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Study of the Thermal Characteristics of a Geomaterial: Case of Savè Granites in the Republic of Benin

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Abstract: This work focuses on the valorization of local materials. The rock that is granite, a material used in construction thanks to its mechanical resistance, is the subject of our study. The granite of the commune of Savè, made it possible to appreciate the thermal behavior of this rock studied with a view to its use as a building material. To this end, a thermal diffusivity measurement test was carried out on this material. Thus, we made samples which were then connected to a data acquisition box via thermocouples. A Python script is used to ensure the collection of temperature values over time. From this thermal diffusivity test carried out on the granite taken from the Savè breasts, we obtained an average diffusivity $\alpha = 5.84 \times 10^{-6}$ m²/s. As a result, the thermal effusivity and the heat capacity of the material were determined having respectively the value 1,351.09 J/(K·m^2·s$^{1/2}$) and 547,945.21 J/(m^3·K). These different results highlight a thermal characterization of Savè granites as a relevant material in the design and construction of an energy-efficient eco-housing.

Key words: Local materials, thermal diffusivity, thermal conductivity, thermal effusivity, heat capacity.

1. Introduction

The notions of sustainable development and eco-construction have been topical in recent years through the use of natural materials in building construction processes [1]. A multitude of recent scientific and technical studies related to ancestral building techniques and so-called “traditional” building materials (banco, rammed earth, adobe etc.) have been made [2]. The aim is to produce buildings which allow the environment to be respected as much as possible, both during construction, during their lifetime and at the end of the life cycle, when destroying and disposing of building products. This type of habitat must primarily be based on the use of local resources to reduce transport-related constraints. Natural materials are thus used both for the structure (stone, wood, earth brick, etc.) and for thermal or sound insulation (hemp, linen, straw, etc.) [3]. Their qualities, neglected over time in favour of industrialized materials with large production volumes, are once again highlighted, in particular after the application of the 2005 Thermal Regulations and the conclusions of the Grenelle Environment Forum in 2007.

Among these materials, we have granite which is a basic constituent of many dwellings. It represents a very popular building element because, thanks to its resistance, it is used effectively in the design of concrete [4] but is also used as an ornamental material [5]. It is also recommended in slope stabilization operations [6].

The granite material is very frequently used in the design of traditional African dwellings. In the region of Savè in the department of the hills, in the Republic of Benin, granites are an available natural resource and mechanical properties are well established [7].

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However, the lack of knowledge on the thermal properties of these granites can have an impact on the energy efficiency of constructions and on the thermal comfort of the works carried out. Thus it is then necessary to seek to control its thermal characteristics with a view to efficient use [8].

The thermal characterization of rock materials has divided the research world in recent years, and we can list a few works, including those on the effective thermal conductivity of partially saturated rocks [9]. From this work, it emerges that the use of Mori-Tanaka and Ponte-Castaneda-Willis techniques makes it possible to take into account the solid constituents respectively of the pores refilled with water and air present in the argillite studied. The proposed model takes into account the transverse isotropy of the effective thermal conductivity, which is due to the particular arrangement of the pore systems. For this purpose, an orientation distribution function is used. The numerical simulations were compared with the available experimental data, demonstrating the model's good predictive capabilities. In other work [10], these simulations were used to study the influence of the geometry, spatial distribution and degree of saturation of the porous medium on the effective thermal conductivity.

In the same vein, **Sibiath O. OSSENI** in 2012 in her document “Study of the hot plane method with two temperature measurements for the thermal characterisation of building materials” studied the hot plane method with two temperature measurements for the thermal characterization of building materials [11]. Pre-estimation of the modulus and volumetric heat capacity (E and ρ_c) enables these parameters to be defined using a simulation programme, and the values obtained are used for estimation using experimental data. Research has focused on the thermal characterisation of thin materials [12], using models to assess the thermophysical properties of these materials. Taking laterite as an example, conductivity can be estimated by measuring the temperature of the unheated face. It is therefore preferable to use both temperatures for a good estimate of all the parameters over a shorter heating period [13]. Determining the properties of coarse materials, which is not well covered in the literature, has nevertheless been the subject of relevant research throughout the world. These include the effect of temperature on these materials [14], their thermal conductivity[15] and their thermal transfer capacity [16]. Granite is one of these coarse materials whose use in construction varies according to several factors [17].

