



Simulation of Thermal Conductivity with Comsol Multiphysics of Clay

Zakaria Kbir, Bouazza Tbib, Mohamed Faoussi and
Khalil El-Hami

EasyChair preprints are intended for rapid
dissemination of research results and are
integrated with the rest of EasyChair.

April 20, 2022

Simulation of Thermal Conductivity with Comsol Multiphysics of Clay

Zakaria Kbir¹, Bouazza Tbib¹, Mohamed Faoussi², and Khalil El-hami^{1*}

¹ University of Mohammed V, Rabat,
Scientific Institute, BP 703, Av. Ibn
Batouta, Agdal, Rabat, Morocco,

² Euro-Mediterranean University,
Health Science Laboratory, Fez,
Morocco

*elhami_k@yahoo.com

Abstract. This work focused on the simulation of thermal conductivity for Moroccan Clay. It was obtained that the finite element simulation in Comsol Multiphysics has a remarkable reproducibility with respect to the conventional theoretical model. Besides this type of analysis provides a substantial advantage, being able to vary the different parameters of the experiment, such as the radial distance, the heat flux, the initial temperature, among others, and thereby optimize the results.

Keywords: simulation, thermal conductivity, Clay, finite element, Comsol Multiphysics, theoretical model and heat flux.

1 Introduction

This Heat transfer is the area which describes the energy transport between material bodies due to a difference in temperature, and its development and applications is of fundamental importance in many branches of engineering since provides economical and efficient solutions for critical problems encountered in many engineering items of equipment. Among the parameters that determine the thermal behaviour of a material, the thermal conductivity is especially important because it represents the ability of a material to transfer heat, and it is one of the physical quantities whose measurement is very difficult and it requires high precision in the determination of the parameters involved in its calculations [1, 2]. The hot wire technique is an absolute, no steady state and direct method which is considered an effective and accurate procedure to determining the thermal conductivity of a variety of materials, including ceramics, fluids, food and polymers [3-6]. However, this technique is based in a conventional mathematical model which is an approximation of the physical reality in the experimental setup because the complexity of the mathematical problem has been an obstacle to obtain a more realistic theoretical model [7, 8].

* No academic titles or descriptions of academic positions should be included in the addresses. The affiliations should consist of the author's institution, town/city, and country.

Fortunately, nowadays the development of the advanced numerical methods and computing systems allow the application of high level software for obtain an approximate solution to a complex mathematical problem with a boundary conditions congruent with the physical reality. In particular, Comsol Multiphysics is a powerful Finite Element (FEM) Partial Differential Equation (PDE) solution engine [9] useful to obtain a numerical solution in complex problems. In this work, the Comsol Multiphysics software is used to determinate the numerical solution of a transient temperature distribution in a sample measured by the hot wire technique configuration. The COMSOL Multiphysics software is used to calculate the problem of interest to us, namely the heating of a wire of platinum immersed in Clay. It is a tool for solving finite element partial differential equations. The modelling of a system such as the one studied here takes place in several stages. The first step is to define the physics "modules" that will be used. In this case, it will be the thermal module "heat transfer in solids" and the electricity module "Joule heating". The following phases of modelling are common to other physical modelling software. In chronological order, there are:

1. Drawing of the geometry of the system.
2. Choice of different materials in the property library.
3. Setting up of the boundary and initial conditions in each module with the possible coupling of these.
4. Mesh of the elements of the structure.
5. Choice of the solver and the convergence parameters, then resolution of the problem.
6. Post processing of the calculated data (here temperature and electric current).

In the last phase to process the results, there are several tools available to represent any computable physical quantity in the complete model, along a plan, along a line or a point. The parameters represented in 3D can also depend on time if the study is carried out in an unsteady state. We can then process the results directly in the software via the "report" tab or under another software such as Matlab, Excel or Origin Pro as in our case. The particular interest of COMSOL lies in the possibility that we have to couple different physical models. It is also possible to work in a steady state and in a transient state. The convergence of calculations in stationary mode is obviously faster. The work that is presented below therefore involves following the different stages of creating a model under COMSOL. One of the most delicate parts of this work consists in introducing the physics and the parameters used during the modelling (equation, initial conditions, boundary conditions, electricity modulus). This point and the associated problems are discussed below.

For this study we approach the problem according to two approaches. In the first case, we are interested in the two-dimensional (2D) modelling of a section of the experimental device. Secondly, taking into account the limitations of the 2D model, the last part of this study is centered on the comparison between the results of numerical simulations and the experimental measurements obtained thanks for this study we approach the problem according to two approaches. In the first case, we are interested in the two-dimensional (2D) modelling of a section of the experimental device. Secondly, taking into account the limits of the 2D model, the last part of this study is centred on the comparison between the results of numerical simulations and the experimental measurements obtained thanks to the experimental device.

