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# Influence of Heavy Fuel Oil on the Thermo-Physical and Erodibility Properties of Earthen Materials

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## Abstract

This study focuses on the use of heavy fuel oil in construction material in Burkina Faso. Its mixture with silty or clayey soil is used as a coating to reinforce the walls of raw earth constructions which are very sensitive to water. The interest of this study is to determine erodibility, water content, while highlighting the influence of the porosity accessible by water on thermal diffusion in construction material containing heavy fuel oil. The heavy fuel oil was mixed with a silty-clayey soil, in different proportions, and water to make bricks samples on which tests were carried out. At the end of the experimental tests, it appears that the water content increases gradually, but not significantly with the addition of heavy fuel oil, which causes a slight increase in the speed of heat propagation through the material with reduced porosity, particularly those containing higher quantities of heavy fuel oil. Conversely, we note a good performance of heavy fuel oil in terms of water resistance properties such as porosity accessible by water and erodibility. This allows us to conclude that the mixture of heavy fuel oil and silty-clayey soil used as a coating material could greatly reduce water infiltration into the walls of housing constructions with raw earthen materials.

## Keywords

Porosity Accessible by Water, Erodibility, Water Content, Thermal Diffusion

## 1. Introduction

The envelope of a building is the interface between the interior and the exterior environment, it is the site of heat, humidity, and air transfers. In addition, most materials used in construction are porous materials and therefore permeable to water [1].

Today it is estimated that the housing of a third of the global population is still built using earthen materials. The city of Ouagadougou is not on the fringes, because it is marked by a large urban planning dichotomy, thus its urban fabric is composed by urbanized areas and others made up mainly of spontaneous habitats [2]. Notwithstanding, the land development efforts of the State, Boyer and Delaunay estimate that, the areas with spontaneous habitation commonly called undivided zones sheltered 33% of Ouagadougou people in 2009 and 86.7% of the housing in these undivided areas are in banco (raw earthen brick) [3]. The major factors in the utilization of adobe are its availability, its proximity to the housing construction site, and above all the lack of financial means to acquire more sophisticated construction materials.

Furthermore, some materials, particularly those made of raw earth, in their non-stabilized forms are very porous, and because a very high degree of porosity can cause significant damage to construction, especially during periods of heavy rainfall, and induce poor quality of indoor air, thus affecting human health.

So, controlling the transfer of heat and humidity in construction materials is essential not only for the characterization of the behavior of structures about durability and impermeability but also for the precise evaluation of thermal and energy performance.

Moreover, the desire to protect the walls of their housings which are mainly made of raw earth against the rainwater makes the populations of villages and spontaneous residential areas of large cities use heavy fuel oil. Indeed, in practice, heavy fuel oil is mixed with earth (silty or clayey) wetted with water and used as a coating material on the exterior walls of their housing.

The real motivation of the present study is to expose, through a well-structured approach, the effects of heavy fuel oil on the porosity accessible by water; the water content and erodibility of a building material designed using silty-clayey soil. First, we will highlight the influence of porosity as well as water content on the thermal conductivity in this construction material. Then, using a simplified diffusion model, we will present a simulation of the propagation of heat through our construction materials.

## 2. Materials and Methodology

In the present study, the objective is to determine the effects of heavy fuel oil on the water content, the porosity accessible by water, the erodibility, and thermal diffusion in a construction material. To achieve our goal, we will proceed as follows:

Firstly, we took a soil sample to make our material, from a site in the village of SABTENGA, a commune of PABRE in the central region of KADIOGO province and located at the northern exit of the town of OUAGADOUGOU. Secondly, with that soil, we produce different types of bricks with and without heavy fuel oil. Finally, the phase of determining the parameters of the bricks such as, water content, the porosity accessible by water, the erodibility and possibly the influence of these water properties on the thermal diffusion of materials.