In addition, the thermophysical characterization of some rocks from Benin: the case of granite, basalt and marble from the city of Dassa Zoume has been the subject of relevant research. From this work, it appears that granite has better thermophysical characteristics than marble and basalt. In addition, it should be noted that marble has a high thermal inertia than the other two study rocks [8].

Also, Fillion et al.[18] have worked on measuring the thermal conductivity and the intrinsic permeability of pebble assemblies. From this work, it appears that in all types of embankments, coarse materials such as pebbles and blocks of rock promote greater heat extraction, by air convection in the pores. This phenomenon can have harmful effects on certain types of structures, such as rockfill dams and cause the formation of cracks at the crest of the dam, as well as the freezing of the toe drain. Several studies on convection in rockfill materials [19] have determined that this phenomenon is favored when the materials used have low thermal conductivity and high intrinsic permeability. However, there is still a gap in knowledge in characterization of these heat transfer properties for coarse materials.

2. Material, Equipment and Method

2.1 Material

The material used for our study is the granite taken from the Mamelles of Savè in the hills department in the Republic of Benin. The site straddles the districts of Djangbé and Agbaigodo. It lies between the meridians 2°29′55″ and 2°30′25″ longitude East and the parallels 8°1′20″ and 8°2′00″ latitude North. Table 1 presents the geographical coordinates of the project's host site.

2.2 Equipment

The equipment needed to perform the thermal diffusivity test consists of:

1. a computer, making it possible to read and record temperature variations as a function of time;
2. a data acquisition station, serving as a link between the thermocouples and the computer;
3. thermocouples, for measuring temperatures;
4. a heating lamp; allowing the material to be heated;
5. a cylindrical PVC (Polyvinyl Chloride) test piece;
6. drilling equipment, allowing the bottom of the specimens to be drilled in order to insert the thermocouples.

Table 1 Values of time and corresponding α-values.

t (s)	α (m^2/s)
2,500	4.41×10^{-7}
2,600	4.01×10^{-7}
2,700	4.01×10^{-7}
2,800	3.39×10^{-7}
2,900	3.39×10^{-7}
3,000	3.15×10^{-7}
3,100	3.15×10^{-7}
3,200	2.94×10^{-7}
3,300	2.94×10^{-7}
3,400	2.75×10^{-7}
3,500	2.75×10^{-7}

Fig. 1 Site overview.

Fig. 2 Study material.

The device used to measure thermal diffusivity. The sample was prepared, the heating lamp was placed at a distance of 30 mm from the upper surface of the material and the 3 thermocouples were introduced into the material through a hole drilled at the bottom of the compacted material so that the first thermocouple was halfway up the sample.

2.3 Results Analysis

The 3 thermocouples inserted into the material are connected to an acquisition box (acquisition system), itself connected to the computer (Fig. 3) The software used is a Python script which ensures the collection of temperature values over time. Once the thermocouples have been inserted into the material, the lamp in place and the thermocouples connected, the test can start.

An example of how temperature changes as a function of time is shown in the Fig. 4.

2.4 Finite Difference Method

The finite difference method consists in approximating the derivatives of physical equations by means of Taylor series expansions. It is due to the work of several 17th century mathematicians (Euler, Taylor, Leibniz, etc.). This technique makes it possible to approximate the value of a function at a neighboring point in space or time [20]. Thus it is possible to obtain an approximation of the first and second order partial derivatives found in the heat equation.

Consider a function Ψ(x) defined in the field of study. If we place ourselves at a given position X, and if we assume that we know Ψ(X) as well as Ψ(X - δx) and Ψ(X + δx), δx being an infinitesimal variation around position X, then:

$$(\partial\Psi(\mathrm{x}))/\partial x = \Psi(\mathrm{X} + \delta\mathrm{x})/\partial x \qquad (1)$$

$$(\partial\text{^}2\ \Psi(\mathrm{x}))/(\partial x\text{^}2\ ) = (\Psi(\mathrm{X} + \delta\mathrm{x}) - 2\Psi(\mathrm{x}) + \Psi(\mathrm{X} - \delta\mathrm{x}))/(\partial x\text{^}2\ ) \qquad (2)$$

