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REVIEW ARTICLE **OPEN ACCESS**

Thermal characterization of a new bio-composite building material based on plaster and waste chicken feathers

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Abstract. The building materials used in Morocco characterized by a low thermal resistance which generates a huge expense in terms of energy consumption. Promoting new sustainable construction and insulation materials become a necessity. This research study aimed to develop the thermal proprieties of plaster building material by mixing it with waste chicken feathers (WCF) in order to be used as wall exterior rendering. For the purpose of determining the thermal properties of the biocomposite material Plaster-WCF, several experimental measurements of thermophysical proprieties had been performed in order to determine apparent density, thermal conductivity, and thermal diffusivity using the hot plate method in steady-state regime and the Flash method, respectively. The results showed that the addition of waste chicken feathers leads to a remarkable reduction in apparent density of about 12.3%, the thermal conductivity and diffusivity have been reduced by about 30.2% and 18%, respectively, which shows the interest of using this biocomposite material in the construction buildings in order to ensure thermal comfort and reduce greenhouse gas emissions (CO_2).

1 Introduction

For the purpose of ensuring good thermal comfort in building without harming the environment, it is necessary to search for more energy-efficient construction mode by reducing the need for heating and air conditioning. The building is the second largest energy-consuming sector after transportation with consumption rate of 28%. In Morocco, this sector accounts for 25% of the country's total energy consumption. In this context, Morocco has adopted an energy efficiency strategy applied to build sector. This strategy aims to save about 1.2 MTep of energy and reduce greenhouse gas emissions about 4.5 MTeqco$_2$ by 2020 [1].

The thermal insulation of building envelopes is one of effective techniques adopted to ensure thermal comfort and to save climate change while reducing greenhouse gas emissions. The materials commonly used in construction characterized by low thermal insulation properties [2,3], which has attracted the interest of many researchers to develop new bio-composite materials by incorporating natural and sustainable additives into different matrices. These additives have excellent mechanical, thermal and acoustical properties [4]. Also, the new composite material is renewable, recyclable and available.

Several studies have been carried out to study the improvement of thermal performance by adding natural fibers. The effect of the addition of date palm fibers on the thermophysical properties of cement mortar was investigated by Boumhaout et al. [5]. Authors in this work found out that the addition of fibers reduces the thermal conductivity of the mortar about 70%, declines the thermal diffusivity about 52% and decreases the density about 39%. Another work studied the mortar matrix reinforced with coconut and durian fibers [6]. The results obtained show a decrease in thermal conductivity and a gain in lightness of about 85% and 52% respectively for coconut fiber reinforced mortar composite. Concerning the sample reinforced by durian nut fibers, thermal conductivity and density were reduced by about 79% and 27% respectively. Compressive strength decreased by 89% and 85%, respectively. Belhadj et al. [7] have characterized the thermomechanical behavior of concrete reinforced with barley straw fibers, the results show that these fibers can improve thermal conductivity (5.71%), thermal diffusivity (21.97%), specific heat (29.04%) and density (7%). However, the compressive strength is reduced by 38%. The work of Ricciardi et al. [8] was devoted to study two insulating panels based on paper waste and textile waste, with a total thickness of 12 mm and 20 mm, respectively. The results reveal thermal conductivity values similar to that of synthetic insulators (0.037 W/m.K), while the densities are much higher. Ouakarrouch et al. [9] conducted

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an experimental and numerical study to assess the thermal comfort of "Ksar Lamaadid" located in Erfoud region. This ksar is built with a new biocomposite material based on clay and sisal fibers. The results showed that the addition of 4% of sisal fibers can reduce the thermal conductivity of the material by about 11.2%, which can ensure thermal comfort by reducing greenhouse gas emissions by about 62442 kg of CO_2/yr.

