Thermal diffusivity and adiabatic limit temperature characterization of consolidate granular expanded perlite using the flash method

Saad Raefat\textsuperscript{1b}, Mohammed Garoum\textsuperscript{1a+}, Najma Laaroussi\textsuperscript{1}, Macodou Thiam\textsuperscript{2} and Khaoula Amarray\textsuperscript{1}. \\
\textsuperscript{1} Materials, Energy and Acoustics TEAM, Higher School of Technology Salé, Mohammed V University in Rabat, 11060, 227 Avenue Prince Héritier, Morocco. \\
\textsuperscript{2} University Institute of Technology of the University of Thiès, Senegal. \\
\textsuperscript{a}garoum1@yahoo.fr, \textsuperscript{b}saad.raefat@gmail.com

Abstract: In this work experimental investigation of apparent thermal diffusivity and adiabatic limit temperature of expanded granular perlite mixes has been made using the flash technic. Perlite granulates were sieved to produce essentially three characteristic grain sizes. The consolidated samples were manufactured by mixing controlled proportions of the plaster and water. The effect of the particle size on the diffusivity was examined. The inverse estimation of the diffusivity and the adiabatic limit temperature at the rear face as well as the heat losses coefficients were performed using several numerical global minimization procedures. The function to be minimized is the quadratic distance between the experimental temperature rise at the rear face and the analytical model derived from the one dimension heat conduction. It is shown that, for all granulometry tested, the estimated parameters lead to a good agreement between the mathematical model and experimental data.

1. Introduction 
In order to guarantee a better thermal performance inside buildings decrease their high energy demand and ensure a better occupant’s comfort, the Moroccan Thermal Regulation of Construction (MTRC) has become mandatory in November 2015. Indeed, its establishment requires creating favorable conditions for its implementation. For this purpose, this work aims to improve the thermophysical properties of one Moroccan building material. Accordingly, several samples were prepared mixing the gypsum plaster with granular expanded perlite; some of their thermophysical properties were then investigated on three different granular size. The thermal diffusivity was determined using the flash
method and the adiabatic temperature at the rear face of the sample was estimated using several numerical global minimization procedures.

Recent studies on mixing expanded perlite with building materials were investigated such as in [1] studied the effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete or in [2] who compared the thermal properties of clay when it’s embedded with expanded perlite or granular cork. Reference [3] also determined an experimental and numerical investigation of a hollow brick filled with perlite. Moreover [4] addressed the thermal properties of syntactic metal foam made by embedding expanded perlite particles in aluminum.

The present study aims to estimate the thermophysical properties of expanded perlite mixed with gypsum plaster.

2. Description of used materials

2.1 Expanded perlite.

The material subject of work is the granular expanded perlite (Figure 1); it was taken from Berchid’s industrial zone located in the northwestern part of Morocco. The perlite is a siliceous volcanic natural rock, family of the pearlitic rhyolites. At first, the rock is crushed, and calibrated by particle sizes. Industrial expansion perlite is carried out in special ovens, stationary or rotating. Under the effect of heat (up to 1200 °C), the perlite grains expand: a multitude of closed cells are formed inside the grains. Indeed, the steam expands the material to 15 times its original volume. For this reason, it is mainly used in new construction and rehabilitation as lightweight concrete and aggregate for floors of any kind. In panel form, it is suitable as a sealing support to all types of roofs and all environmental medium.

2.2 Gypsum plaster

The gypsum plaster used in this comparison study is manufactured in Morocco, more precisely, in Safi’s industrial zone. It is used to protect the external walls from moisture and damp, the internal walls from the influence of water vapor, and it plays an esthetic role as well.

3. Experimental approach

3.1 Samples preparation

Three samples were prepared corresponding to three granular expanded perlite categories: C1 [0.625mm; 2.5mm], C2 [2.5mm;5mm] and C3 [5mm; 8mm] shown in Figure1. Particle size distribution of the expanded perlite is presented in Table1. In order to compare the effect of expanded perlite on the thermophysical properties of the samples, a fourth one was prepared using only gypsum plaster. All the samples were formed in a circular mold with 10.3cm in diameter d and 2cm in thickness e. The full mold apparent volume was filled with expanded perlite, right after a certain volume of gypsum plaster was added until that the inter-granular space is entirely occupied. The four samples were covered by a thin black painting, and then introduced into a stove for two days. To ensure that all the pores moisture is totally removed, they were weighted several separate times until their mass became constant. Finally they were packed in plastic bags to maintain zero humidity until experimental measurements use. Water to gypsum plaster ratio was kept equal to 100% in all mixtures. The four samples are presented in Figure 2.
3.2 The flash method

The flash method is adopted for thermal diffusivity determination of many materials. It’s based on the emission of an energy pulse parallel to the tested material front face; and for a very short time, a thermocouple in contact with the rear face enables the record of the temperature increasing in function of time once the front face has received the flash. Its schematic is shown in Figure 3.

