raising the temperature. At the same time, the sensor is responsible for recording the variation of this value, taking into account the time elapsed in the test.

On the other hand, there are 4617 hectares of wheat planted in the country (INEC, 2017), which when harvested produce straw as a waste product, which is usually burned. That is, it is a totally wasted material, despite its importance in volume. With the purpose of including an ecological construction alternative that takes advantage of this material, this study also addresses its insulating properties.

2. Methodology

Below are the materials and methods of data collection and analysis used in this investigation.

2.1 Materials

The "traditional" materials that were used to determine their thermal conductivity were: burned clay, which is used in artisanal bricks, and cement concrete with and without pumice, which are used in concrete block walls.

A total of 26 trials were carried out with burned clay, and 20 with cement concrete with and without pumice. The samples were obtained from bricks and blocks of greater production in the Mejía Cantón, Pichincha Province, Ecuador**. Table 1** shows a summary of elements, material, identification, number of trials, average density and moisture content.

Element	Material	Type	Number of trials	Average dry density (kg/m^3)	Average moisture content (%)
Artisanal bricks	Burned Clay	LA	8	1504.56	1.95
		LB	8	1467.98	0.80
		LC	10	1476.67	0.74
Artisanal blocks	Cement concrete with pumice	BA	10	1586.13	13.81
Industrial blocks	Cement concrete	BB	10	1298.22	18.89
Straw bale	Straw	F	13	60.65	10.91
Plaster		R	10	1651.06	15.14
		Total	69		

Table 1 also shows that as a "non-traditional" material, straw bale was used, which also has a plaster mortar made with lime and cement, in a proportion of 1 to 6 as indicated by the North American standard (ICC, 2015). A total of 23 trials were performed. The test was carried out with the thermal needle perpendicular to the direction of the straw fibers. The material was obtained from wheat crops in the Mejía Cantón.

2.2 Methods of data collection and analysis

The method to determine the thermal transmittance was that of the thermal needle. The necessary apparatus was built by the researchers of this study, complying with ASTM D5334. [8]

Figure 1 and **Figure 2** show a plan view and the fundamental elements of the apparatus specially constructed for this work. It is observed that it is a device that captures temperature variations, which are transformed into digital signals by means of an Arduino board. Its cost is around 10% of the commercial

Figure. 1. Thermal needle.

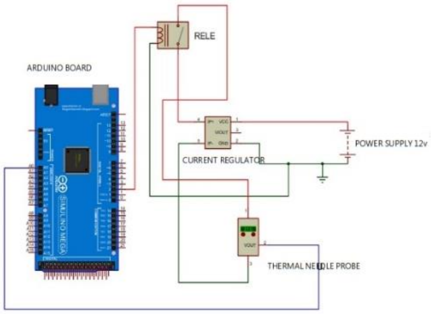

Figure. 2. Thermal needle layout.

In general, the theory indicates that the thermal needle method consists of a needle-shaped probe that has a large length-to-diameter ratio to simulate the conditions of a heat source of infinite and extremely thin length. The sensor (needle) must heat the medium under study and record the temperature variation of the medium.

The thermal needle sensors used in this research were produced by the East 30 Sensors Company (East 30 Sensors, 2019), and allowed the capture of temperature variation data, as well as the input of a direct current to increase heat in the medium to be tested. The dimensions of the needle sensor are: 6.00 cm in length and 1.00 mm in diameter. Additionally, the manufacturer provided the resistance values of each sensor purchased, which is summarized in the **Table 2.**

Table 2. Resistance of sensors used in the tests (SOURCE: EAST 30 SENSORS CALIBRATION CERTIFICATE. (EAST 30 SENSORS, 2019)

Sensor serial number	Heating element resistance (ohms)
1619	69.6
1620	69.6
1621	69.6

Calibration of these needle sensors was performed in two stages. The first consisted of correlating the voltage and bit values that it threw, to transform them into temperature data. For this, known values were used that correlate: voltage, bits and temperature of a waterproof submersible ds18b20 thermocouple from HK Shan Hai. (HK Shan Hai Group Limited, 2019).

Both the needle sensor and the thermocouple were subjected to a process of heating and cooling in water, to find an equation that in turn correlates the data from the thermocouple with the data from the needle sensor.

