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## **Dynamic behavior and economic analysis of sustainable building integrating cob and Phase Change**

### **Materials**

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### **Abstract**

The will of reducing energetic and environmental impact of building sector has led to a renewed interest in earth construction. For its low environmental impact compared to conventional construction materials, cob construction could help achieve the previous mentioned will and also value local materials. In this work, new thermal insulation and structure made from cob were developed and thermo-physically characterized. The impacts of these new materials equipped in a residential house on heating loads and the indoor comfort are analyzed by means of dynamic simulation using TRNSYS software considering a Typical Meteorological Year (TMY) of eight French cities referring to the representative zones of the RT2012. Thermal performance of the cob house assessed by comparison to a conventional case of the house built with conventional construction materials. A PCM layer is integrated into the external wall ( $0.24\text{W/mK}$ ) of the Cob house. The major finding of this work is that the investigated cob house integrated PCM layer allows reducing the annual temperature oscillation and the heating loads compared to the conventional case. Moreover, a Life Cycle Cost (LCC) analysis is performed with the local market cost in order to investigate the competitiveness of the cob house enhanced PCM compared to the conventional case.

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## 1. Introduction

Nowadays, the topics of environmental preservation and energy resources management has been getting the consideration of a broad research community worldwide due to their great consequence for the next generations[1]. Building sector is one of these highly discussed topics because it is one of the largest consumer of natural resources and the most contributor to the greenhouse gases emissions that participate to climate change[2]-[3]. Flowingly, various passive energy efficiency measures can be adapted by the building sector leading to a more sustainable building. In this framework, some practices can be implemented among others using green building materials which must be local, abundant and renewable.

In the literature, numerous authors have proposed the use of different green materials such as cereal, straw, corn stalk [4], bagasse, rice, straw [5], sunflower hulls and stalks, banana stalks, coconut coir [6], bamboo, durian peel and palm leaves oil [7]. Among these green materials, earth materials are preferred due to their low embodied energy [8]. These kinds of materials can be manufactured and used instantaneously on the building site and does not require industrial processing. Earth construction is a very common construction in the whole world due to its simplicity. It is mainly situated in less developed countries [9] but also can be found in France and UK that has an excess of 500,000 earth based dwellings [10]. It is estimated that the number of existing cob building heritage is about 50 000 in Germany [11], 40 000 in Devon (UK) [12], 30 000 in Ille-et-Vilaine (France) [13] and 20 000 in Manche (France) [14]. This data demonstrates the durability of cob construction which will save as much energy as it would be necessary for the construction of new building. France government is still promoting the earth construction through the foundation of the CRATerre laboratory in 1979 which is connected to the School of Architecture in Grenoble. Through this laboratory, an educational project consists of 150 interactive experiences has been implemented in order to keep a robust and durable act in the promotion of earth construction [15]. This later can be wattle and daub, rammed earth (including earth projection), earth bricks (adobe) or compressed earth blocks (CEB) and cob. In the first technique (i.e. wattle and daub), a woven lattice of wooden strips called wattle is daubed with earth which is used for at least 6 000 years [16]. Rammed earth is a technique of construction, which involves compaction of damp mixture of earth inside a wooden or steel formwork, making either a solid wall or individual blocks. Earth bricks (adobe) or compressed earth blocks is made by compressing damp soil at high pressure to form blocks using a mechanical press [17]. Finally, Cob material made out of a mixing of soil, water and fibrous organic materials. The term cob means “a lump of rounded mass” and is inspired from the technique of construction with cob in which it processed to round lumps and then are put together to build wall. The main components of a cob building are [18][19]: (i)

foundation in order to bring up the cob structure from water coming from the ground and to decrease the menace of sinking through the distribution of the building load; (ii) walls which are made of cob in a mix of clay, water, straw in varying share, (iii) roof which must prevent the rain from hitting the walls by using wide roof overhang, (iv) finally the drainage system in order to prevent the water damages.