Poultry waste, especially chicken feathers, is destroyed by incineration or burial in landfills. This makes the process of their degradation extremely toxic for humans as well as for the environment due to the pollution of soil, air, surface water and groundwater. In order to combat these environmental constraints, a direct treatment of waste chicken feathers can be carried out in two steps, the first related to anaerobic digestion in a bioreactor to produce biogas and the second that upgrade the digestate into compost [10]. However, several studies have been conducted on biocomposite construction materials based on waste chicken feather. The mechanical properties of composites of epoxy, polyester and phenyl ester reinforced with chicken feather fibers have been characterized by Srivatsav et al. [11] and Subramani et al. [12]. The similarity in stiffness and strength between cement-based composite materials reinforced with chicken feather fibers (5–10%) and those reinforced with wood fibers with the same thickness and density has been demonstrated by Acta [13]. The work of Wahab et al. [14] indicated that the addition of a chicken spine in concrete has a remarkable effect on its compressive strength and fracture. However, fibers degradation of chicken feather in cementations composite materials can be caused by high concentration of pH as demonstrated in [15,16] then was approved by Zhang et al. [17]. They compared the mechanical properties of two types of mortars reinforced with different mass fractions varying from 1% until 5% and they noted that the chicken feather fibers adhere excellently to magnesium silicate hydrate cement mortars ($pH = 10$) compared to Portland cement mortars ($pH = 12.6$).

This paper consists to elaborate a new bio-composite material based on plaster with different mass fractions of waste chicken feathers (0%, 2%, 3%, 4%, 5%), in order to use it as coating roof ceilings and interior wall coating. This new material can meet the requirements of thermal comfort while reducing energy consumption, and ensure a healthy environment through the valorization of waste issues. An experimental characterization of thermo-physical properties of this material has been conducted so as to identify the key factor of material properties, namely the apparent density, the thermal conductivity, and the thermal diffusivity using the hot plate method in steady-state regime and the Flash method, respectively. The experimental results are presented and discussed.

2 Used materials

2.1 Plaster

Plaster is a very popular material used in the building. It is characterized by a powder texture which is obtained by gypsum exploitation. It is widely used as a wall coating and roof ceiling due to its low density, fairly malleability and its availability in the market.

2.2 Waste chicken feathers

Chicken feathers (WCF) are considered to be the waste products of the poultry industry, representing about 5 to 10% of the chicken total weight [18]. The intensive production of this waste is related to the excessive consumption of white meats 20.5 kg/habit/year [19]. Moreover, the generated waste is landfilled without any treatment or exploitation and has adverse environmental impacts.

Samples preparation

The studied waste chicken feathers (WCF) were collected from Benavic Company, washed with hot water mixed with 5% of the detergent solution during 2 h, in order to remove all kinds of blood, manure, impurity, and smell (Fig. 1a). Then they were drying in ambient temperature for 3 days. After this step, the dried chicken feathers were cut into 2 cm in length (Fig. 1b). The preparation of the composite materials (WCF) carried out in parallelepiped steel molds of dimensions $150 \times 150 \times 30\ \text{mm}^3$. The studied samples were prepared by mixing plaster with various mass fractions of (WCF) (2%, 3%, 4%, and 5%). A water ratio ($W/P = 0.6$) was gradually added and escorted by manual stirring to ensure a good homogenization of the various components (Fig. 1c). The resulting mixture was pouring into the mold. A reference sample was manufactured using pure plaster to analyze the impact of adding fibers on the thermos-physical properties of the composite samples.

The five samples were then drying in ambient temperature for 24 h. A smoothing of the outer surface was carried out to ensure perfect contact during experimental measurements. After, the samples were dried in the oven at 60 °C for 2 days in order to eliminate the moisture. The drying process will be stopped until the sample mass was constant ±2 g. Finally, they were packing with plastic to keep their dry states (Fig. 1d).