![Figure 3. Schematic of the flash method.](image)

Once the steady state is reached the flash is started manually and the temperature of the rear face is recorded with adequate sampling rate. The same procedure is repeated many times on the same sample until three satisfactory curves are obtained.

4. Theoretical approach and global numerical minimisation

A modeling has been done to estimate the thermal diffusivity and the adiabatic limit temperature using the global minimization. Assuming the uniformity of the absorbed energy and an initial temperature $T_0$ equal to the ambient temperature, the rise temperature $T$ is governed by the following system.
\[
\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{a} \frac{\partial T}{\partial t} = 0.
\]
\[
\frac{\partial T(x,t)}{\partial x} \bigg|_{x=0} = -h_1 T(0,t) + Q_0 f(t).
\]
\[
\frac{\partial T(x,t)}{\partial x} \bigg|_{x=e} = h_2 T(e,t).
\]
\[
f(t) = \begin{cases} 
1 & , 0 \leq t \leq t_d \,
0 & , t_d \leq t.
\end{cases}
\]
\[
T(x,0) = 0.
\]

(1)

\(a\) is the thermal diffusivity, \(h_1\) and \(h_2\) are the global heat exchange coefficients on both sides of the sample, \(Q_0, f(t)\) is the finite pulse with duration \(t_d\), \(Q_0\) (W/m²) is the finite amount of heat absorbed at the front boundary \((x=0)\) and \(f(t)\) is the time dependence of the heat generation. For all measurements \(t_d\) is kept equal to 2s. This duration is sufficient to reach more than 1 °C of the maximum rise temperature at the rear face.

The Laplace transform of Eq. 1 allows expressing the solution of the temperature in the Laplace space as:

\[
T(e,p) = T_{ma} F(p) e^{2} \frac{1}{a} \frac{1}{\sqrt{c^2 / a} + (b_{i1} + b_{i2})B(p) + A(p)\sqrt{c^2 / a}}.
\]

(2)

With:

\[A(p) = \text{Sinh} \left( \frac{c^2}{a p} \right).\]

(3)

\[B(p) = \text{Cosh} \left( \frac{c^2}{a p} \right).\]

\(e\) is the thickness of the sample. \(b_{i1}\) and \(b_{i2}\) are the Biot numbers respectively.

\[b_{i1} = \frac{h_{i1} e}{\lambda}.
\]

\[b_{i2} = \frac{h_{i2} e}{\lambda}.
\]

(4)

\(F(p)\) is the Laplace transform of \(f(t)\) expressed as:

\[F(p) = \frac{1 - e^{-p t_d}}{p t_d}.
\]

(5)

\(T_{ma}\) is the adiabatic limit temperature. Where \(\rho\) is the density and \(c\) is the specific heat.

The time dependence of the temperature on the rear face \(T_{th}(e,T_{ma},a,b_{i1},b_{i2},t)\) is then obtained by inverting numerically the solution in Eq. 2. Several algorithms were tested and compared (Papouilis, Talbot, Piessen, Crump, DeHoog, Gaver–Stehfest); among them the numerical method Gaver–Stehfest[5] was chosen for its swiftness and its easier numerical implementation. A special script was written in Mathematica language.

In order to characterize the samples thermally, parameters related to the theoretical model predicting \(T_{th}\) namely \(T_{ma}\), the diffusivity \(a\) and the Biot numbers \(b_{i1}\) and \(b_{i2}\), were simultaneously estimated from experimental data. The optimal values of these parameters were simultaneously estimated by minimizing the quadratic distance \(M\) between the theoretical model stemming from the numerical inversion and the experimental thermogram.

\[M(e,T_{ma},a,b_{i1},b_{i2}) = \sum_{i=1}^{N} \left[ T_{exp}(t_i) - T_{th}(e,T_{ma},a,b_{i1},b_{i2},t_i) \right]^2.
\]

(6)
\( t_i \) is the time points and \( N \) is the length of the experimental data vector taken into account.

To solve the minimization problem in Eq. 6 of the multimodal function \( M \), the Nelder Mead algorithm was implemented using Mathematica language.