The material and equipment used in this study are, among others, an oven set at 100˚C to determine the water content of the material. Figure 1 shows a hydraulic weighing device with a digital balance for testing the porosity accessible by water, this device is used to measure the needed mass for the calculation of the porosity $\varepsilon$. Figure 2 shows a device for testing the erodibility of the material. For the simulations, we use COMSOL Multiphysics software.

Figure 1. Hydraulic weighing device.

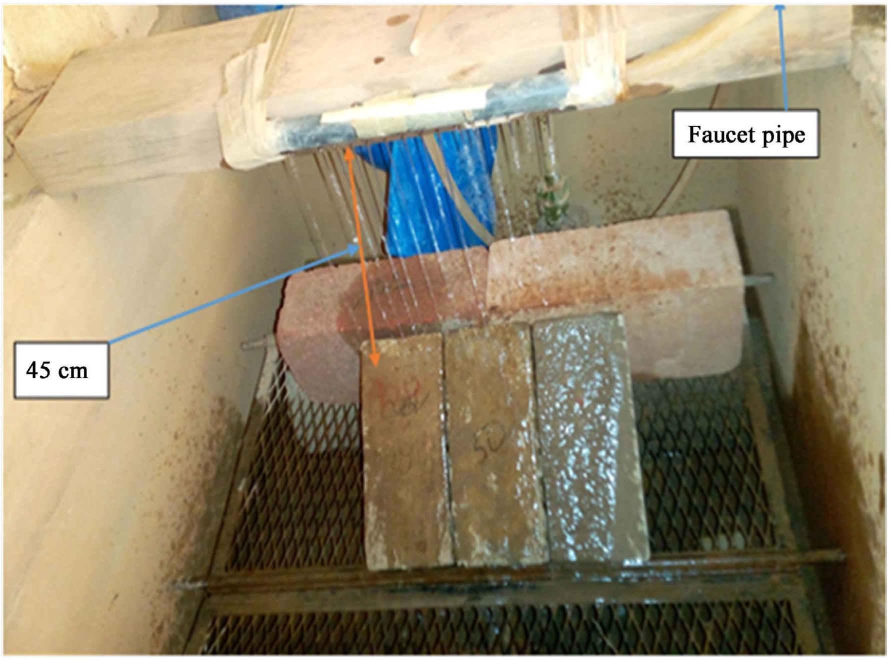


Figure 2. Device for the erodibility test.

### 2.1. Descriptions of the Technique

This construction technique practiced by the populations consists of mixing soil and heavy fuel oil, by adding water to use the mixture obtained as a coating material to reinforce the walls of their various housing in raw earth. It should be remembered that fuel oil is a liquid fuel at a temperature of 25˚C, black in color, and of high calorific value, produced by refineries. It is a mixture of hydrocarbons of mineral or synthetic origin intended to produce heat in installations by its combustion [4]. The first reason for fuel oil importation in Burkina Faso is for supplying the large generators of the country's National Electricity Company (SONABEL). The heavy fuel oil used has very low sulfur content with a density of approximately 0.97 g/cm$^3$.

### 2.2. Methods for Producing the Material

In this phase of producing the bricks, a manual press equipped with two rectangular molds of the same size, 5 × 11 × 21 cm$^3$ was used to compress the materials into bricks to minimize. This allows to homogenize the pressure exerted on each brick during their production as well as the quantity of water in each brick.

For the production, we first sieved the soil on 1 mm sieve. Then the sieved earth is poured into a mechanized mixer. About 2 kg of soil were mixed with the quantity of water of 200 mL to make the mixture (soil + water) homogeneous. In the manufacturing process, there is the molding phase where a quantity of the mixture is simultaneously poured into the molds of the press. Pressure is then exerted on the molds using the lever of the press to obtain the bricks which are finally removed from the molds.

To determine the effects of heavy fuel oil on the soil after the experimental tests that were carried out in the laboratory on the different types of bricks, we have designed other types of bricks containing a certain amount of heavy fuel oil.