Figure 3 shows the relationship that exists between the data identified as temperature in the thermocouple ds18b20, in relation to the voltage data thrown by the needle sensor. After a regression process within a spreadsheet, the equation shown in **Figure 3** was obtained. This equation models the behavior of the needle sensor, with a coefficient of determination value of 0.9993.

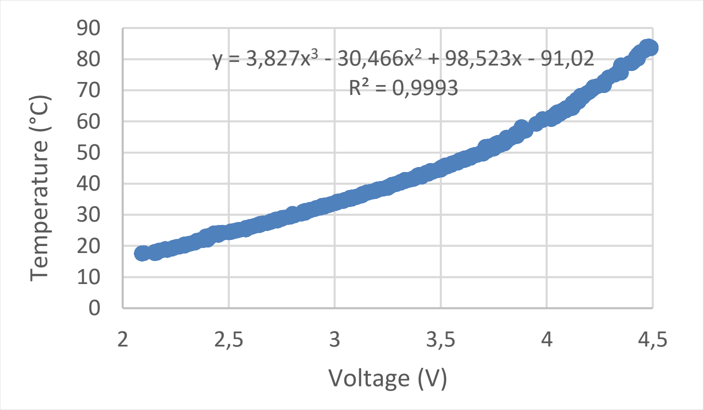

Figure. 3. Temperature vs Voltage.

From this information, the equipment as such was assembled, which schematically consists of a 12-volt power supply, a current regulator, a relay board and an Arduino board, on which the programming was carried out. and definition of the logic for the operation of the equipment as specified in the ASTM D5334 standard. **Figure 1** and **Figure 2.**

In the case of this study, the needle was heated for 120 seconds: initial 30 seconds, which are not taken into account in the data log, as it is the time required for the sample to enter thermal equilibrium; 90 seconds, in which data were taken from an average of 46 measurements per sample.

The dimensions of the sample, again according to ASTM D5334 (ASTM D5334, 2014), have to be at least those of the calibration specimen, which is made with anhydrous glycerin: cylinder of 7.20 cm in length and 4 cm in diameter. Additionally, the calibration of the apparatus was carried out with reference to the conductivity of glycerin (0.286 W/Km (ASTM D5334, 2014)) as shown in **Figure 4.** A calibration factor "C of 0.9698"was obtained.

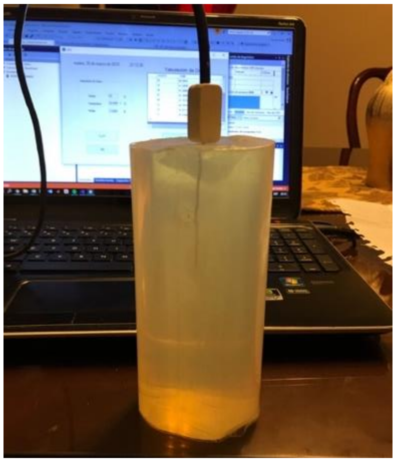

Figure. 4. Calibration process of the equipment in a glycerin cylinder

The samples were left inside the laboratory 24 hours prior to the test, so that they enter into thermal equilibrium with the environment.

It should be noted that, depending on the hardness of the sample, the needle may simply be sunk or perforation of a gap of slightly larger dimensions may be required.

To ensure the contact between the needle and the material, and therefore the transmission of heat to the medium under study, a thermal grease (thermal paste / grease) of high conductivity was used. The perforation had the same needle length (6 cm in length). The diameter of the needle is 1 mm.

Figure 5 shows one of the tests carried out on the blocks of cooked clay, where the needle was placed at the top, after drilling the sample and placing thermal grease**. Figure 6** shows the test carried out on the straw bale.

Figure. 5. Thermal needle probe on a block of cooked clay

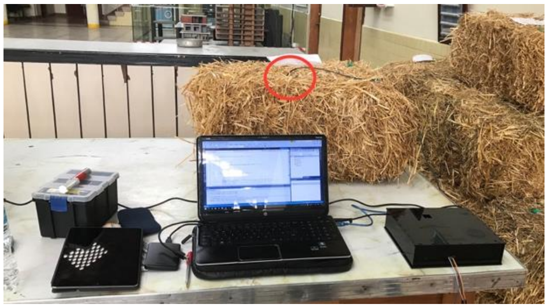

Figure. 6. Thermal needle probe on a straw bale

Once the needle is entered, a constant current is applied, so that the recorded temperature changes are less than 10 Kelvin in 1000 seconds. Relating the current with the voltage value (Ohm's law) the following values were used: 8.50 volts for the bricks and block, 8.55 for the plaster and, for straw 3.20.

