A Simple Method to Measure the Thermal Conductivity of a Compressed Earth Brick

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Abstract. In this study, a simple method for measuring the thermal conductivity of a compressed earth brick is presented. The principle of the method is based on the measurement of the temperature on one side of the brick while the opposite side is subject to a constant density of heat flux. Five thermocouples were placed on each side to monitor the temperatures on both sides of the brick. A numerical model of heat transfer by single-dimensional conduction at transient speed is developed to calculate the temperature at any point in the brick. The estimation of thermal conductivity is carried out by an inverse technique to reduce the difference between the measured and calculated temperature profiles respectively. The proposed method is validated by direct measurement of thermal conductivity by the hot disk technique TPS 1500. The obtained results showed that the developed device enables the measurement of the thermal conductivity with good precision.

Keywords: Compressed earth brick · Thermal conductivity · Thermal diffusivity · Hot disk · Reverse technique

1 Introduction

Improvement of the thermal properties of common/usual construction materials such as earth brick, concrete, and fired bricks has been a focus of interest for many scientists. Heat transport through a material is typically described using three primary properties: thermal conductivity, thermal diffusivity, and specific heat. The thermal conductivity is the ability of a material to transfer the heat it captures whereas the thermal diffusivity determines the speed at which heat is propagated in a material or the ability of this material to slow down the transfer of heat.

Measuring the thermal properties of construction materials is essential to determine their aptitude to insulate a building and to bring thermal comfort indoors. In fact, building materials are the primary barrier for protection from outside conditions. Several methods have been developed in the literature for measuring the thermal properties of these materials. These methods are divided into two groups: those working in a steady state, such as the hot plate method and the box method, and those working in a transient regime, like the hot wire method and the hot disk method.

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The hot plate method consists of placing the sample between a heating plate which imposes uniform flux on one side of the sample, while the other side is kept cold at a constant temperature. Laaroussi et al. [1] used the hot plate method to measure the thermal conductivity of fired bricks. Boumhaout et al. [2] also used this technique to evaluate the thermal insulation properties of a composite material based on cement mortar and date palm fibers. Moreover, Saidi et al. [3] used the same technique to highlight the effects of some stabilizers on the thermal conductivity of raw earth bricks.

The hot wire method, which works in a transient regime, is one of the most widely used methods to measure the thermal conductivity. The principle behind this technique is rather simple. It is based on the measurement of the transient temperature resulting from the heat transfer produced by a local heating of the sample [4, 5]. The hot disk method uses the same principle as the hot wire technique with the difference that the heating element is a hot disk sandwiched between two identical samples of the material to be characterized. Likewise, Bouchefra et al. [6] used the hot disk method to measure the thermal conductivity of earth bricks reinforced by doum fibers.

However, the above-mentioned techniques remain expensive even though they are accurate. Therefore, it is expected that the development of simple techniques for the measurement of thermal conductivity that only require simple instrumentation lead to innovative devices.

Following this idea, Derbal et al. [7] developed a simple method to measure the thermal conductivity and volumetric heat capacity. The building material to be characterized is sandwiched between two layers of a reference material whose thermophysical properties are known. The method consists of recording the temperature time variation when the entire multilayer component is subject to stimulation. The thermal properties of the sample were identified using a numerical model. In the same way, Xu et al. [8] presented an analytical model for predicting the transient temperature distribution for determining the thermal properties of asphalt concrete.

The purpose of this paper is to present a novel experimental method of measuring the thermal conductivity of a compressed raw earth brick. The brick is subject to a constant heat flux density. The thermal conductivity of the brick is estimated by applying Fourier's law and measuring the temperature gradient between the two sides of the brick. The thermal conductivity was also measured directly using the hot disk method to validate the results obtained using this method.