Thus, for the same quantity of the mixture (soil + water) used to design a simple brick (without fuel oil) named "BS", we added 50 mL, 100 mL, and 150 mL of heavy fuel oil to obtain three other types of bricks named "BS + 50 mL", "BS + 100 mL" and "BS + 150 mL". These volumes of fuel oil added correspond respectively to 2.2%, 4.4% and 6.6% by mass of the mixture (soil + water). The bricks were dried in the sun in the open air for at least two months before the experimental tests.

### 2.3. Methods for Characterization of Bricks

The water content ($w$) of a material is a quantity well suited to the description of transfers in a porous material. The water content is defined, as the ratio between the mass of water ($m_w$) contained in the material and the mass of the dry material $m_s$, in percentage:

$$w = \frac{m_w}{m_s} \times 100(\%) \quad (1)$$

In our case, for the determination of the water content ($w$) of the materials, a sample of each type of brick is taken and placed in an oven set at 100˚C for 24 hours for drying. The sample is then removed from the oven and weighed after cooling. Thus, the water content of each type of brick is calculated using Equation (1).

Regarding the porosity of different types of materials, it's about an open porosity which is a porosity accessible by water. The determination of porosity accessible by water is made according to the NF P18-459 standard [5].

The porosity ε is then obtained by the following relationship:

$$\varepsilon = \frac{M_{asat} - M_d}{M_{asat} - M_{wsat}} \times 100(\%) \quad (2)$$

$M_{asat}$ is the mass in free air of the saturated sample; $M_{wsat}$ represents the mass of the sample saturated in water and $M_d$, the mass of the dry sample (dried in an oven at 100˚C for 24 hours).

For determining the mass loss (erodibility) of different types of material, the test used to evaluate the resistance of earth coatings to rain erosion consisted of projecting water in the form of rain droplets without pressure and at a constant flow rate of 1.12 L/Min for 10 min onto test specimens. The sample was placed on an inclined plane at an angle of 30˚ to the vertical (**Figure 2**). The mass loss was estimated from Equation (3):

$$C = \frac{M_0 - M_S}{M_0} \times 100(\%) \quad (3)$$

With $M_0$ the dry mass before the test and $M_S$ the dry mass after the test [6] [7].

## 2.4. Simulation of Heat Diffusion through Materials

### 2.4.1. Chosen Thermal Diffusion Model

This part presents a simplified model of heat diffusion. This model is based on the partial differential equation (Equation (4)) which describes diffusion processes, including conductive heat fluxes.

### 2.4.2. Simplifying Assumptions.

In modeling heat transfer, we consider the following simplifying assumptions:

- The wall is simply made of a single layer of material.
- The materials (bricks) without fuel oil and those with fuel oil are all homogeneous.
- The thermo-physical properties ($\lambda$, $\rho$ and $C_p$) of the materials are assumed to be constant.
- Heat fluxes vary only in the x direction.

### 2.4.3. Equation

For a three-dimensional model of space, the heat diffusion equation is written as follows.

$$\frac{\partial T}{\partial t} - \alpha \nabla T = 0 \quad (4)$$

$$\frac{\partial T}{\partial t}-\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \quad (5)$$

With $T$ function of, $x$, $y$, et $z$, is the temperature at time $t$ and at the position ($x$, $y$, $z$) inside the wall, $\alpha$ is the thermal diffusivity which depends on the nature of the materials of construction.

In the one-dimensional case, the heat diffusion equation becomes: [8]

$$\frac{\partial T}{\partial t}-\alpha\left(\frac{\partial^2 T}{\partial x^2}\right)=0 \quad (6)$$

#### 2.4.4. Modeling of the Model

For modeling, we consider our sample of material (bricks) whose dimensions are 5 cm of height; 11 cm of width, and 21 cm of length. We simulate the heat transfer through the brick from the upper wall exposed to a temperature flow of 40˚C to the lower wall which is at a temperature of 20˚C. This simulation is done through the length $x$ of the material (**Figure 3**), considering the case of Burkina Faso where the maximum temperature during the hottest months (March and April) reaches 40˚C, according to the national metrology agency. After the step of an extremely fine mesh of the brick sample, we obtain **Figure 4**.