In literature, numerous authors declared plenty of interest regarding the use of earth in building construction as alternative materials. Mansour et al. [20] studied the effect of bulk density on thermal (thermal conductivity and thermal diffusivity) and mechanical properties (compressive strength and modulus of elasticity) on compressed earth blocks (CEB). They demonstrate the use of  $1750 \text{ kg/m}^3$  as bulk density can reduce the thermal conductivity to  $0.75 \text{ Wm}^{-1}\text{K}^{-1}$  without penalizing the mechanical properties. Using CEB, Olivier and Mesbah [21] have analyzed the impact of the compacting pressure and the optimum water content of sample on the dry density and the compressive strength. Soudani et al. [21] analyzed the thermal performance, from in-situ measurement for two years, of a house located in South-Eastern France. The studied house is a non-insulated rammed earth with low heating energy in winter and no cooling device in summer. Their results indicate that the studied house affords a good thermal comfort in summer in regards to stability and level of temperatures and a very low heating loads.

As highlighted by the previous cited references, the cob materials are encouraged due to their embodied energy, relative simplicity and abundance. However, for the same thickness as the conventional house walls, cob walls have a low thermal resistance due to their high thermal conductivity. To overcome this limitation, the use of thick cob wall is recommended which also help to achieve the strength and mechanical criteria. Another solution is the use of Phase Change Materials (PCM) due to their large latent heat. These kinds of materials can enhance the thermal mass of the cob building by storing the heat coming from the exterior or the internal gain for later use. It is well documented, that the integration of the PCM in building wall can reduce the heating and cooling loads. Gounni et al. [23] summarized the techniques on how the PCM can be integrated in building envelop which can be either direct immersion or micro-encapsulation. The direct immersion presents the risk of leakage phenomenon for PCM in liquid state [24]. PCM micro-encapsulation is used to overcomes this leaking problem. To be suitable for the integration into building envelop, PCM can be microencapsulated in sheets laminated with aluminum [25].

This paper investigates a single family house annual thermal performance based on bio-sourced materials integrated cob and Phase Change Materials by comparison to the same architectural house built by conventional materials. The paper deals with the development of two kind of cob materials (i.e. structural and thermal

insulation) and their thermo-physical properties are determined and analyzed. Afterwards, the dynamic behavior of two houses (i.e. Conventional and cob house) are modeled using TRNSYS. The annual thermal performance of each studied house is analyzed for the same indoor temperature and ambient outdoor temperature. The effect of integrating the Phase Change Materials in the cob house is assessed in terms of annual heating loads. Finally, a thermo-economic analysis is used to compute the total cost including the cost of labor and materials as well as the cost for heating during the life cycle of the building.

## **2. Thermo-physical properties of the Energain PCM panel and cob materials**

### **2.1. Cob preparation**

Cob structural material (Figure 1) used in this study is characterized by its stiffness to resist important loads thanks to their low fiber content less than 5%. It is a mix of soil, 2.5% hemp straw and 28.5% water content while insulation material contains soil, 25% hemp shiv and 107.3% water content. Cob thermal insulation material (Figure 1) contains important amount of fiber 25-50% affording good thermal insulation. The soil is mixed with water and preserved for 3 days before adding fibers. Once the fiber is added to soil, the mixture is kept in  $20\pm 2^{\circ}\text{C}$  within relative humidity of  $50\pm 5\%$  one day before making samples. After, the mixture is put in molds for 2 days, then is unmolded and kept in a stove within  $40^{\circ}\text{C}$ . Cob structural and insulation materials are already accomplishing all strength and mechanical criterions and also providing good thermal insulation. the structural and insulation materials.



Figure 1 : Photographic view of the developed bio sourced materials.