3 Experimental methods

3.1 Hot plate method in a steady-state regime

The hot plate in steady-state regime is used to determinate the thermal conductivity of the studied composite materials. The experimental device is shown in Figure 2. The method consists to transmit a uniform heat flux ϕ_T by heating element through the lower face of the sample to measure the temperature evolution of both upper faces [20]. The heating element having a parallelepiped form with the dimensions $150 \times 150 \times 0{,}2\ \text{mm}^3$ and electrical resistance of $R_e = 37.89\ \Omega$. The three elements are arranged between two aluminum blocks in order to ensure a constant temperature on the unheated faces.

Three thermocouples type K are placed at the centers of faces. The uncertainty value of the test devices, these thermocouples, is $+/- 0.6$ °C. The measured temperatures are T_0 at the center of the lower face of the heating element,

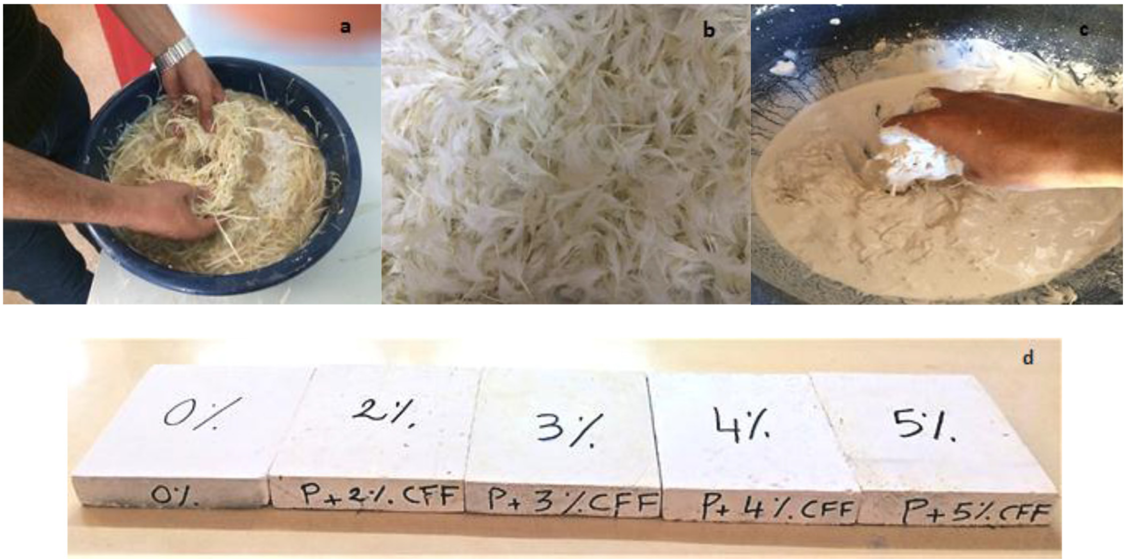

Fig. 1. Different stages of sample preparation.

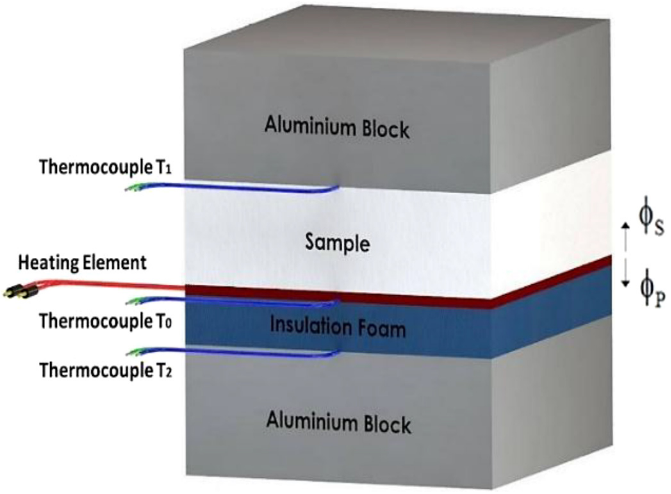

Fig. 2. Experimental device of hot plate method in a steady-state regime.

T_1 at the center of the unheated face of the sample and T_2 at the center of the polyethylene foam, as shown in Figure 2.