## 3. Results and Discussions

### 3.1. Hydrous and Thermophysical Properties of the Materials

The measurements of the thermophysical properties such as the specific heat capacity; thermal conductivity; thermal diffusivity and density of the different types of material in [9] allowed us to obtain the results mentioned in **Table 1**.

**Table 1** also presents the results generated by the tests of the porosity $\varepsilon$ (%)

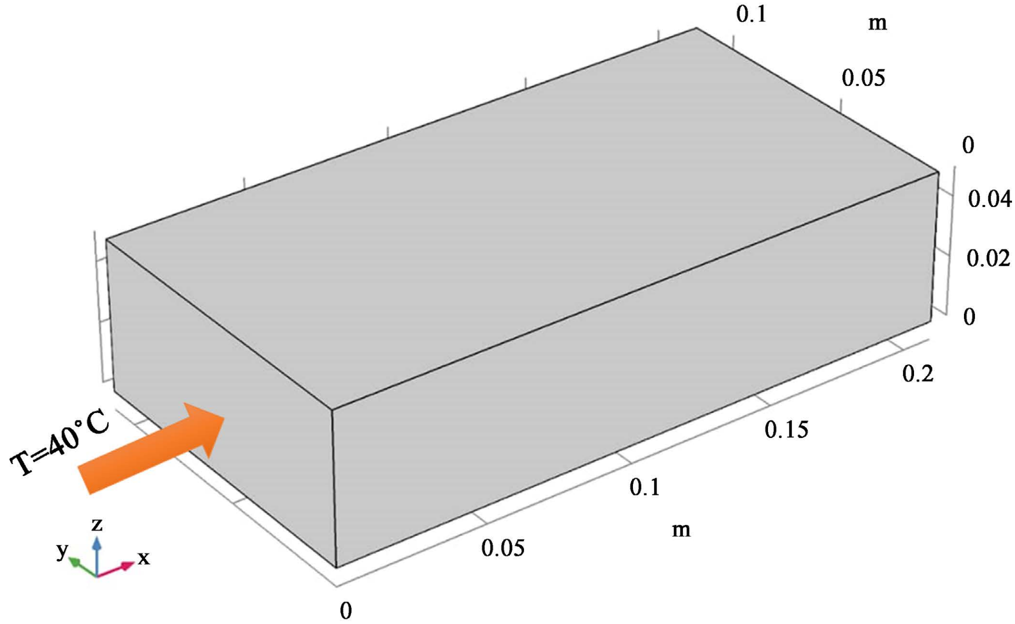


**Figure 3.** Modeling of the simulation model.

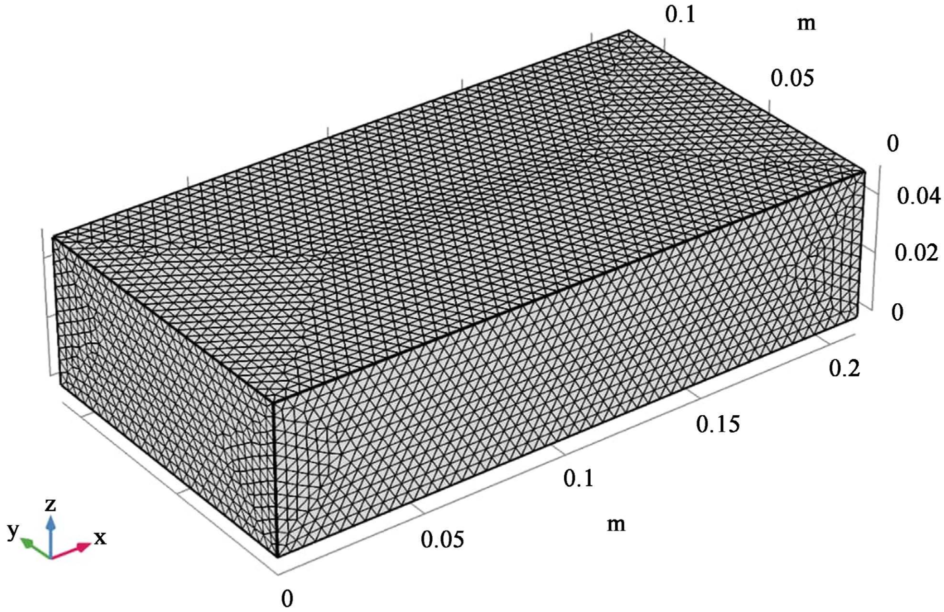


Figure 4. Material mesh.

Table 1. Values of the thermophysical and hydrous characteristics of different types of bricks.

| Property | BS | BS + 50 mL | BS + 100 mL | BS + 150 mL |
|---|---|---|---|---|
| Water content $w$ (%) | 0.51 | 0.65 | 0.67 | 0.71 |
| Porosity ε (%) | 20.53 | 7.39 | 1.66 | 1.55 |
| Thermal conductivity $\lambda$ (W/m·K) | 0.617 | 0.624 | 0.677 | 0.901 |
| Density $\rho$ (kg/m$^3$) | 1772.439 | 1884.026 | 1775.564 | 1788.629 |
| specific heat capacity $C_P$ (kJ/kg·K) | 1.361 | 1.227 | 1.353 | 1.205 |
| Thermal diffusivity $\alpha$ (mm$^2$/s) | 0.256 | 0.270 | 0.282 | 0.418 |

and the Water content $w$ (%) of each type of material whose measurement methods are mentioned above.