2 Production of the Brick

The soil used in this study was extracted from the Amizmiz region in Morocco. The bricks are made by sieving soil at 2 mm before drying it at 60°C for 24 h. To ensure the stability of the bricks, 9% of lime was added to the soil. The mixture composed by soil and lime was mixed for 3 min before the optimal amount of water determined by the Proctor test was added. After that, the mixture was put in a mold of 5 cm × 5 cm × 4 cm and pressed to 9.7 MPa using a hydraulic press (Fig. 1). After demolding, the sample was wrapped with plastic film and stored in the laboratory for 28 days of cure. The specimen was then dried in an oven at 60°C until it had a constant weight before measuring the thermal properties.

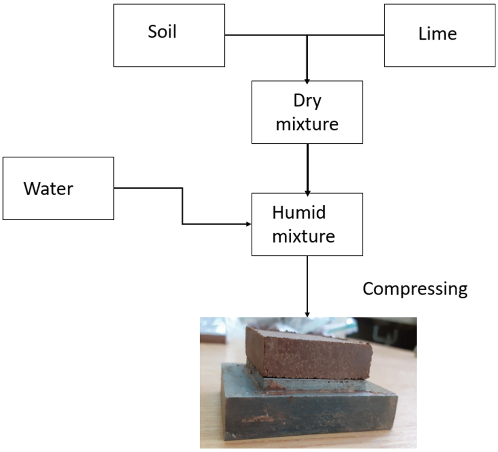

Fig. 1. The process of compressed earth brick production

3 Thermal Conductivity Measurement Using the Developed Method

The proposed method in this work consists of imposing a constant density of heat flux on one side of the brick. The heating is provided by a thin electric resistance heating plate (7Ω) which is glued on the face of the brick to diffuse constant electrical power. Five thermocouples were placed on each side, as shown in Fig. 2 to monitor the temperatures on both sides of the brick. To reduce heat loss, the device was insulated with a 10 cm layer of polystyrene and covered with aluminum paper. The experiment was carried out in an air-conditioned room at a temperature $T_a = (20 \pm 1)$°C to reduce temperature fluctuations that may affect the measurements (Fig. 3).

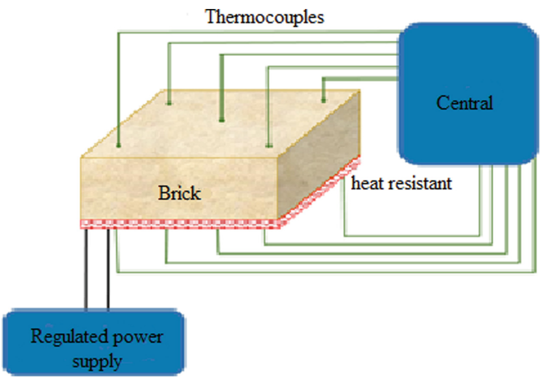

Fig. 2. Diagram of the brick with the location of the thermocouples for the temperature measurement of each side as a function of time

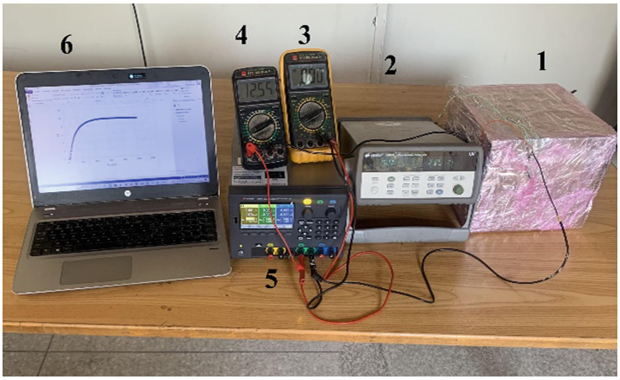

Fig. 3. Picture of the experimental device used for measuring thermal conductivity including **1** a polystyrene box containing the brick with thermocouples, **2** an acquisition unit, **3** a voltmeter, **4** an ammeter, **5** a stabilized power supply, and **6** a computer for processing

4 Principle of Measurement

The heat transfer in a brick subject to a constant flux density on one of its two faces can be modeled by the mono-dimensional transient conduction as shown in Fig. 4.