### **2.2. Thermo-physical properties of the Cob materials**

The experimental thermal characterization of cob samples consists on thermal conductivity, thermal diffusivity and bulk density measurements. The apparent volume of the samples and its weight measured using an electronic balance are used to determine the bulk density according to NF P18-559 AFNOR French standard

[20]. The thermal conductivity measurements are carried out in-situ using experimental apparatus made in the laboratory based on the heat flow meter method. The test section includes one heater and one copper multi-microchannel heat sink (250 mm × 250mm × 3mm) of 50 parallel micro channels as a cold source connected to an isothermal bath with a temperature regulator and a 12 g/s flow rate. K-type thermocouples are inserted in the inlet and outlet of heat sink. The specimens are put between two copper plates located in direct contact with the heater and microchannel heat exchanger. Finally, the thermal diffusivity is determined using KD-2 needle probe conductivity meter.

Thermo-physical properties of the insulation and the structural cob materials are summarized in Table 1. The structural material has low thermal conductivity 0.24 (W/m K) regarding the important amount of fibers content 5%. In the same way, the thermal insulation material, has thermal conductivity of 0.19 W/mK. This value remains higher than that of classical thermal insulation, which does not exceed 0.05 W/mK. The thickness of cob insulation material is increased to enhance its thermal resistance.

Table 1 : Thermo-physical properties of the cob samples.

Sample	Density (kg/m <sup>3</sup> )	Thermal conductivity (W/mK)	Thermal diffusivity (mm <sup>2</sup> /s)
Cob structural material	1145	0.24	0.19
Cob insulation material	625	0.19	0.13

### 2.3. Thermo-physical properties of the PCM layer

In order to enhance energy performance of the cob house, Energain PCM panel is integrated. Figure 2 shows the composite PCM panel of 5 mm thickness, constituted of 60% of microencapsulated paraffin within a copolymer. The PCM melting temperature is about 22°C. The PCM density is about 850 kg/m<sup>3</sup>.

In the previous work, numerous investigations were conducted using Energain PCM panels. Kuznik et al. [26] have studied building included Energain PCM panels. They measured thermo-physical properties of Energain PCM panels at different temperatures using guarded hot plat apparatus and DSC method. They obtained for temperatures of 5°C and 35°C, a thermal conductivity of 0.22W/mK and 0.18W/mK respectively for solid and liquid states. They assumed that thermal conductivity decreases linearly from 0.22W/mK to 0.18W/mK for temperature between 5°C and 35°C.

The Energain PCM heat capacity is measured by means of a differential scanning calorimeter [26] as presented in Figure 3. Distribution of the PCM specific heat capacity according to the temperature is defined for the freezing and heating modes where the peak temperature is of 18 °C and 22 °C respectively. For temperature below than 18°C, the PCM is in solid state. When ambient temperature reaches 22°C, the PCM phase change (from solid to liquid phase) occurs and absorbs heat from the ambient source. In the freezing mode, when the ambient temperature reaches 18°C, heat from the PCM layer is generated solidifying PCM in the Energain panel. The latent heats measured by Kuznik et al. for melting and freezing modes are 107.5kJ/kg and 104.5kJ/kg at temperature of 13.5°C and 23.5°C.



Figure 2 : PCM panel.