The heat fluxes transmitted through the sample ϕ_{S} and the polyethylene foam ϕ_{P} are assumed unidirectional (Eq. (1)). As soon as the steady-state regime is established, the thermal conductivity of the sample is calculated by equation (2).

$$\phi_{\mathrm{T}} = \phi_{\mathrm{S}} + \phi_{\mathrm{P}} = \frac{U^2}{R_e S} \tag{1}$$

$$\lambda_{\mathrm{S}} = \frac{e_{\mathrm{S}}}{T_0 - T_1} \times \left[\frac{U^2}{R_e S} - \frac{\lambda_{\mathrm{P}}}{e_{\mathrm{P}}} \times (T_0 - T_2)\right] \tag{2}$$

where λ_{s} and e_{s} designate the thermal conductivity and the thickness of the sample, respectively. $\lambda_{\mathrm{p}} = 0.043\,\mathrm{W/m.K}$ and $e = 9.6\,\mathrm{mm}$ are, respectively, the thermal conductivity and the thickness of the polyethylene foam.

3.2 Flash method

The Flash method enables the estimation of the thermal diffusivity a ($\mathrm{m^2/s}$) to characterize the heat flux rate passing through a given material, as described in Figure 3. The method consists to send a high power luminous flux (1000 W) for a short time (10 s) on the front side before the material and to follow the temperature development from its backside. The sample must be tinted in black to absorb the totality of generated light flow. Then, the sample is surrounded by a polystyrene guard ring arranged to minimize the flux losses on the sides. The contact area between the sample and the sample holder must be plugged using glass wool. The system is placed in well-insulated thermal with a reflective faces box.

The absorbed light output ϕ_0 is uniform across the sample surface, the initial temperature T_0 is equal to the ambient temperature at $t = 0$. The lateral heat losses are negligible and the heat transfer is unidirectional.

Given these assumptions, we can write:

$$\begin{cases} \dfrac{\partial^2 T(x,t)}{\partial x^2} = \dfrac{1}{a}\dfrac{\partial T}{\partial t} = 0 \\ \left.\dfrac{\partial T(x,t)}{\partial x}\right|_{x=0} = -h_1.T(0,t) + \phi_0.f(t) \\ \left.\dfrac{\partial T(x,t)}{\partial x}\right|_{x=0} = h_2.T(e,t) \\ f(t) = \begin{cases} \dfrac{1}{t_d} & , \quad 0 \le t \le t_{\mathrm{d}} \\ 0 & , \quad t_{\mathrm{d}} \le t \end{cases} \\ T(x,0) = 0 \end{cases} \tag{3}$$

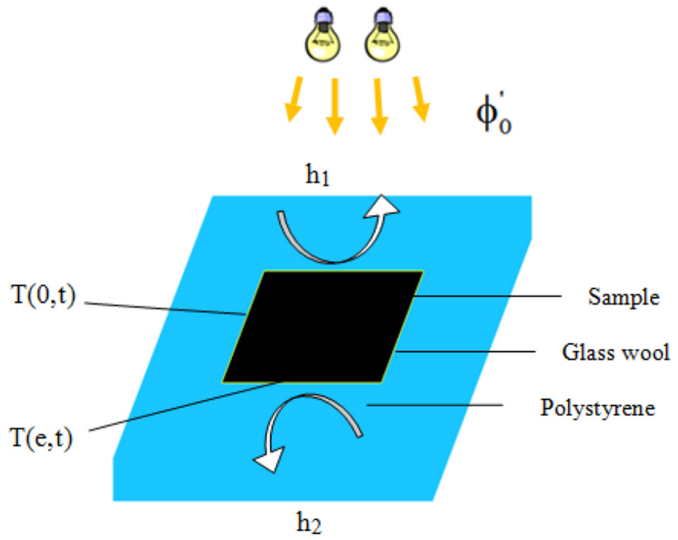

Fig. 3. Schema of the flash method.