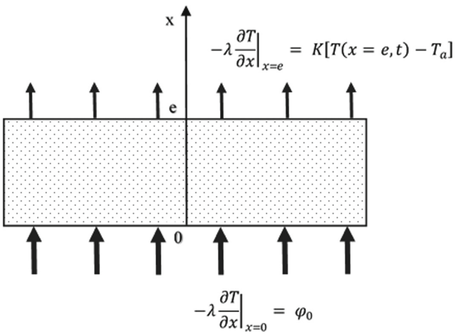

Fig. 4. Model of the brick subject to a constant flux density with its boundary conditions

Assuming that the thermal properties of the brick are constant, the equation of the model with its initial and boundary conditions are written based on Fig. 4 as follow:

$$\frac{1}{a}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} \tag{1}$$

$$T(x,\ t = 0) = T_a \tag{2}$$

$$-\lambda \frac{\partial T}{\partial x}\bigg|_{x=0} = \varphi_0 \tag{3}$$

$$-\lambda \frac{\partial T}{\partial x}\bigg|_{x=e} = K[T(x = e,\ t) - T_a] \tag{4}$$

In Eqs. (1) to (4), a is the thermal diffusivity, λ is the thermal conductivity and K is the global heat transfer coefficient between the top face of the brick and the outside air. By accounting for the thickness of the insulation and the ambient temperature of the room where the measurements were undertaken, the calculated value of K amounts 0.4 W m^{-2} K^{-1}.

The resolution of Eq. (1) is performed by the numerical method of centered finite differences. The discretization of the solution interval [0; e] is done with a constant step. The solution of the discrete problem is achieved by the relaxation technique of Gauss-Siedel by taking 10^{-5} as the criterion of convergence.

5 Numerical Results

Figure 5 shows the temperature profile in the brick at $t = 600$ s ($a = 10^{-7}$ m s^{-2}, $\lambda = 1$ W m^{-1} K^{-1}) with a flux density of 800 W m^{-2}. The heat flux is found to be locally variable. Figure 6 shows the variation of the temperature difference between the two sides of the brick, ΔT, as a function of time. We observe from Fig. 6 that ΔT first increases as a function of time and then tends towards a constant value in the steady state.

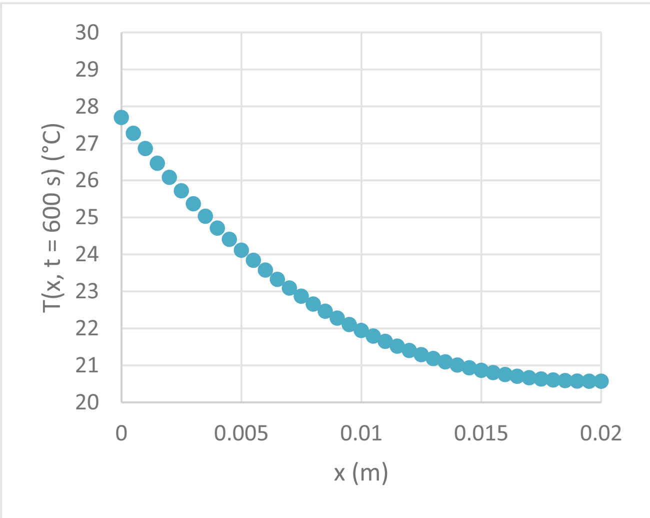

Fig. 5. Numerical simulation of temperature variation in the brick

Based on Figs. 5 and 6, we can estimate the thermal conductivity at steady state using the Fourier law applied for $x = e/2$, as given in Eq. (5):