### 3.2. Erodibility

The erodibility test C (%) whose method used is described by Figure 5 produces the following results: 23.01%; 0.21%; 0.19% and 0.18% respectively for BS materials; BS + 50 mL; BS + 100 mL and BS + 150 mL. For a better comparison of these results, we have represented them in the diagram in Figure 5.

### 3.3. Relationship between Thermal Conductivity, Porosity, and the Water Content of Materials

The variation of the porosity accessible by water, the water content as a function of the thermal conductivity of the materials is an important aspect to consider in this study. It is helpful to perceive the effect of pores on thermal diffusion through the different types of materials and the influence of the water content on the thermal conductivity of the materials (Figure 6).

### 3.4. Heat Diffusion through Materials

After having integrated for each type of material, the parameters $\rho$, $\lambda$ and $C_P$ which we obtained by experimental measurements mentioned in Table 1, then set the boundary conditions. And considering a broadcast duration of 12 hours (43,200 s) on a daily cycle, with a time step of one hour (3600 s), we obtain the simulation results of heat transfer by diffusion for each type of material Figure 7.

### 3.5. Discussions and Interpretations

From the viewpoint of water contents of the materials (Table 1), we note a water

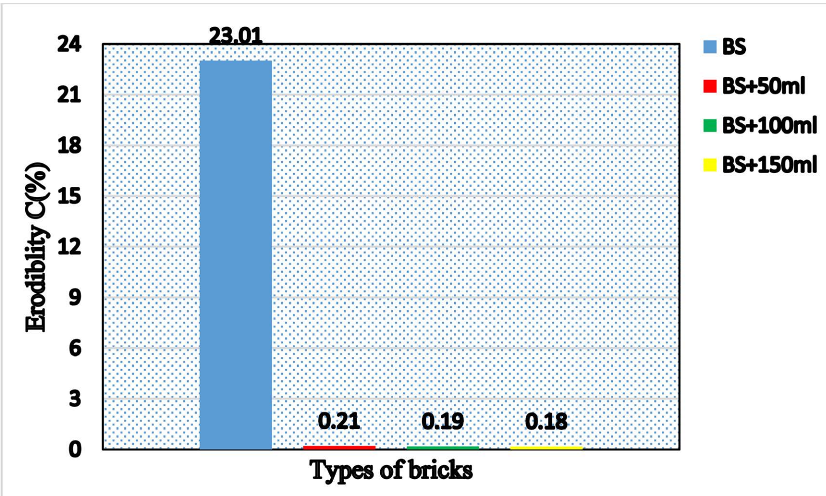


Figure 5. Representation of erodibility of different types of bricks.