- Numerical resolution of the one-dimensional heat equation

The heat equation in the one-dimensional case is written:

$$\begin{cases} \frac{\partial \mathrm{T}}{\partial t} = \propto \frac{\partial^2 \mathrm{T}}{\partial x^2} \\ 0 \leq x \leq L \\ \quad t \geq 0 \end{cases} \qquad (3)$$

with T = $(x,)$ the temperature at time t and position x, and α the thermal diffusivity of the medium. Eq. (3) is written in the case of a semi-infinite medium of thickness L. The initial conditions (at t = 0) at the boundaries (for x = 0 and x = L) are such that:

$$(0,) = T0,\ (L,) = (x,\ 0) = f0\ (x) \qquad (4)$$

with $f0(x)$ the initial relative temperature distribution such that $f0(x)$ = $T(x,t)$ - $T(x$, 0). Eq. (3) is a so-called partial differential equation, the numerical resolution of which requires the discretization of the field of study considered, in time as well as in space. It is assumed for this that the time interval is divided according to a grid with a finite number of points and intervals. The calculation of the solution is done only in these instants. If we denote by Δt the time interval (assumed constant) of the temporal discretization grid, and Δx the space step (assumed constant) of the spatial discretization grid, then the calculation of the solution will be done at the points $x = i\Delta x$ and $t = m\Delta t$ with i = 1, 2, ... N and m = 1, 2, ... M; N and M being the total number of space and time nodes respectively.

Replacing δx by the time step Δt in Eq. (1), and by the space step Δx in Eq. (1), then Eq. (2) becomes:

$$(T(x,t+\Delta t)+T(x,t))/\Delta t=\alpha\ (T(x + \Delta x,t)- 2T(x,t)+T(x-\Delta x,t))/\Delta x\ ^2 \qquad (5)$$

Referring to Fig. 11, if we set:

$$(x,t) = Ti\ m\ (x, + \Delta t) = Ti\ m{+}1$$

$$(x - \Delta x,t) = T\mathrm{m}i{-}1\ (x + \Delta x,) = Tmi{+}1$$

then the thermal diffusivity is given by the following relation:

$$\propto=(\ Ti\text{^}(m+1)-\ Ti\text{^}m)/(T(i-1)\text{^}m+ T(i+1)\text{^}m-2Ti\text{^}m\ )\ x\Delta x\ {}^2\!/\Delta t \qquad (6)$$

2.5 Calculation of $\boldsymbol{\alpha}$

As previously described, the discretization of the space is given by the spacing between the thermocouples. Therefore, from Fig. 5 we have:

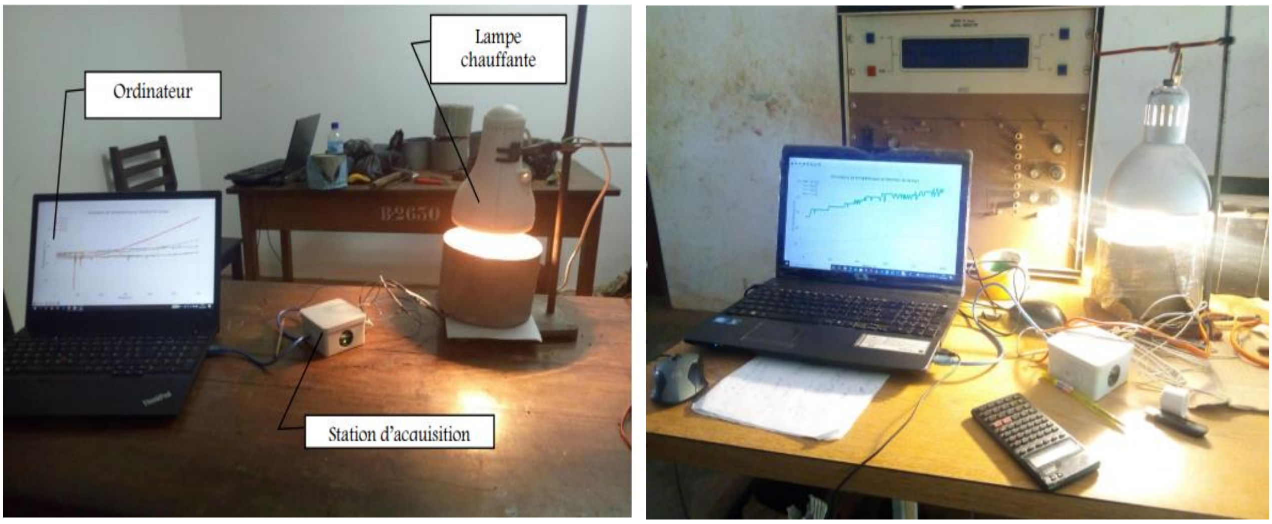

Fig. 3 Equipment required for the thermal diffusivity test.