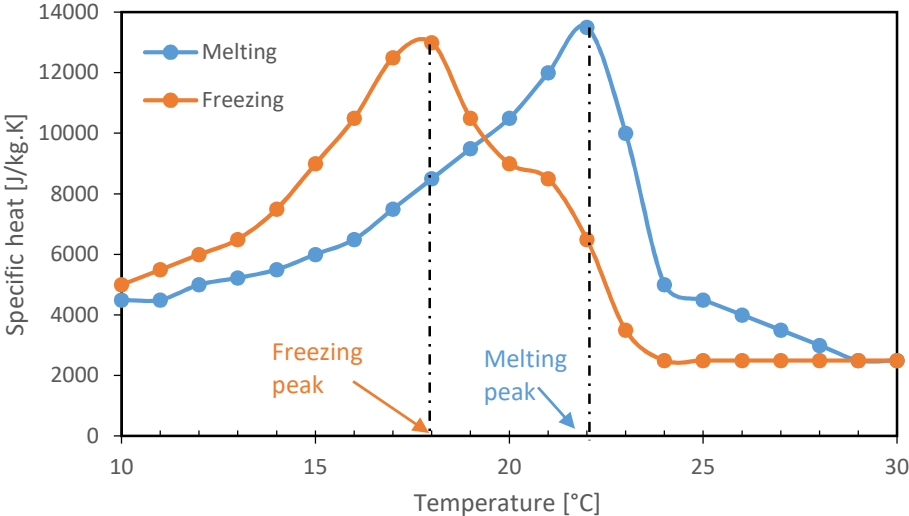


Figure 3: PCM heat capacity measurement [26].

### 3. Physical model

The thermal performance of studied building is investigated using TRNSYS software. The transient thermal behavior of the building is done using Type 56 (TRNBuild) which represents the studied building by one thermal zone (one representative temperature) is calculated as follows:

$$\dot{Q}_1 = \dot{Q}_{\text{surf}} + \dot{Q}_{\text{inf}} + \dot{Q}_{\text{solar}} + \dot{Q}_{\text{cond}} \quad (1)$$

Where,

- $\dot{Q}_{\text{surf}}$  is the convective heat flux of the considered thermal zone. It is given by:

$$\dot{Q}_{\text{surf}} = U_w A_w (T_w - T_{\text{air}}) \quad (2)$$

With,  $U_w$  is the transmission coefficient ( $\text{kJ} \cdot \text{h}^{-1} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ),  $A_w$  the inside wall area ( $\text{m}^2$ ),  $T_w$  and  $T_{\text{air}}$  are the inside wall and indoor ambient temperatures respectively in (K).

- $\dot{Q}_{\text{inf}}$  is the infiltration which presents the air flow from outside only. It is given by:

$$\dot{Q}_{\text{inf}} = \dot{V} \rho C_p (T_{\text{ext}} - T_{\text{air}}) \quad (3)$$

With,  $\dot{V}$  is the infiltration flow rate in ( $\text{m}^3/\text{h}$ ),  $\rho$  and  $C_p$  are the density and heat capacity of the air respectively in ( $\text{kg}/\text{m}^3$ ) and ( $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ), and  $T_{\text{ext}}$  is the outside temperature (K).

- $\dot{Q}_{\text{solar}}$  is the rate of the absorbed solar gains through windows (kJ/h).
- $\dot{Q}_{\text{cond}}$  is the rate of heat transmitted through the envelope (kJ/h).

Temperature in the zone is calculated hourly from its energy balance as follow:

$$C_p \frac{d}{dt} T_{\text{air}} = \dot{Q}_1 \quad (4)$$

Therefore, heating loads are deduced assuming set points of 18 °C when the house is occupied and 12°C when it is unoccupied. The important assumptions are:

- The thermal zone is defined by an air node representing the uniform temperature of the volume.
- An arbitrary uniform temperature and humidity fields are assumed and initially set to 20 °C and 50%, respectively.
- The doors and windows are closed (no free cooling).
- The infiltration rate is 0.6 Air Changes per Hour (ACH) for all zones. Only the building leakage through cracks due to the pressure and temperature difference between indoor and outdoor is considered here without mechanical ventilation.



- Diffuse solar radiation is calculated from the global solar radiation on a horizontal surface using Perez model.
- Solar absorptivity of the white mortar in the external walls and the roof is 0.4.
- Convection heat transfer coefficients for internal surface are calculated using the relation [27]:

$$h_{\text{inside}} = c (T_{\text{surf}} - T_{\text{air}})^n \quad (5)$$

With  $c$  and  $n$  are constants reported in Table 2 which depend on the surface orientation.

Table 2 : Input parameters for the calculation of heat transfer coefficient.