2 Numerical modelling

In this first section, the basic equations and the boundary condition equations used in COMSOL to make numerical simulations are recalled. We then present the main stages of a typical modelling. A sub-section is also devoted to the determination of the convective exchange coefficient.

2.1 Thermal transfer module

In a solid, the heat transfer equation is written:

$$\rho C_p \frac{\partial T}{\partial t} - \lambda \Delta T = Q \quad (1)$$

With:

- ρ the density, in kg.m^{-3}
- C_p the thermal capacity, in J/kg .
- λ thermal conductivity, in W/m.K
- Q the term internal heat source, in W .
- T the temperature field, in K .

Conditions to the limits:

- Thermal insulation: $-n \cdot (-k \cdot \Delta T) = 0$.
- Natural convection: heat transfer coefficient by convection h imposed.
- Imposed initial temperature, equal to the ambient temperature ($T_{\text{init}} = T_0 = 293.15 \text{ K}$).

2.2 Electric module

The equations solved by the electrical module are:

$$\Delta J = Q_c \quad (2)$$

$$J = \sigma E + J_e \text{ Localized ohm's law}$$

$$E = -\nabla V \quad (3)$$

With:

- J is the density of the electric current, in A.m^{-2}
- σ : electrical conductivity, in S.m^{-1}
- E : electric field, in V.m^{-1}
- V : the electric potential, in Volt V .
- Q_c : the source term, in W .

The experimental heating system is modelled by the term internal heat volume source Q and which represents the energy dissipated by the Joule effect in the control volume considered. This energy results from an electric power dissipated by the Joule effect, namely:

$$P = U^2/R = U^2/(\rho \cdot l/s) = R \cdot I^2$$

With:

- P the electrical power, in W .
- R the resistance, in Ω .
- I the intensity of electric current, in A .

Boundary condition:

- Electrical insulation: $-n \cdot J = 0$
- Density of electric current imposed: $-n \cdot J = J_n$

3 System design and mesh

In order to represent the heating system used during the experiments, we will simplify the data of the problem by keeping only the characteristic dimensions of the key elements, namely the geometry of the platinum track and the overall size of the substrate.

3.1 System design

The platinum wire is 10mm in diameter, 32cm long. The sample of the syylinder of 32cm in high and 16cm in the diameter. The figure 1 presents the sample to be characterized with the heating wire.

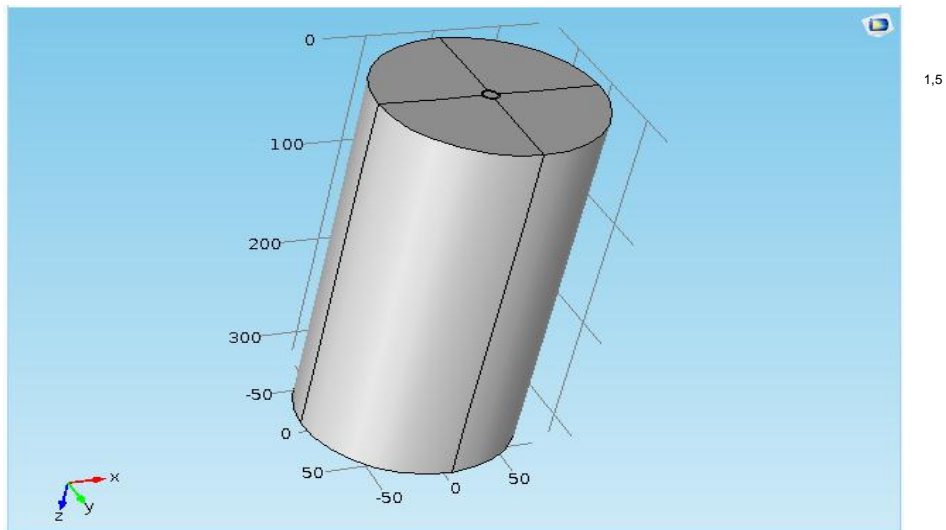


Fig. 1. Represents the sample to be characterized with the heating wire

3.2 Mesh

The mesh chosen is of fine size at the micrometric scale, the results of these parameters are given by the following figure 2.