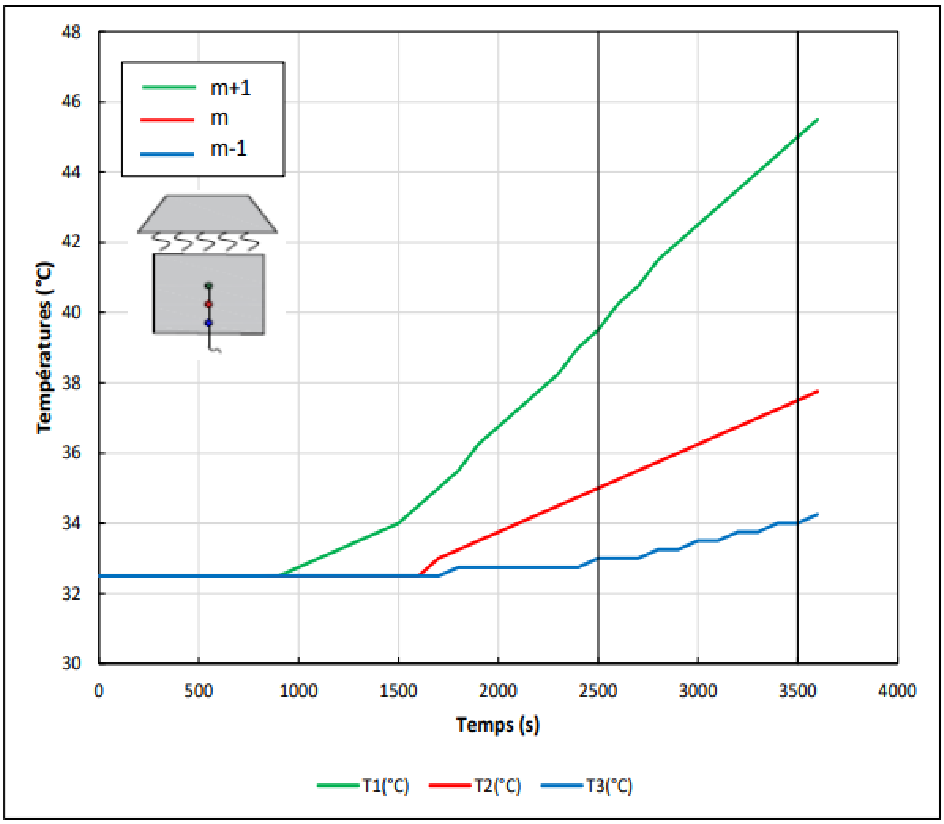

Fig. 4 These data come from a calibration test carried out on dry gully sand.

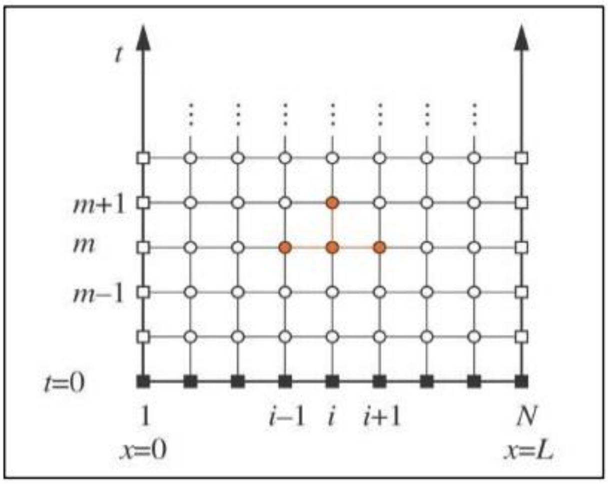

Fig. 5 Mesh of the semi-infinite domain used to calculate the solution to the one-dimensional heat equation.