$$\lambda = \frac{\varphi_0 e}{2\Delta T} \tag{5}$$

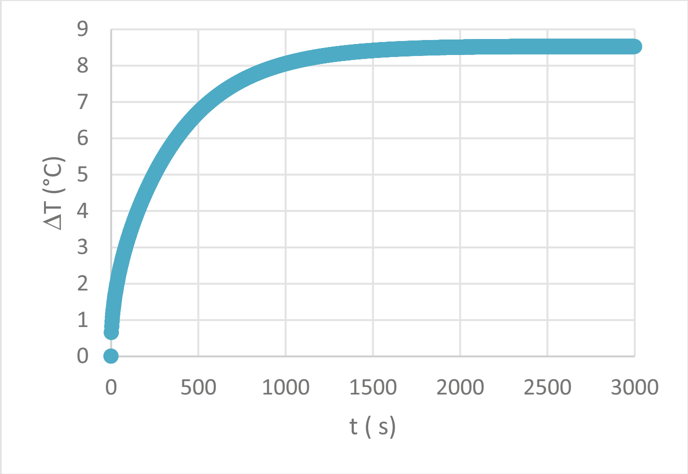

Fig. 6. Simulation of the temperature difference between the two sides of the brick as a function of time

To validate Eq. (5), we performed several simulations with different thermal conductivity values. After each simulation, the thermal conductivity calculated by Eq. (5) was compared to the value fixed as the calculation data. Table 1 summarizes the results of these simulations. It is observed that as thermal conductivity increases, the relative error decreases. However, this error remains low and less than 2%, which validates the estimation of thermal conductivity by the proposed method.

Table 1. Thermal conductivity estimation test using Eq. (5)

	Simulation N°1	Simulation N°2	Simulation N°3	Simulation N°4
The fixed thermal conductivity (W m^{-1} K^{-1})	0.5	1.0	2.0	3.0
Thermal conductivity recalculated by Eq. (5) (W m^{-1} K^{-1})	0.508	1.008	2.008	3.008
Relative error (%)	1.72	0.85	0.42	0.28

6 Experimental Results

The thermal conductivity is measured for 4 tests using the experimental setup shown in Fig. 3.

Figure 7 shows the variation of the temperature difference between the two sides of the brick for 4 values of the heat flux density φ_0. The thermal conductivity is deduced for each case using Eq. (5). The results of these tests are shown in Table 2. Thus, the thermal conductivity of the brick is estimated at (0.93 ± 0.03) W m^{-1} K^{-1}.

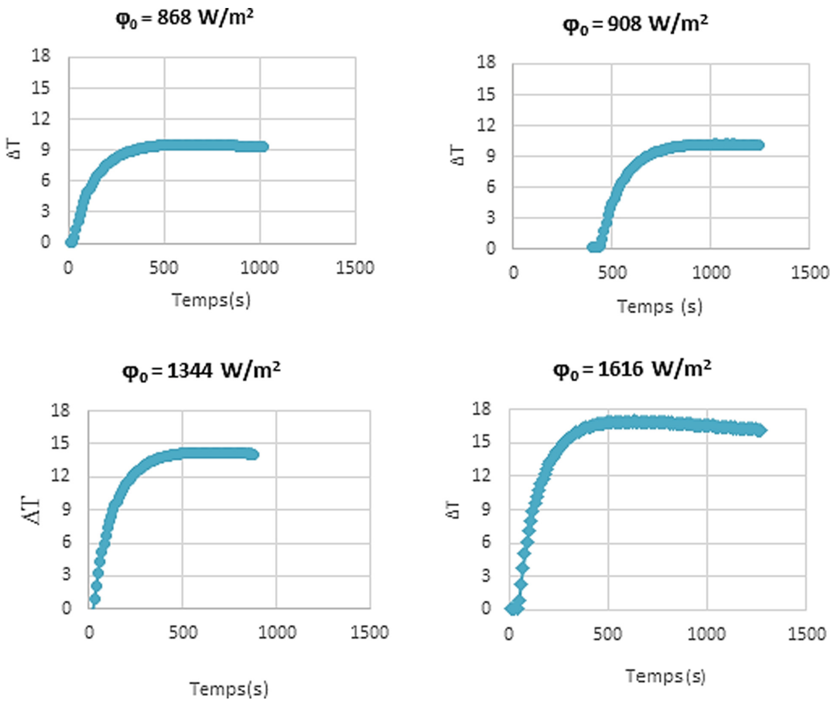

Fig. 7. Variation of the temperature difference between the two sides of the brick subject to different values of heat flux density