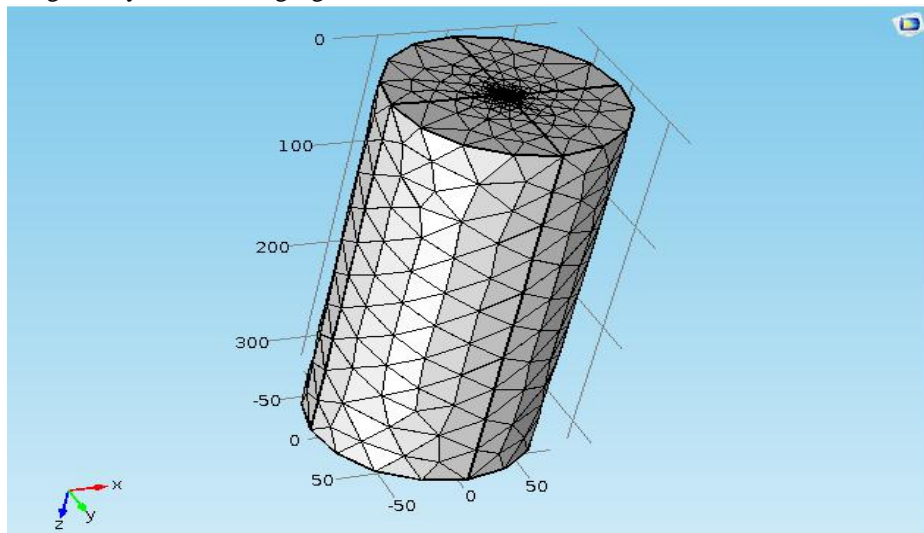


Fig. 2. Represents the sample to be characterized with the heating wire

- J is the density of the electric current, in $A.m^{-2}$
- σ : electrical conductivity, in $S.m^{-1}$

- E: electric field, in $V.m^{-1}$
- V: the electric potential, in Volt V.
- Q_c : the source term, in W.

The experimental heating system is modelled by the term internal heat volume source Q and which represents the energy dissipated by the Joule effect in the control volume considered. This energy results from an electric power dissipated by the Joule effect, namely:

$$P = U^2/R = U^2/(\rho \cdot l/s) = R \cdot I^2$$

With:

- P the electrical power, in W.
- R the resistance, in Ω .
- I the intensity of electric current, in A.

Boundary condition:

- Electrical insulation: $-n \cdot J = 0$
- Density of electric current imposed: $-n \cdot J = J_n$

or formulas are centered and set on a separate line (with an extra line or half line space above and below). Equations should be numbered for reference. The numbers should be consecutive within the contribution, with numbers enclosed in parentheses and set on the right margin. Please do not include section counters in the numbering.

$$x + y = z \tag{1}$$

4 3D simulation results

On the following diagram, we present the evolution of the temperature field in the 3D model.

The calculations were made for a linear electric power of 24.5W, which corresponds to the experiment exposed in the part of measurement experimental. The temperature field was obtained in transient permanent regimes with the chosen medium is Clay in figure 3.

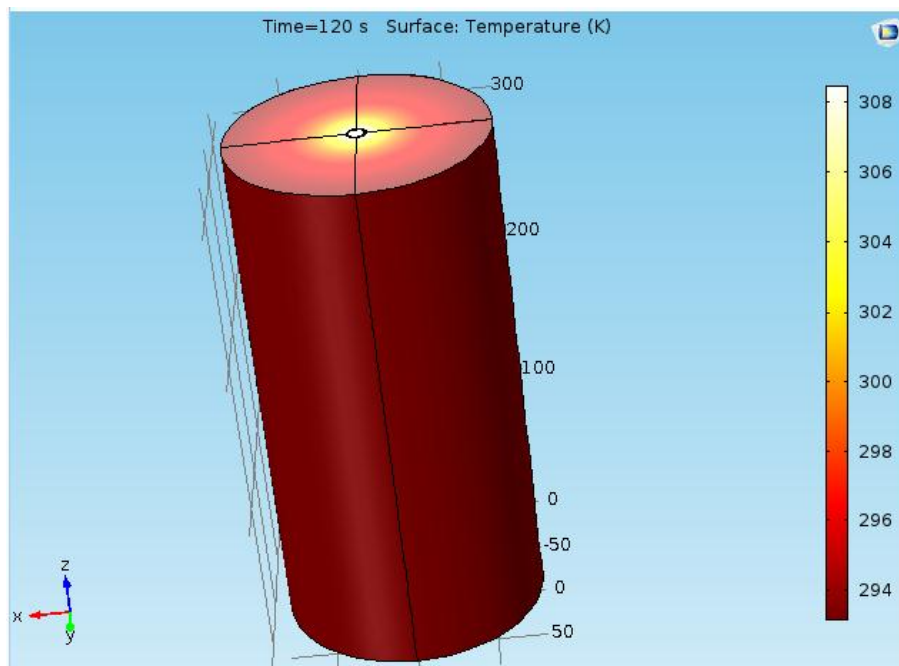


Fig. 3. Temperature at 120s

To have a good precision of thermal conductivity measurement it is necessary to avoid the effect of convection, and this requires a long time for opting the measurement in a

6
permanent regime.

4.1 The temperature variation in the wire

Over time the temperature of the wire increases in a logarithmic manner which is in agreement with the theory of the hot wire, the following figure represents the variation of the temperature of the 3 position as a function of time in figure 4.