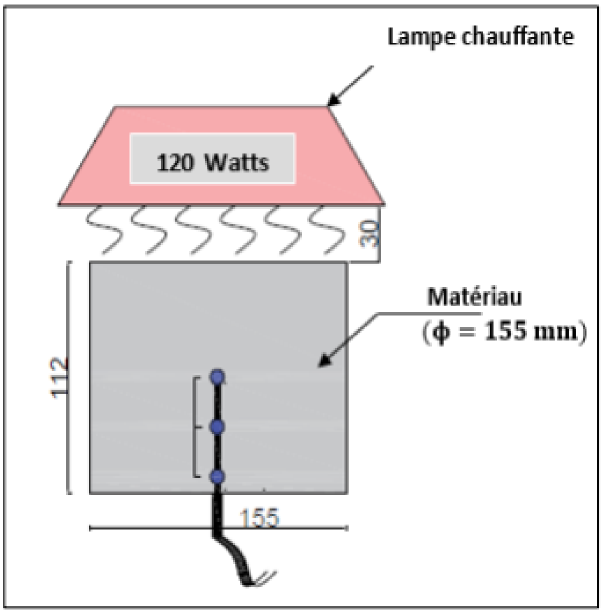

Fig. 6 Schematic representation of the thermal diffusivity measurement method (dimensions are in millimeters).

$\Delta x = 21 \times 10^{-3}$ m. The choice of the time step must be made in agreement with a condition of stability specific to the method chosen for the resolution of the problem posed. Stability is the property which ensures that the difference between the numerical solution obtained and the exact solution of the discretized equations is bounded. The choice of the time step was therefore made by considering the evolution of the relative error of the results of calibration tests as a function of the time step and the value chosen is $\Delta t = 100$ s.

Since the calculation of the thermal diffusivity requires that there is a variation of the temperature at the three measurement points, it is natural to consider the temperature values only beyond a certain time. This portion of the curve starts at td = 2,500 s and ends at tf = 3,500 s.

Considering t = 2,800 s, we then have that:

$(x,t) = (m, 2{,}800) = 35.75$ ℃

$(x,t + \Delta t) = (m, 2{,}900) = 36$ ℃

$(x - \Delta x, 2{,}800) = (m - 1.2800) = 33.25$ ℃

$(x + \Delta x, 2{,}800) = (m + 1.2800) = 41.5$ ℃

Thus we have:

$(36-35.75)/100=\alpha\ (41.5-2\times35.75+33.25)/(21\times10^{-3})^2$

$\alpha = (36-35.75)/(41.5-2\times35.75+33.25)\times(21\times10^{-3})^2/100$

$\alpha = 3.39\times10^{-7}$ m²/s

By keeping the same time step, the previous calculation can be repeated by placing itself at different positions along the time axis. In our case, a calculation is performed every 100 s (let us denote this translation time tdt). In other words, each value of t corresponds a value of α.

3. Results and Discussion

3.1 Thermal Diffusivity

3.1.1 Calibration

As this is a test that does not have a standard or norm, a preliminary calibration phase was necessary in order to determine the correct configuration and the correct approach to follow for carrying out this test. The thermal diffusivity of dry sand being well documented [21] it was used for the calibration of the measuring device.

Numerous tests were initially necessary in order to adjust the various test parameters such as the relative position of the 3 thermocouples or the location of the heating lamp. For each test, several thermal diffusivity values were obtained. Table 2 gives the mean value of the thermal diffusivity measured for the calibration.

Relative error: $\boldsymbol{\delta\alpha r} = \mathbf{100}.\ (|\bar{\alpha} - \boldsymbol{\alpha cible}|)\ /\boldsymbol{\alpha cible}$

Table 2 Thermal diffusivity of dry sand.

Material	α_{target} (m²/s)	Condition	Reference
Dry sand	3.17×10^{-7}	ρ = 1.6 g/cm³	http://fourmailletard.canalblog.com/archives/2008/12/13/12589580.html

Table 3 Thermal diffusivity obtained.

Essay	α x10⁷ m²/s	σ	$\delta\alpha r$ (1) (%)
Mean	3.17	5.58	5.4

Table 4 Thermal diffusivity of granite.