5. Results and discussion

5.1 Density:
Knowing the samples exact dimensions and dry masses, the apparent density can be easily deduced, all these parameters are presented in Table 2.

| Sample | e [cm] | d [cm] | m [g]  | \( \rho \) [kg/m\(^3\)] |
|--------|-------|-------|-------|-----------------|
| PP0    | 2.00  | 10.2  | 140.9 | 215.54          |
| PP1    | 1.95  | 10.1  | 112.5 | 176.51          |
| PP2    | 1.95  | 10.3  | 102.7 | 158.02          |
| PP3    | 2.00  | 10.2  | 090.4 | 138.28          |

\( \text{pp1, pp2 and pp2 represent the plaster mixed with perlite for the three granular expanded perlite categories: [0.625mm; 2.5mm], [2.5mm; 5mm] and [5mm; 8mm] respectively. It is clear from Table 2 that the higher the expanded granular perlite size is the lower is the apparent density of the sample. The density decreased from 216 kg/m}^3 \text{ for plaster alone up to 138 kg/m}^3 \text{ for the biggest perlite category C3 (PP3 sample), with 36\% of gain on lightness.} 

5.2 Thermal diffusivity and adiabatic limit temperature:

| Sample | Test | Degiovanni [6] | Parker [7] | Present study | Estimated \( T_{ma} \) [°C] |
|--------|------|----------------|------------|---------------|-----------------|
| PP0    | 1    | 2.92           | 3.16       | 2.79          | 1.66            |
|        | 2    | 2.99           | 3.24       | 2.90          | 1.57            |
|        | 3    | 2.92           | 3.16       | 2.79          | 1.66            |
|        | Mean value | 2.94           | 3.19       | 2.83          | 1.63            |
| PP1    | 1    | 2.79           | 3.16       | 2.80          | 2.00            |
|        | 2    | 2.80           | 3.17       | 2.80          | 2.00            |
|        | 3    | 2.93           | 3.20       | 2.92          | 2.00            |
|        | Mean value | 2.84           | 3.18       | 2.84          | 2.00            |
| PP2    | 1    | 2.84           | 3.24       | 2.96          | 2.00            |
|        | 2    | 2.86           | 3.27       | 2.91          | 2.00            |
|        | 3    | 2.98           | 3.44       | 3.11          | 2.00            |
|        | Mean value | 2.89           | 3.32       | 2.99          | 2.00            |
| PP3    | 1    | 3.23           | 3.73       | 3.53          | 2.00            |
|        | 2    | 3.12           | 3.70       | 3.55          | 2.00            |
|        | 3    | 3.14           | 3.70       | 3.67          | 2.00            |
|        | Mean value | 3.16           | 3.71       | 3.58          | 2.00            |

Table 3 shows the thermal diffusivity of the four samples using three models; the Parker and Degiovanni known models and the proposed global minimization, and the adiabatic limit temperature using the numerical inversion.

From Table 3, the thermal diffusivity values estimated from the Global minimization method are close to those of obtained using the Degiovanni procedure; moreover, these values are included between the Degiovanni and Parker estimated values.

From the analysis of the adiabatic limit temperature, it is clear that it increases for mixtures compared to the plaster alone, which means that \( \rho_c \) decreases. However, for all different mixtures studied \( T_{ma} \) remains constant, which means that \( \rho_c \) also remains constant. We can deduce that \( c \) is increasing with the increase of the particle size since the density decreases (Table 2).
The estimated parameters are then injected into $T_{th}$ in order to compare theoretical and experimental data. Figure 4 presents the predicted and measured thermogram for the four samples. It is interesting to note the well agreement between $T_{th}$ with predicted values of parameters and experimental data.

![Figure 4](image)

**Figure 4.** Comparison between the theoretical model and experimental data.

### 6. Conclusion

This paper has presented an experimental study of the new material gypsum plaster embedded with expanded granular perlite using the flash method. Three thermophysical properties were returned, the density was directly deduced knowing the samples dimensions and masses, the thermal diffusivity was determined through three different mathematical models and the adiabatic limit temperature was estimated using the global minimization procedure. It was concluded that with the increase of the perlite particle size, the thermal diffusivity along with the thermal capacity increased, and the density decreased, this might be due to the water absorption of the expanded perlite particles. Moreover, a good agreement between $T_{th}$ with predicted values of parameters and experimental data was obtained. As perspective, a second numerical procedure is in progress in order to examine precisely the thermal conductivity and the specific heat using only the flash method.

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