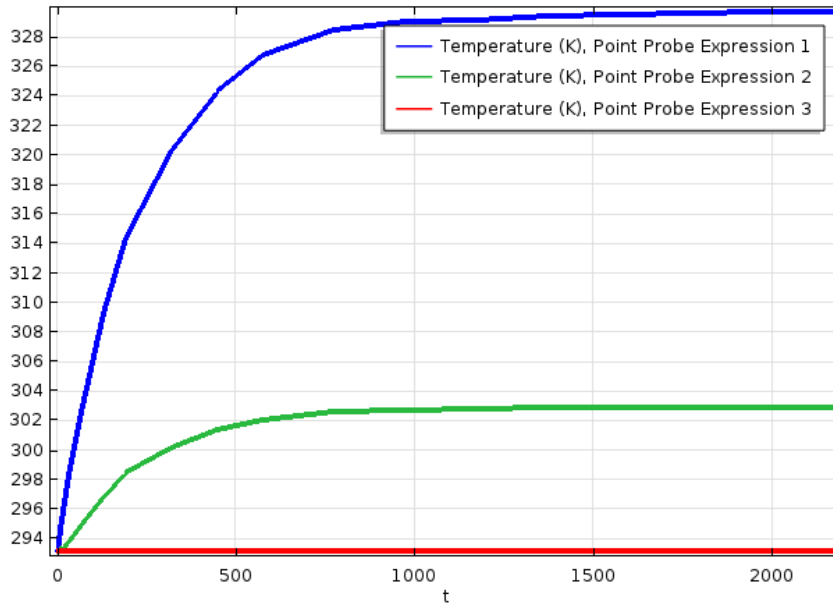


Fig. 4. Evolution of the temperature in 3 point r=6mm; r=40mm; 80mm

4.2 Calculates the thermal conductivity of Clay

The values found of the thermal conductivity in all the experimental, bibliographic and simulated are:

$$\lambda_1 = \lambda_2 = \lambda = \frac{\Phi \ln\left(\frac{r_3}{r_1}\right)}{2 \pi L (T_1 - T_3)} \text{ en régime permanent.}$$

With φ is the electrical power $\varphi = 24,5W$

The value of simulation current work

$$\lambda_{cal} = \frac{\varphi \ln\left(\frac{r_3}{r_2}\right)}{2\pi L (T_2 - T_3)} = \frac{24,5 \ln\left(\frac{80}{40}\right)}{2\pi * 0,32 (303 - 293)} = 0,84 W.m^{-1}.K^{-1}$$

The bibliographic value

$$\lambda_{cal} = 0,7 W.m^{-1}.K^{-1}$$

4.3 Manufacture of specimens

A metal mold 16 cm in diameter by 32 cm in height and a 12-tonne hydraulic compacting press are used to make the test specimens. The water content is assessed during the preparation of the specimens. Once the mixture is well homogenized, it is introduced into the mold and subjected to a pressure of some MPa to obtain a cylindrical specimen (see figure 37). It is first dried at room temperature within the company for a week and then in an oven for 24 hours at 80°C. The specimens are arranged for the measurement of the conductivity according to the paragraph (experimental device above) and the results are presented in tables 1 to 6 and figure 5 to 13.



Fig .5. Manufacture of specimens [current work]

4.4 Experimental apparatus

The thermal characterizations were carried out at the LERMAB Laboratory. The diagram of the experimental device is shown in figure 33. It consists:

- A special stainless steel ACIM JOUANIM heating cartridge with 50 W power and 10 mm in diameter.
- From a 10/12 copper tube.
- Type K thermocouples, jacketed 0.5 mm in diameter with welding
- warm insulated. Data acquisition (temperatures) is done using an ALMEMO 2290-8 acquisition unit which has been calibrated beforehand.
- Voltage and current are measured by a BBC M 2042 precision multimeter.
- The voltage is adjusted by a “Variac” type variable resistor.