Time (s)	Temperature T_1 (℃)	Temperature T_1 (℃)	Thermal diffusivity α (10^{-6} m²/s)
1,700	34.95	35.58	5.91
1,800	34.75	35.75	4.2
1,900	34.97	36.97	7.41
Mean α			5.84

The precision of the measurements is on the whole quite good with an average relative error of 5.4% compared to the target value. Following these tests, this version of the assembly was deemed suitable for use with the material under study.

3.1.2 Study material

The table below gathers the thermal diffusivity values at different times as well as the average value retained.

From Table 4, we retain that the average value of the thermal diffusivity of the material is $5.84\times\mathbf{10}^{-6}$ m²/s. This value represents the value of the thermal diffusivity of the granite used for the construction of the domes. It should be noted that the higher the value of the thermal diffusivity, the faster the heat propagates in the material.

Compared to the results obtained by other authors, we can notice that the value of the thermal diffusivity obtained is superior to those obtained firstly by Ambelohoun et al. [8] then by Berraha [22] and finally Weber [23]

It is noted that among these materials, the Savè granite has the highest value of thermal diffusivity. Since diffusivity is the rate at which heat propagates by conduction in a body [24], the heat will pass through a given thickness of the Savè granite faster than the other materials studied by the authors mentioned above. This thermal diffusivity of the Savè granite is nevertheless relatively low. This means that this granite takes less time to transfer heat but longer to dissipate it. In conclusion, the thermal diffusivity of Savè granite can be beneficial for the design of an energy-efficient eco-housing [25], providing thermal stability, reduced heat loss and comfortable and stable internal conditions. So it can guarantee thermal comfort and fast heat transfer.

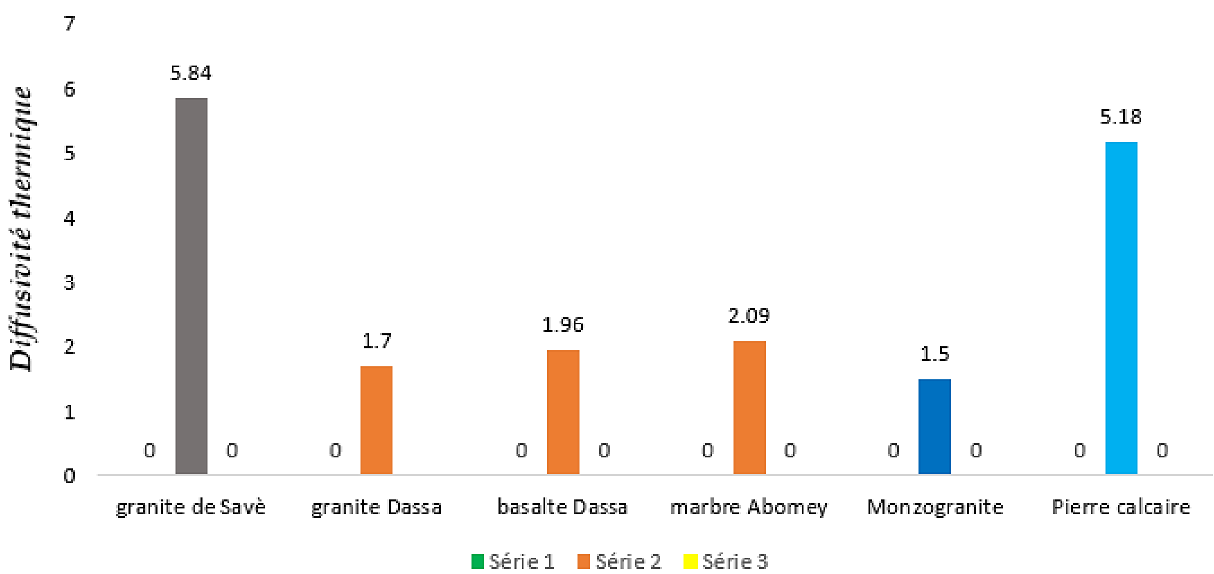

Fig. 7 Comparison of the thermal diffusivity of Savè granite with other materials.

3.2 Thermal Effusivity

The value of the thermal effusivity is determined by going through the thermal conductivity and the thermal diffusivity.

With a granite thermal conductivity value from the literature confirmed by Bachir Ambelohoun [8] and others authors we have λ = 3.2 W/(m·K).