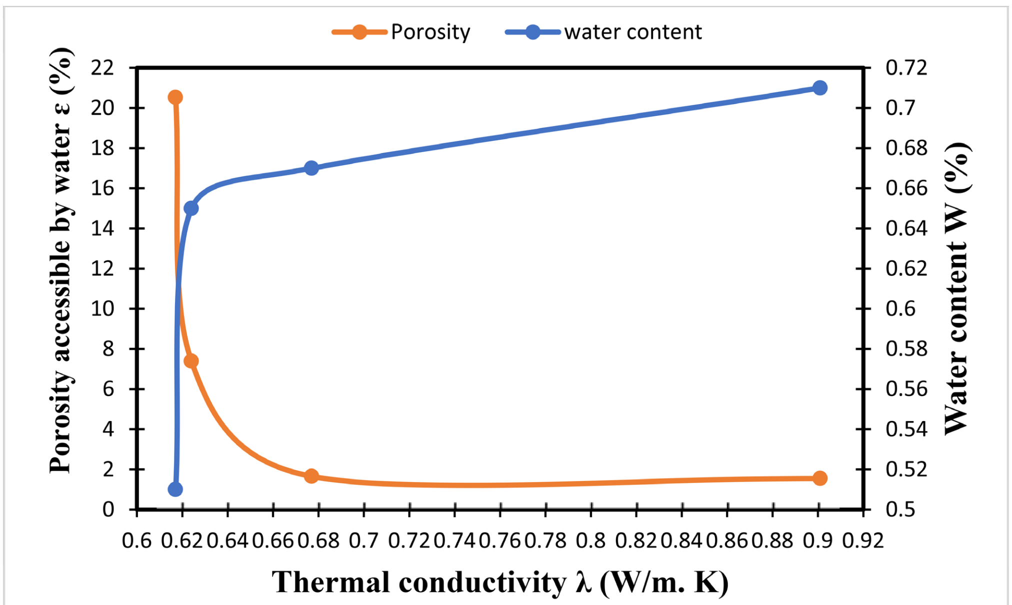


Figure 6. Water content and porosity accessible to water curves as a function of the thermal conductivity of the different types of brick.