Table 2. Thermal conductivity measurements using setup of Fig. 2

Flux Density (W m^{-2})	868	908	1344	1616
Thermal conductivity (W m^{-1} K^{-1})	0.913	0.899	0.939	0.958

7 Validation of the Measures

In this study, the thermal properties of the compressed earth brick were measured using the TPS 1500 hot disk device (Fig. 8). This device allows simultaneous evaluation of thermal conductivity and diffusivity. The hot disk sensor is placed between two identical bricks (5 cm × 5 cm × 2 cm) and acts as a heat source and temperature sensor. The measurement principle is based on the transient plane source method. Table 3 presents the values obtained by the proposed method as well as the hot disk method.

The obtained results are similar to those obtained by Boussaa et al. [9] and Hany et al. [10].

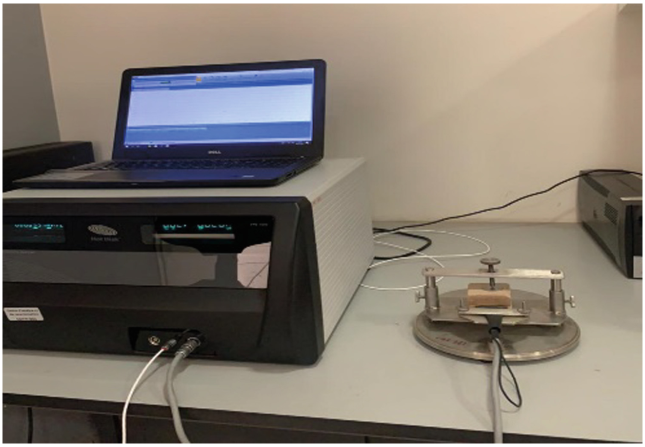

Fig. 8. Thermal conductivity measurement by TPS 1500 hot disk method

Table 3. Thermal conductivity values as measured by the proposed method and by the hot disk method

	Proposed method	Hot disk method
Thermal conductivity (W m^{-1} K^{-1})	0.93 ± 0.03	0.92 ± 0.02
Relative deviation (%)	1.1	

8 Conclusion

This article has presented a simple method for the thermal characterization of a brick material. A constant density of heat flux is imposed on one side of the brick. Five thermocouples were placed on each side to monitor the temperatures on both sides of the brick. Thus, the variation of temperature as a function of time is recorded to establish a relationship between the thermal diffusivity, thermal conductivity, temperature, and time. A mathematical model was implemented to stimulate the variation of temperature versus thickness and time. Based on this stimulation and the Fourier law, the thermal conductivity in the steady state was identified depending on the heat flow imposed. To validate the obtained results, we measured the thermal properties of compressed earth bricks using the hot disk method TPS 1500. This research could lead to the following findings:

- The measured thermal conductivity of compressed earth brick using the developed method was found to be 0.93 ± 0.03 W m^{-1} K^{-1}.
- The measured thermal conductivity of compressed earth brick using the hot disk device was found to be 0.92 ± 0.02 W m^{-1} K^{-1}.
- The comparison of the result obtained with that measured using the hot disk device yielded a slight relative deviation of 1.1%.
- This model allowed to measure the thermal conductivity with good accuracy.

- This promising result opens a prospect for developing a simple, low-cost technique for measuring thermal conductivity.

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