Thus:

$$E = \sqrt{\lambda \rho c} \tag{1}$$

The thermal diffusivity is defined by the following expression:

$$\alpha = \lambda / \rho c \tag{2}$$

From the expression of α we have:

$$\rho c = \lambda / \alpha \quad 3)$$

Substituting the expression for ρc into that for E we have the following:

$$E = \sqrt{(\lambda^2 / \alpha)} \tag{4}$$

So we have

From Table 5, we retain that the average value of thermal effusivity is 1,351.09 J/(K·m² s$^{1/2}$). This value represents the value of the thermal effusivity of the granite used for the construction of the domes.

Effusivity being the sensation that the material gives on contact with the skin, a high effusivity value means that the material quickly absorbs a lot of energy without noticeably heating up on the surface.

We note that the value obtained with the granite of Savè is lower than those of the materials studied on the one hand by Ambelohoun et al. [8] and WEBER [23] and on the other hand slightly higher than that of the sandstone by BERRAHA [22] defined by the thermal engineer's checklist. Thermal effusivity is an important characteristic in the building sector since it tells us about the material's ability to transfer heat by radiation. So in view of the measured values, the Savè granite seems less hot in contact with the skin compared to other materials with the exception of sandstone. Thus, it can guarantee the interior comfort of an eco-building, in particular thermal comfort, energy efficiency and optimized acoustic comfort [26].

Table 5 Thermal effusivity of granite.

Time (s)	λ W/(m·K)	α (10^{-6} m²/s)	E J/(K·m² s$^{1/2}$)
1,700	3.2	5.91	1,316.30
1,800	3.2	4.2	1,561.44
1,900	3.2	7.41	1,175.54
Average α		5.84	1,351.09

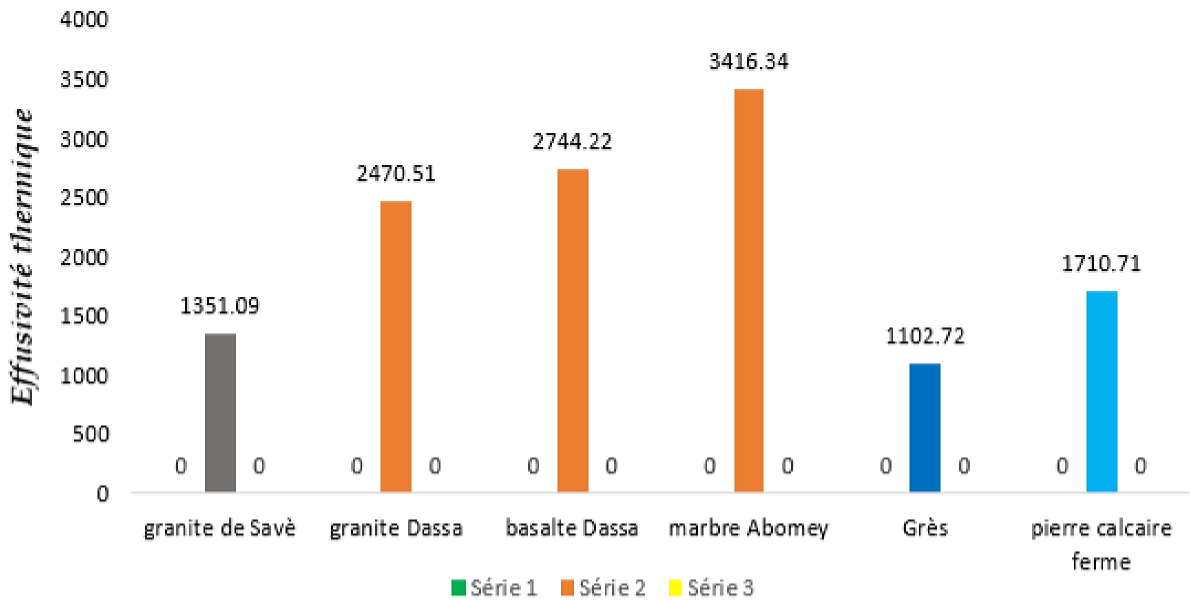

Fig. 8 Comparison of the thermal effusivity of Savè granite with other materials.

Table 6 Heat capacity.