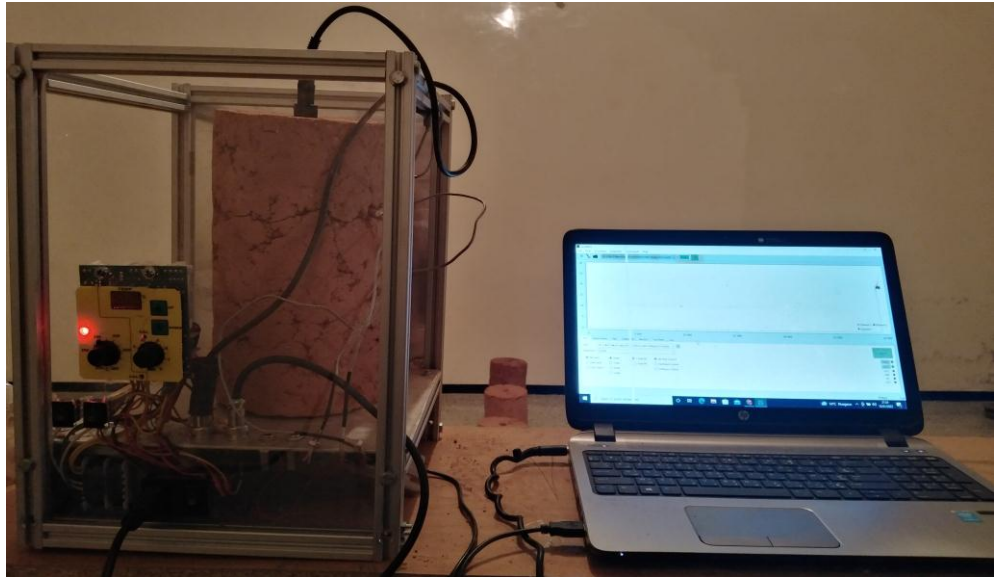


Fig. 6. Experimental device [current work]

Temperature measurements are made with type K thermocouples, jacketed 0.5 mm in diameter with insulated hot junction. The position of the thermocouples is represented by figure 6 and the photograph of the experimental device is represented by figure 5 and 6.

4.5 Thermal conductivity measurement

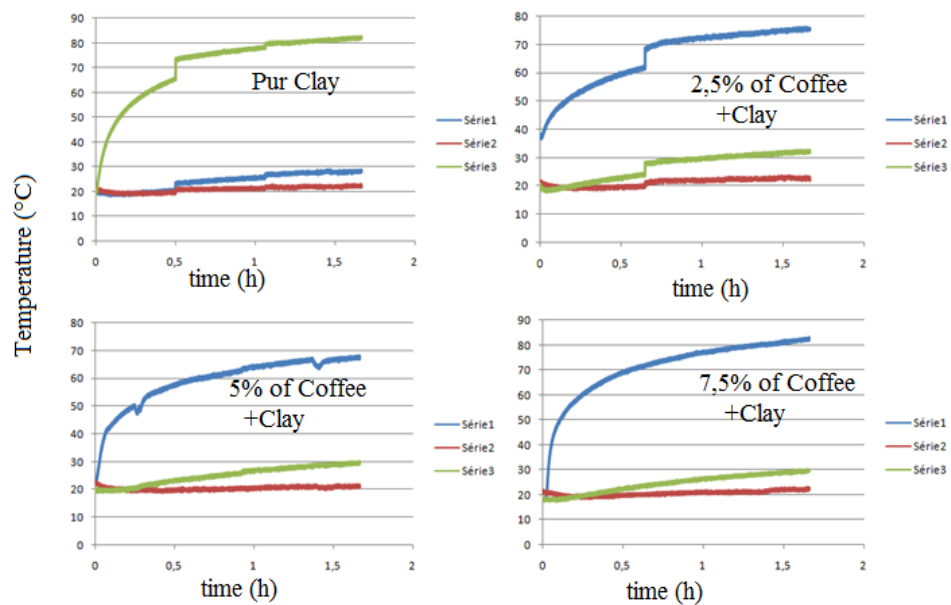


Fig.7. variation of temperature according the time, Blue curve at $r=0$, Red curve at $r=8\text{cm}$ and Green curve at 4cm [current work]

Table 1: illustrate the Thermocouple temperature of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay	Thermocouple temperature (r=0cm) °C	Thermocouple temperature (r=8cm) °C	Thermocouple temperature (r=4cm) °C
0	82,25	22,25	28,25
2,5	75,5	23	32,5
5	67,75	21	29,75
7,5	82,25	22,5	29,75

Table 2: illustrate the Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay %	Temperature difference of thermocouples (r=8 ;r=0) °C	Temperature difference of thermocouples (r=0 ;r=4) °C	Temperature difference of thermocouples (r=8 ;r=4) °C
0	60	54	6
2,5	52,5	43	9,5
5	46,75	38	8,75
7,5	59,75	52,5	7,25