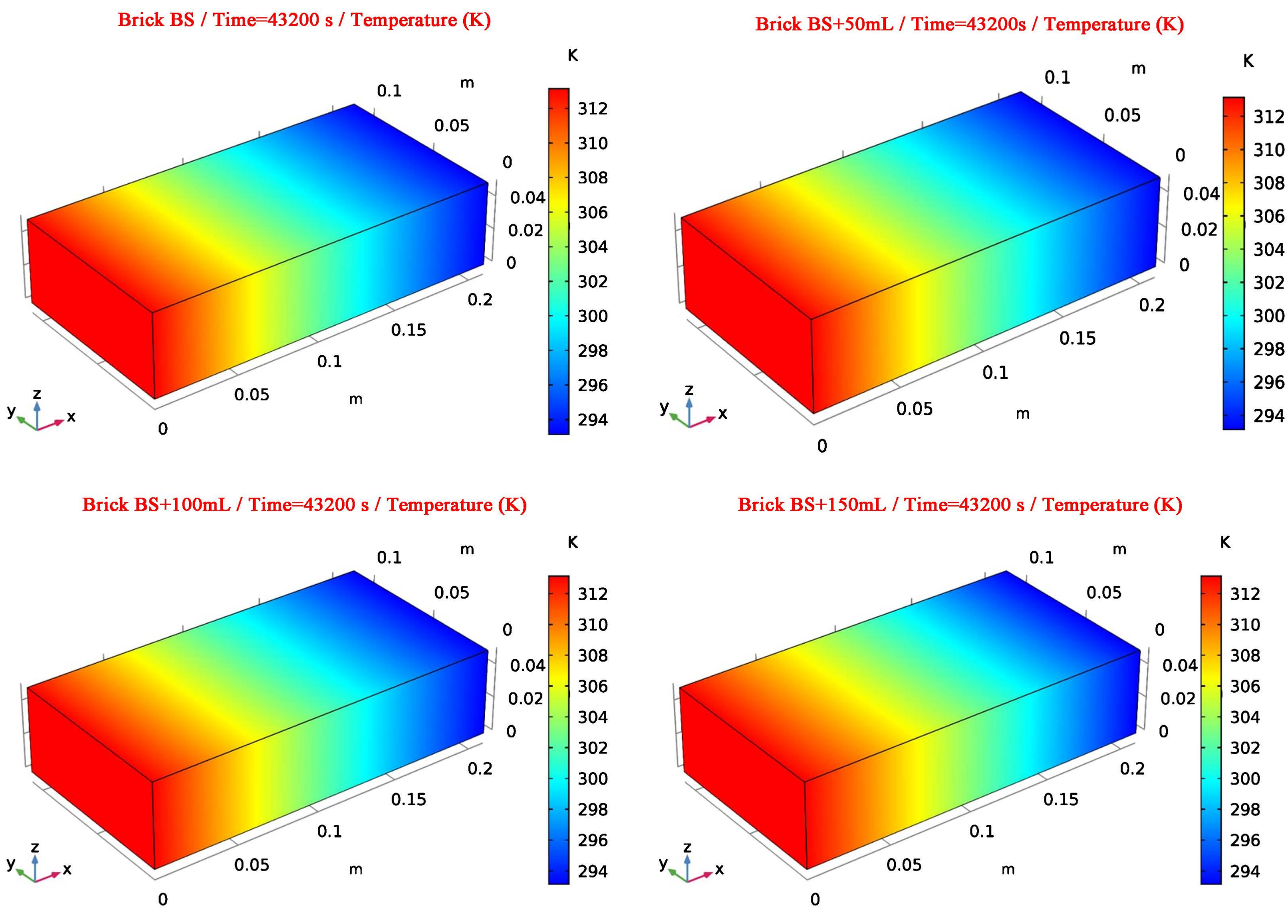


Figure 7. Heat propagation through materials over a period of 12 hours.

content of around 0.51% for the materials (BS) without heavy fuel oil. This water content gradually increases with the addition of fuel oil. We notice a variation in the water content from 0.51% for the material (BS) to 0.71% for the material (BS + 150 mL), *i.e.*, an increase in the water content of approximately 39.21% with the materials (BS + 150 mL) containing 150 mL of heavy fuel oil. The gradual increase in water content depending on the quantity of heavy fuel oil added could suggest the presence of water in the latter. But the objective reason is rather linked to the fact that the oily molecules of heavy fuel oil are impermeable to water and therefore do not allow the water used to make the materials to evaporate completely during drying.

As for the porosity accessible by water for the brick (BS) without fuel oil is equal to 20.53%. And for an addition of 50 mL, 100 mL, and 150 mL of heavy fuel oil respectively, we have a porosity of 7.39%, 1.66%, and 1.55%. So, we note a significant reduction in the porosity of the material to the tune of 64%, 91.90%, and 92.45%, when the material contains respectively 50 mL, 100 mL, and 150 mL of heavy fuel oil. This reduction in pores comes from the fact that the heavy fuel oil ensures good cohesion between the components of the material, thus reducing its pores and accessibility by water.