where a is the thermal diffusivity, h_1 and h_2 are the coefficients of heat exchange at the two sides of the sample; $f(t)$ is the time dependence of the heat generation. The product $\phi_0 \times f(t)$ denotes the finite pulse of a flash duration t_{d}. The above equation will be transformed into the space of Laplace to obtain the following equation:

$$\theta(e,p) = \frac{j.T_{\max}.F(p)}{\left[\mathrm{Cos\,h}(\sqrt{jp})(\mathrm{b}_{\mathrm{i1}}+\mathrm{b}_{\mathrm{i2}})+\mathrm{Sin\,h}(\sqrt{jp})\left[\frac{jp+(\mathrm{b}_{\mathrm{i1}}.\mathrm{b}_{\mathrm{i2}})}{\sqrt{jp}}\right]\right]};$$

$$j=\frac{e^2}{a} \tag{4}$$

F(p) is the Laplace transform of $f(t)$, e is the thickness of the sample, bi_1 and bi_2 are the numbers of Biot, $T_{\max}$ is the adiabatic limit temperature.

$$F(p)=\frac{1-e^{-p.t_d}}{p.t_d};\mathrm{b}_{\mathrm{i1}}=\frac{h_1 e}{\lambda};\mathrm{b}_{\mathrm{i2}}=\frac{h_2 e}{\lambda};T_{\max}=\frac{\phi_0}{\rho ce} \tag{5}$$

Numerical inversion of the equation (4) is necessary in order to obtain the expression of the theoretical temperature T_{h} of the backside of the sample according to the parameters: e, $T_{\max}$, bi_1, bi_2, and t. Those parameters will be estimated from experimental data and their optimal values can be obtained by minimizing the squared distance between the theoretical and experimental curves (Eq. (6)) as explained in [21]. The calculation code has been implemented in Matlab language and the estimation was performed by the Levenberg- Marquardt algorithm [22].

$$M(e,T_{\mathrm{ma}},a,\mathrm{b}_{\mathrm{i1}},\mathrm{b}_{\mathrm{i2}}) = \sum_{(i=1)}^{N}\left[T_{\exp}(t_i)-T_{\mathrm{th}}(e,T_{\mathrm{ma}},a,\mathrm{b}_{\mathrm{i1}},\mathrm{b}_{\mathrm{i2}},t_i)\right]^2 \tag{6}$$

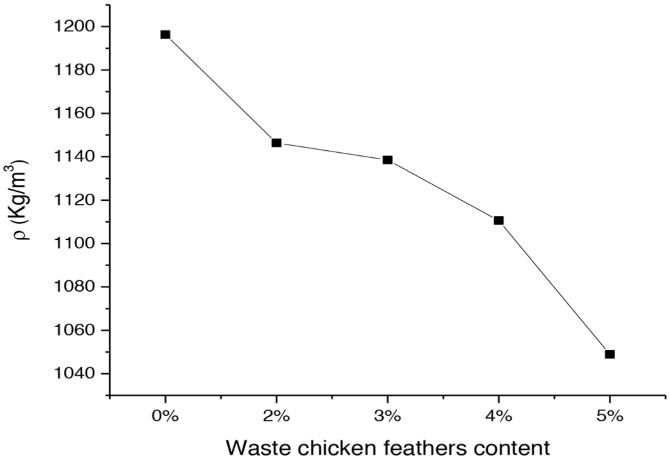

Fig. 4. Apparent density of the various samples.

4 Results and discussion

This section presents the results of the thermophysical characterization of plaster material with different mass fractions of waste chicken feathers: the apparent density ρ_{app} ($\mathrm{kg/m^3}$), the thermal conductivity λ (W/m.K) and the thermal diffusivity a ($\mathrm{m^2/s}$).

Each sample was tested three times in order to get satisfactory thermograms and to respect the accuracy of experimental requirements. It is essential to remove the samples from the device and then replace them between two measurements.