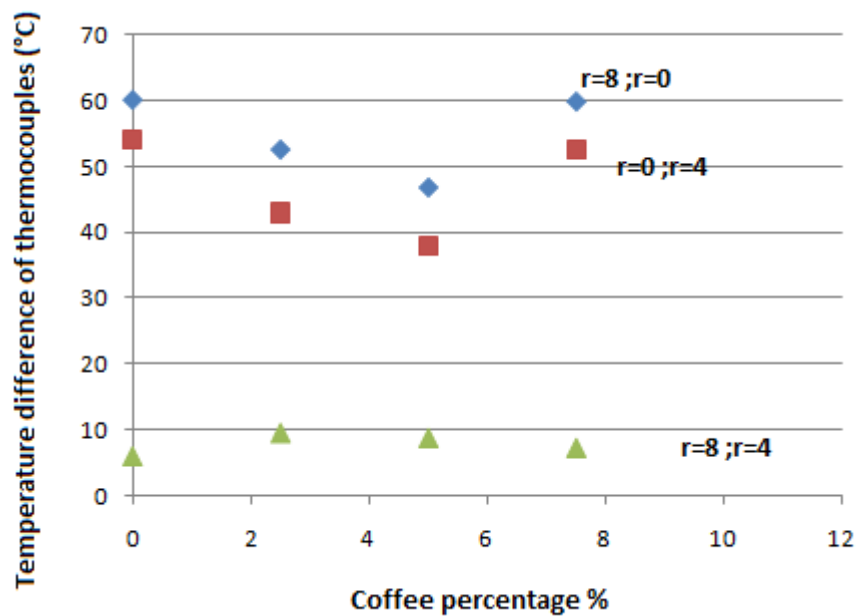


Fig.9. Variation of Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

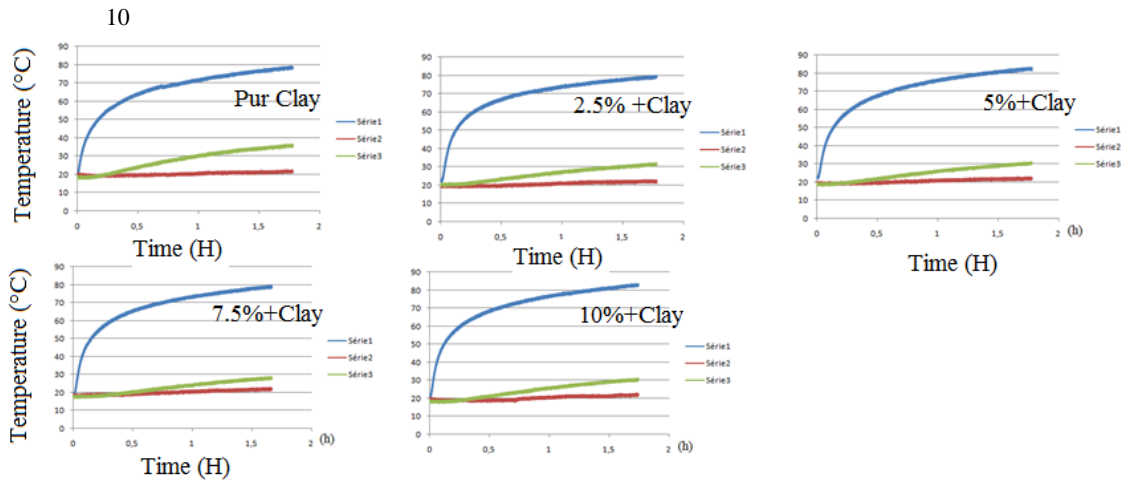


Figure .8. Variation of temperature according the time, Blue curve at $r=0$, Red curve at $r=8\text{cm}$ and Green curve at 4cm [current work]

Table 3. Illustrate the Thermocouple temperature of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay %	Thermocouple temperature ($r=8\text{cm}$) °C	Thermocouple temperature ($r=4\text{cm}$) °C	Thermocouple temperature ($r=0\text{cm}$) °C
0	22,5	39,25	82,25
2,5	23,25	34,25	82
5	22	28,25	78,5
7,5	22,5	30,5	82,75
10	22,25	32	84

Table 4. Illustrate the Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay %	Temperature difference of thermocouples ($r=8 ; r=4$) °C	Temperature difference of thermocouples ($r=8 ; r=0$) °C	Temperature difference of thermocouples ($r=0 ; r=4$) °C
0	16,75	59,75	43
2,5	11	58,75	47,75
5	6,25	56,5	50,25
7,5	8	60,25	52,25
10	9,75	61,75	61,75