For the erodibility, the loss in mass of the materials measured using the water projection test in the form of rain droplets with a water projection rate of 1.12 L/Min. The results (**Figure 3**) reveal a strong loss of mass by erosion of the order of 23.01% for the samples of bricks without fuel oil (BS). For bricks with 50 mL, 100 mL, and 150 mL of heavy fuel oil, we respectively note an erodibility or mass loss of 0.21%, 0.19% and 0.18%. Based on these results, we therefore notice a reduction in mass loss of 99%, 99.17%, and 99.21% respectively for samples containing 50 mL, 100 mL, and 150 mL of heavy fuel oil. For only 50 mL of heavy fuel oil contained in our brick sample, the loss of mass or erodibility is almost stopped over a period of ten minutes. Thus, heavy fuel oil incorporated into a construction material made using silty-clay soil has a very good performance on the erodibility of this material. This virtual cessation of mass loss could be explained by the fact that the oily molecules of heavy fuel oil placed on the surface of the material reduce the friction forces between the water drops and the soil particles. Water can then flow easily over the surface of the material without degrading it.

Referring to the results about the simulation of the heat propagation by diffusion through the materials (**Figure 7**), we note that the depth of heat diffusion through each type of material is around 15 cm over a diffusion period equal to 12 hours. However, it is important to specify that for a given period t, the depth of heat diffusion is a little higher in materials with a higher quantity of heavy fuel oil. The addition of fuel increases the diffusivity of the materials. In terms of the impact of the porosity accessible by water on the propagation of heat, it appears that for a given duration, the depth of diffusion is significant when the material is less porous. This opposing variation in porosity and diffusion depth was predictable. In the sense that the results in **Figure 6** suggested an increasingly important thermal conductivity of the materials when their porosity decreased.

We can therefore see more clearly, from **Figure 6**, that the water content influences the value of the thermal conductivity of the materials. This influence is characterized by the increase in the value of thermal conductivity when the initial water content of the material increases. We can therefore conclude that the value of the thermal conductivity of bricks increases with the humidity level. This phenomenon is illustrated by the fact that when the water content in the material increases, the air contained in the pores decreases, but the thermal conductivity of the air is 0.024 W/(m·K) and the thermal conductivity of the water being of the order of 0.6 W/(m·K), is 25 times more than that of air [10]. Hence the progressive increase in conductivity, following the increase in the water content of the material. Thus, for a porous material, the thermal conductivity changes with the humidity level, if the latter increases then it is the same for the value of thermal conductivity.

## 4. Conclusions

This study, helps to understand by following laboratory tests on the thermal and water properties of the materials, particularly, the water content; the porosity accessible by water; the erodibility, that heat spreads slightly faster through materials that contain fewer pores. And heavy fuel oil drastically reduces the pores in material made by raw earth. Satisfaction comes from the water properties where heavy fuel oil has a good performance on the significant reduction of the porosity accessible by water and a decrease of the loss of mass (erodibility). These results could be very beneficial to people in such conditions, practicing this technique to protect the walls of their housing which are made by raw earth and prevent water from precipitation to seep in it during the rainy season. In fact:

- the water content gradually increases with the addition of fuel oil, an increase in the water content of approximately 39.21% with the materials containing 150 mL of heavy fuel oil (BS + 150 mL);
- there is a reduction in erodibility of around 99%, *i.e.*, half to the loss of mass for only 50 mL of heavy fuel oil incorporated in approximately 2 kg of silty-clayey soil wetted with 200 mL of water;
- heavy fuel oil reduces to approximately 92.45% of the porosity accessible by water when 150 mL of it, is mixed with approximately 2 kg of silty-clayey soil wetted by 200 mL of water;
- there is a relationship between the thermal conductivity, the porosity accessible by water and the water content of the material improved with heavy fuel oil;
- the greater the water content, the less porous the material and the less porous the material, the higher the thermal diffusion speed;
- the increase in water content due to the addition of fuel oil causes an increase in the depth of heat diffusion but this does not exceed 15 cm on each material for a period of 12 hours of diffusion.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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