4.1 Apparent density

The economic focus in the building sector is on lightweight materials that the identification of apparent density becomes an important process. To determine the apparent density, it is necessary to measure the weight of the sample and its dimensions. The mass of the studied samples was weighed in the dry state using an electric balance and their dimensions were measured using a high-precision caliper. The apparent density is therefore calculated based on the following equation:

$$\rho_{\mathrm{app}}=\frac{m_{\mathrm{app}}}{V_{\mathrm{app}}} \tag{7}$$

Figure 4 shows the variation of the apparent density of the composite materials based on plaster and different percentage of (WCF) (0%, 2%, 3%, 4%, and 5%). It can be noted that the incorporation of (WCF) in plaster material leads to a remarkable reduction in the bulk density of the material from 1196.3 to 1048.9 $\mathrm{Kg/m^3}$, which allows again in the lightness of about 12.3% for the sample containing 5% of fibers. This reduction is mainly due to the material porosity created with the addition of waste chicken feathers. The result proves the efficiency of the application of those materials as interior wall coating and roof ceilings. Moreover, those bio-composite construction materials show a good adherent structure.

Table 1. Measurement input data and experimental results for the thermal conductivity of various samples.

	Test	e_s (cm)	U (V)	Re (Ω)	T_0 (°C)	T_1 (°C)	T_2 (°C)	λ (W/m.K)
Pure plaster	1	3.02	14.157	37.89	32.779	21.923	20.735	0.523
	2				33.908	22.969	21.873	0.519
	3				34.654	23.724	22.658	0.520
	Mean value of thermal conductivity (W/m.K)							**0.520**
	Standard max deviation (%)							0.6
P+2% WCF	1	3.22	14.101	37.89	40.167	27.360	27.600	0.445
	2				36.413	23.884	23.037	0.445
	3				37.403	25.484	23.862	0.466
	Mean value of thermal conductivity (W/m.K)							**0.452**
	Standard max deviation (%)							3.1
P+3% WCF	1	3.22	14.101	37,89	36,523	23,865	21,437	0,421
	2				39,073	25,861	23,905	0,403
	3				35,78	22,809	21,602	0,420
	Mean value of thermal conductivity (W/m.K)							**0.415**
	Standard max deviation (%)							2.9
P+4% WCF	1	3.24	14.101	37.89	37.656	23.663	22.853	0.386
	2				39.001	24.595	23.665	0.370
	3				37.322	23.293	23.983	0.401
	Mean value of thermal conductivity (W/m.K)							**0.386**
	Standard max deviation (%)							4.1
P+5% WCF	1	3.40	14.101	37.89	39.042	23.809	23.526	0.365
	2				40.235	24.774	24.746	0.360
	3				40.696	25.281	25.426	0.364
	Mean value of thermal conductivity (W/m.K)							**0.363**
	Standard max deviation (%)							0.8

4.2 Thermal conductivity

The measurement of thermal conductivity of the studied samples was performed using the hot plate method in a steady-state regime. The input data such as sample thickness, voltage, and electrical resistance and the recording of the three temperatures T_0, T_1 and T_2 and the thermal conductivity measurement of the different samples were summarized in Table 1. The maximum deviation is about 4.1% showing that the used method is so reliable. It is clear that the thermal conductivity decreases with the increasing of waste chicken feathers contents with a rate of 30.2%, starting from 0.520 W/m.K which represents the thermal conductivity of the pure plaster until 0.363 W/m.K corresponding to the composite P+5% WCF. This reduction is mainly due to two principal factors, the first one is related to the chicken feathers low thermal conductivity, the second one is associated with the creation of air-filled pores generated inside the composite material through the incorporation of chicken feathers. In fact, the air has a very low thermal conductivity (0.026 W/m.K) that will cause a decrease in the thermal conductivity of the composite.