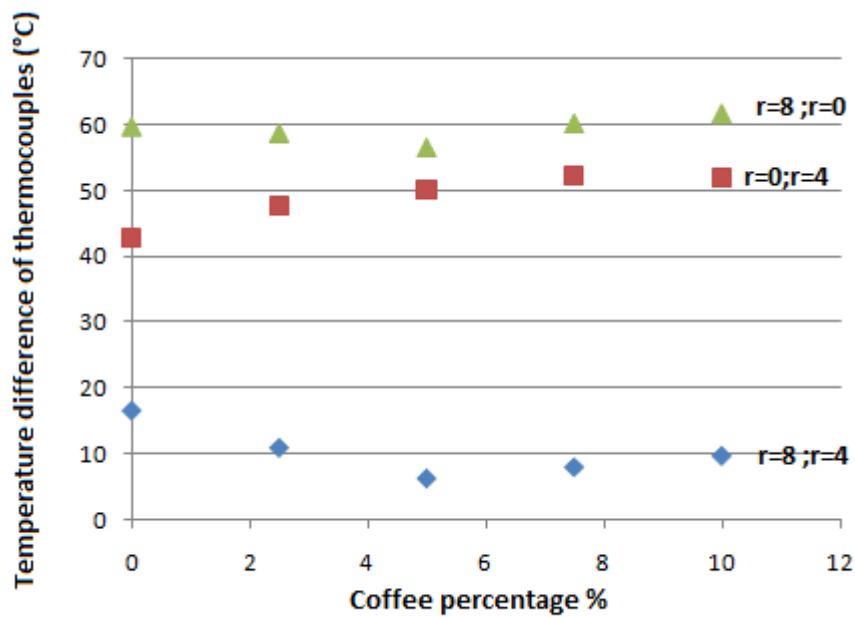


Fig.10. Variation of Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

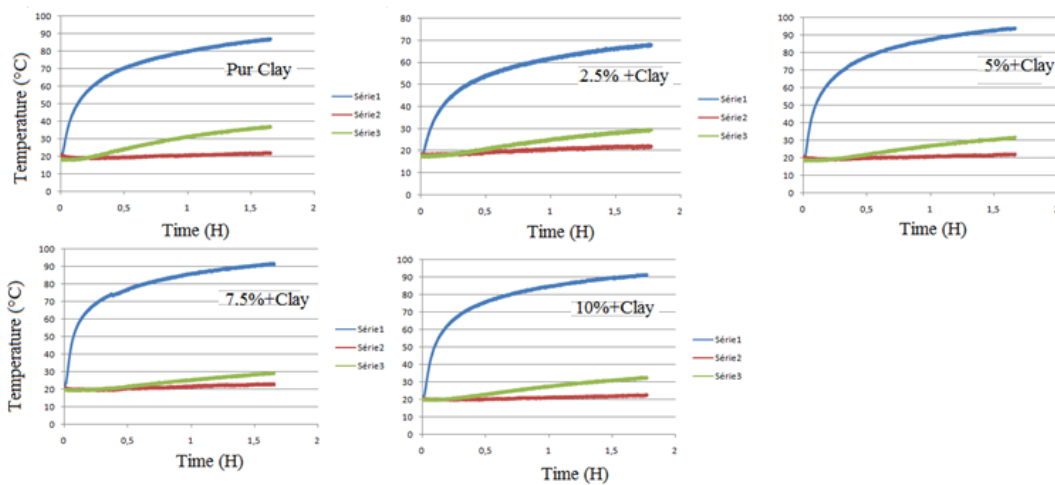


Fig.11. Variation of temperature according the time, Blue curve at $r=0$, Red curve at $r=8\text{cm}$ and Green curve at 4cm [current work]

Table 5. Illustrate the Thermocouple temperature of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay %	Thermocouple temperature ($r=8\text{cm}$) °C	Thermocouple temperature ($r=4\text{cm}$) °C	Thermocouple temperature ($r=0\text{cm}$) °C
0	22,25	36,75	86,5
2,5	23,5	33	71,5
5	23	29,75	92,5
7,5	22,75	32,5	91,15
10	22,5	31,75	94,25

Table 6. Illustrate the Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

Coffee percent in Clay %	Temperature difference of thermocouples (r=8 ;r=4) °C	Temperature difference of thermocouples (r=8 ;r=0) °C	Temperature difference of thermocouples (r=0 ;r=4) °C
0	14,5	64,25	49,75
2,5	7,5	49	48,5
5	6,75	69,5	62,75
7,5	9,75	69,5	58,6
10	9,25	71,75	62,50

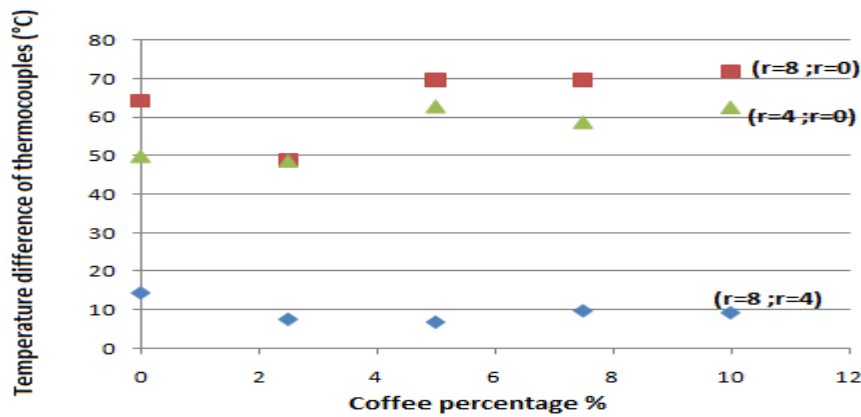


Fig.12. Variation of Temperature difference of thermocouples of deferent percentage of coffee in the range permanent [current work]