With the data obtained, a linear regression of the temperature vs the natural logarithm of time was performed. An adjustment curve was obtained whose slope (S) is related to the heat input (Q) and the calibration factor (C) to calculate the thermal conductivity (λ):

$$Q = \frac{V^2}{R*L} \quad (1)$$

$$\lambda = \frac{C*Q}{4*\pi*S} \quad (2)$$

V= Voltage
R = Characteristic resistance of the needle (69.9 ohms, provided by the manufacturer)
L = Needle Length (6cm)

Of all the trials (69) in the different samples (26 artisanal bricks, 10 artisanal blocks, 10 industrial, 13 bales of straw and 10 plaster mortars), the median was calculated to characterize the materials. The NTE INEN 3066 Standard, Concrete Blocks. determines that the number of blocks to be tested according to the selected property is at least three.

The tests were conducted during the month of April 2019. The average temperature of the laboratory was 19.64 degrees Celsius and the relative humidity 59.91%.

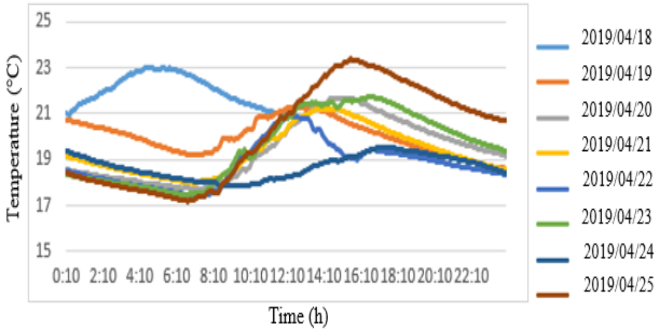

Figure. 7. Hourly Temperature of Materials testing laboratory in Faculty of Engineering and Applied Sciences Universidad Central del Ecuador.

From the previous figure, minimum temperature values of 17.20 ° C and maximum of 23.38 ° C were recorded, and that the average temperature in the analyzed period was 19.64 ° C.

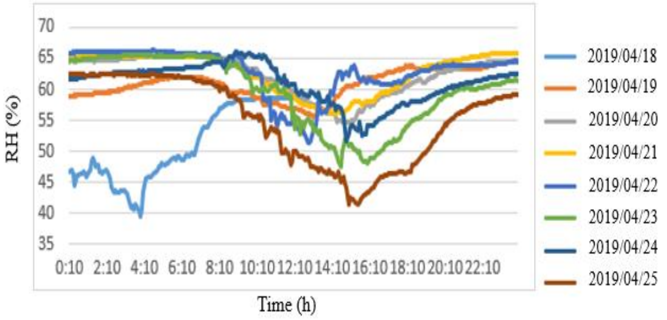

Figure. 8. Hourly Relative Humidity of Materials Testing Laboratory in Faculty of Engineering and Applied Sciences Universidad Central del Ecuador.

Similarly, the minimum relative humidity value recorded was 39.43%, the maximum was 66.25% and the average was 59.91% (**Figure 8**).

These data (**Figure 7** and **Figure 8**) determine the atmospheric conditions in which the tests were developed and should allow their repetition in future research. This is due to the fact that the influence of these factors is not fully understood. In fact, the effects of temperature and pressure on thermal conductivity are ambiguous: "Temperature is known to affect thermal conductivity, but how and to what extent is still uncertain" (Midttømme & Roaldset, 1999).

3. Results and Discussion

The thermal conductivity results are shown in **Table 3**.