λ (W/m K)	α (10^{-6} m²/s)	ρc (J/(m³ K))
3.2	5.84	547,945.21

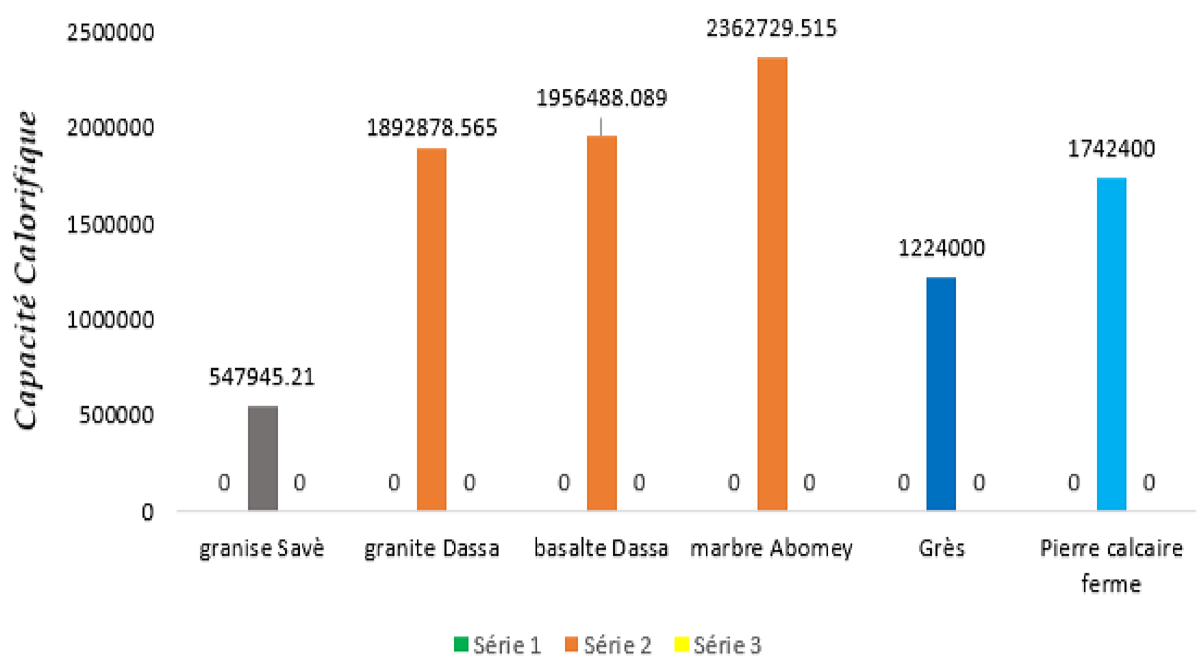

Fig.9 Comparison of the heat capacity of Savè granite with other materials.

3.3 Heat Capacity

From the expression of ρc we have:

$$\rho c = \lambda / \alpha$$

From Table 6, we retain that the average value of the heat capacity is 547,945.21 J/(m^3 K).

It can be seen that the value of the heat capacity of Savè granite is much lower than that of other materials. The heat capacity of granite is the amount of energy required to raise the temperature of a unit volume of granite by one unit temperature [27]. So the Savè granite has a low thermal inertia, that is to say has a low capacity to store heat compared to the other materials illustrated above. Thanks to this thermal property, Savè granite in hot and dry climates can help maintain a comfortable interior temperature by preventing heat accumulation. Buildings constructed with this material may require less energy for cooling and offer increased thermal comfort to the occupants of an eco-habitat built with Savè granite.

4. Conclusion

Building your habitat by favouring locally available material and human resources has beneficial impacts on the economic, social, cultural and environmental levels. Nevertheless, care should be taken to maintain an ideal thermal environment within the room. It is with this in mind that we were able to determine the thermal characteristics of the granite material present in the town of Savè in order to better understand its behavior to ensure compliance with the conditions sought mainly inside an eco-habitat: energy efficiency and thermal comfort. It emerged that the material has interesting thermal properties in terms of thermal diffusivity, thermal effusivity and heat capacity, the values of which are perfectly suited to the construction of an eco-housing. However, it should be remembered that the extraction of granite and its use are not without consequences on the environment. The control of these impacts can constitute tracks of improvement of this work.

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