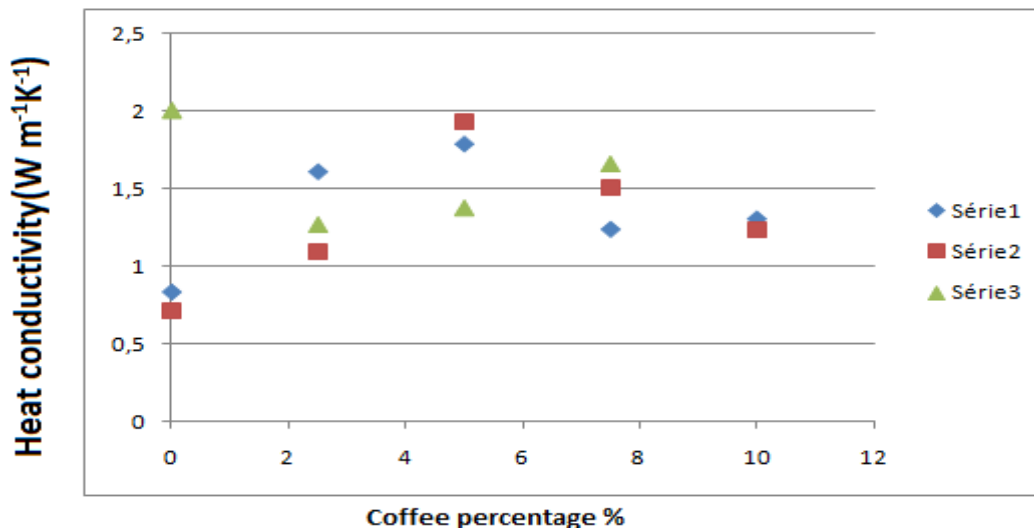


Fig.13. Heat conductivity of clay according percentage of coffee [current work]

In this part, the thermal conductivities and the mechanical characteristics of the specimens prepared in several formulations will be analyzed and discussed in order to understand the influences of coffee in the mixture as well as the compaction stress and the rate of sand. The thermal conductivity values of all formulations vary as shown in the figures below. The highest value is given by the formulation prepared with 90% clay and 10% coffee. A material composed of fine and coarse elements gives a much denser final product than a material prepared with only fine elements. Indeed, the value of its thermal conductivity is also high. For coffee-stabilized specimens, the higher the coffee content, the lower the thermal conductivity value. This phenomenon is explained

by the fact that 7.5% of coffee in the mixture is enough for high values. Voids are created in the sample. This causes the thermal conductivity value to drop. As the amount of coffee increases, all pores are sealed and the material becomes compact. Consequently, the thermal conductivity value increases up to 6.5% and then remains stable up to 10% coffee.

5 Conclusion

This research work has highlighted the advantage of local materials in construction. They are economical and have a low environmental impact. A new method for determining thermal conductivities has been implemented at jball nour. This is the hot wire adapted to a cylindrical test piece 16 cm in diameter by 32 cm in height. This device takes into account some difficulties stated on the other methods, such as radial and axial heat leaks and edge effects. It can be validated as a new hot wire method if the experimental conditions are improved (control of atmospheric conditions). The thermal conductivity values obtained by this method prove that the different formulations tested in this research work do not lead to insulating materials. We rely on the high thermal inertia of the material to improve interior comfort.

References

1. Terry M. Tritt, Thermal Conductivity, theory properties and applications, Springer, New York USA (2004).
2. Roland W. Lewis, Perumal, Fundamentals of the finite element method for heat and fluid flow,
3. Nithiarasu, Kankanhally N. Seetharamu, Wiley (2008).
4. W. N. dos Santos, J. Eur. Ceram Soc. 23, 745- 755 (2003).
5. M. Khayet and J. M. Ortíz Zarate, Int. J. Thermophys. 26, 637-646 (2005).
6. H. B. Nahor, N. Scheerlinck, J. F. Van Impe, B. M. Nicolai, J. Food Eng. 57, 103-110 (2003).
7. W. N. dos Santos, Polym. Test. 26, 556-556 (2007).
8. H. S Carslaw, J. C Jaeger, Conduction of Heat in Solids, Second Edition, pag 255-262 Editorial Oxford Science Publications (1954).
9. W. N. dos Santos, J. European Ceramic Society, 28,15-20 (2008).
10. R. Pryor W., Multiphysics Modeling using Comsol 4 A First Principles Approach, Mercury Learning and Information. (2012).
11. G. B. Arfken, H. J. Weber, Mathematical methods for physicists, Fourth Edition, Academic Press, London U. K. (1995).