4.3 Thermal diffusivity

The thermal diffusivity of the various samples characterized in this study was estimated using the flash method. According to several tests results, it is found that the flash duration (10 s) is largely sufficient to ensure a 0.9 °C of maximum rear face temperature increase. The maximum error measurement does not exceed 5.2%. Figure 5 shows an experimental thermogram which describes the rear face temperature rise of the P+5%WCF composite. Table 2 summarizes the results obtained for the five studied samples. As a result, the thermal diffusivity of the composite material decreases as the mass fraction of waste chicken feathers increases. The thermal diffusivity decrease from 3.45×10^{-7} m^2/s for the sample containing 100% of plaster to 2.84×10^{-7} m^2/s for the composite P + 5% WCF with an average reduction of 18%. This is probably due to the creation of air-filled pores inside the composite through the integration of waste chicken feathers. Knowing that air represented high thermal insulation properties, the composite containing more pores will have more ability to hold back the heat transfer rate.

Table 2. The experimental results for thermal diffusivity of various samples.

W (%)		0%	2%	3%	4%	5%
a ($\times10^{-7}$.m^2/s)	Test 1	3,616	3,212	3,052	2,901	2,808
	Test 2	3,270	3,132	3,207	2,898	2,863
	Test 3	3,450	3,164	3,035	2,979	2,842
	Mean value	**3,45**	**3,17**	**3,10**	**2,93**	**2,84**
Standard max deviation (%)		5,2	1,3	3,3	1,6	1,1

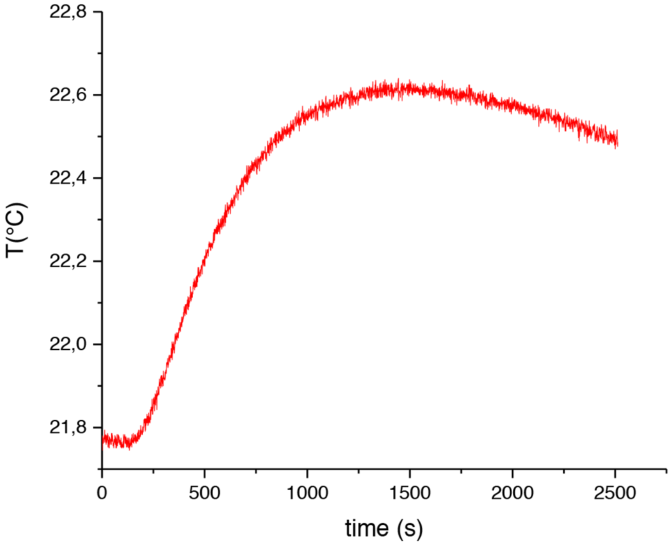

Fig. 5. Experimental thermogram of flash method.

The result found demonstrates the impact of adding waste chicken feather on the reinforcement and improvement of the fundamental thermal properties of building materials, which will sequentially ameliorate insulation quality and thermal comfort of buildings.

Similar results were obtained by Lachheb et al. [23] which studied the influence of adding coffee grounds, on the thermal properties of plaster. The authors of this work showed that adding 6% in the mass fraction of the used coffee grounds to the plaster might reduce its thermal conductivity from 0.5 to 0.314 W/m.K (38%).

An experimental study was conducted by Cherki et al. [24] on the improvement of thermal conductivity and lightness of plaster by incorporating granular cork. The results of this study show a reduction in thermal conductivity of about 30%.

5 Conclusion

The main objective of this paper is to study the thermal performance of new bio-composite material based on plaster and waste chicken feather. Experimental methods were used to estimate apparent density, thermal conductivity and thermal diffusivity of plaster material with different mass fractions of waste chicken feathers (0%, 2%, 3%, 4% and 5%). As a result, it follows that:

- the addition of WCF (5%) can reduce the thermal conductivity of the composite material with about 30.2%. Similarly, the thermal diffusivity has been reduced by about 18%. In addition, WCF lightens the building material, as its density has been reduced to 12.3%;
- the use of new composite material in building construction can ensure thermal comfort without heating or cooling systems and can reduce greenhouse gas emissions because the reduction of energy consumption has a big impact on CO_2 emissions.

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