Table 3. Thermal conductivity of the materials tested. [12](IRAM, 2004) [5](Costes et al., 2017) [13](Lira-Cortés et al., 2008) [3](Bustamante et al., 2018) [6](Cuitiño et al., 2015) [7](Dondi et al., 2004) [18](Sassine et al., 2017) [8](Gurskis & Skominas, 2013)

Id	Element	Thermal Conductivity (W/K.m)				
1	*Artisanal bricks*	0.344	0.910 [12]	0.492 [7]	0.690 [4]	0.811 [5]
2	*Artisanal blocks*	1.207	0.810 [12]	0.391 [13]	0.312 [3]	1.630 [6]
3	*Industrial blocks*	0.986	0.810 [12]	0.391 [13]	0.312 [3]	1.630 [6]
4	*Straw bale*	0.045	0.070 [5]	0.0487 [8]	0.050 [8]	0.067 [6]
5	*Plaster*	1.243	1.160 [12]	1.410 [4]		

In **Table 3**, the first column of data is that of the median of the experimental results of thermal conductivity of the materials with which the tested mountings are made. The other columns show results obtained in different studies.

In analysis of results, it shows variability of the thermal conductivity values obtained with respect to various references. This variation, (Ouedraogo et al., 2019), is due to factors such as: density, porosity, content of averagee humidity and temperature of the material.

In the case of straw bale, its variations are much smaller compared to those of other materials.

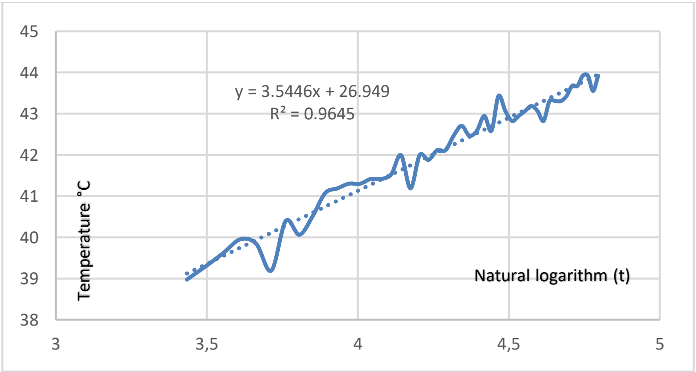

Figure. 6. Temperature vs natural logarithm of time plot.

The figure above shows the standard plot that it´s obtained analyzing the results of the thermal conductivity test. As seen, the adjusted curve has a positive slope pointing out that, with an increase of time, the temperature will rise. This behavior shows significant variances along the curve, in points where the data trend indicates an abrupt drop or rise of temperature in a small interval of time (Mosquera, 2013). This method has a high sensibility to temperature variations. Based on the results of this investigation, we can speculate that this discrepancy depends on the porosity and density of the material on study. To assure this, on all the tests performed the correlational coefficient (R2) was calculated. The trend shows that bricks, whom are more compact in this case, tends to have a greater coefficient than the others materials in study. This implies that this kind of materials (compact and with less porosity), show less variance of temperature.

The following **Table 4** shows the standard deviation of the obtained thermal conductivity data.

TABLE 4. Standard deviation of the obtained thermal conductivity data.

Element	Material	Type	Standard Deviation of the data (Thermal Conductivity)
Artisanal bricks	Burned Clay	LA	0.385
		LB	0.332
		LC	0.314
Artisanal blocks	Cement concrete with pumice	BA	1.149
Industrial blocks	Cement concrete	BB	0.986
Straw bale	Straw	F	0.045
Plaster		R	1.243

According to the Ecuadorian Construction Standard NEC 11, (MIDUVI, 2018) is considered thermal insulating material when its surface heat exchange coefficient is λ less than λ < 0.085 kcal / m2.°C measured at 20°C (mandatory) or 0.10 W / m2.K. The thermal transmittance is inversely proportional to the thermal resistance.

Likewise, an insulating material is one that has a thermal conductivity value less than 0.05 W/K.m. (Sassine et al. 2017)

4. Conclusions

The thermal needle probe method yields result of the same order of magnitude as those presented in the literature.

The results are especially close to those of the literature in the case of straw and plaster mortar. For artisanal brick, the results are relatively low, but it is the opposite for artisanal and industrial blocks. These differences can be explained by considering the constructive differences between Quito and other sites.

The thermal needle probe method clearly shows differences between construction materials, which allows to establish, in a first approximation, its thermal quality.

A limitation of the study is the cost of commercial thermal probes, around 8,000 USD, apart from the need to import them, which forced its handmade construction. This may affect the results due to the need for probe calibration.

On the other hand, the results of the bales of straw indicate their excellent insulating properties, which makes it an alternative to obtain indoor environments with controlled temperatures with low energy consumption.

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