Surface type	$c$ ( $\text{W m}^{-2} \text{K}^{-1-n}$ )	$n$
Floor	2.00	0.31
Ceiling	1.07	0.31
Vertical wall	1.60	0.30

- Convective heat transfer coefficient for external surface is calculated following correlation which takes into account the wind velocity  $V$ :

$$h_{\text{ext}} = 2.8 + 3.2 V \quad (5)$$

- The ground temperature of the building is determined using Type 77 of TRNSYS, using the Kusuda correlation [62]

$$T_{\text{mean}} = T_{\text{amp}} \exp \left[ -\text{depth} \left( \frac{\pi}{365 \alpha} \right)^{0.5} \right] \cos \left( \frac{2\pi}{365} \left[ t_{\text{now}} - t_{\text{shift}} - \frac{\text{depth}}{2} \left( \frac{365}{\pi \alpha} \right)^{0.5} \right] \right) \quad (6)$$

This correlation determines the temperature distribution at a considered depth given its surface temperature amplitude ( $T_{\text{amp}}$ ), the surface annual mean temperature ( $T_{\text{mean}}$ ), the time difference between the beginning of the calendar year and the day that occur the minimum surface temperature and thermal diffusivity of the soil ( $\alpha$ ).

### 3.1. Building architecture

The studied building is a single-family house with two floors of 2.5 m height per floor, located at Normandy, France. The 2D and 3D architectural plans of a single-family house are seen in Figures 4 and 5. The floor area is 65m<sup>2</sup>. As shown in Figure 4, for both studied conventional and cob houses, the first floor has one kitchen, one living room and one laundry room; while the second floor consists of four bedrooms and one bathroom.



Figure 4 : 2D Architectural plans of the studied house.

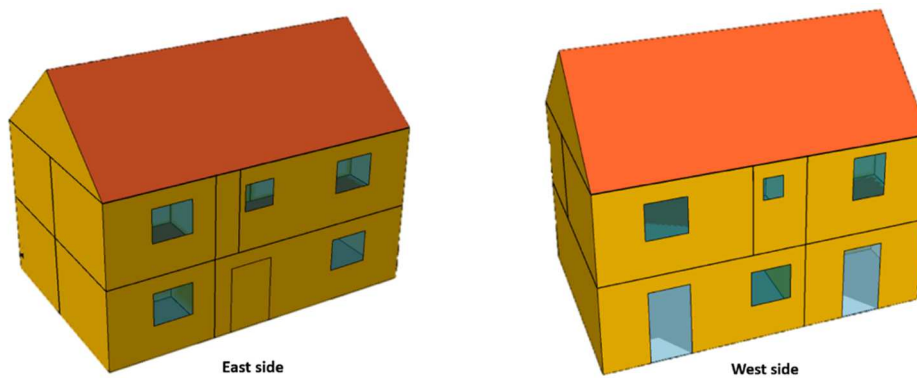


Figure 5: 3D architectural plans of the studied house.

In this paper, thermal performance of the cob house and conventional house are compared using the same house design plans as showed in Figure 4. The conventional house is defined according to the French thermal regulation RT2012 using the conventional building materials with sizes and thermal properties listed in Table 3. The external wall of the conventional house consists of plasterboard, rockwool, concrete blocks and exterior mortar, which represents the classical tendency in France. Its transmission coefficient including convection transfer is about  $0.262 \text{ W/m}^2\cdot\text{K}$ . The ceiling consists of concrete entrevous, glass wool, and reinforced concrete slab, with a global heat transfer coefficient of  $0.293\text{W/m}^2\text{K}$ .

Table 3 : Thermo-physical properties of the conventional house building materials.

Building component	Composition	Thickness (mm)	Thermal conductivity (W/m.K)	Density (kg/m <sup>3</sup> )	Heat capacity (J/kg.K)	U-Value (W/m <sup>2</sup> .K)
External wall	Plasterboard	13	0.25	900	1000	0.262
	Rockwool	150	0.047	150	1030	
	Concrete blocks NF P 18-307	200	0.52	1500	1000	
	Exterior Mortar plaster	15	1.3	2000	1000	
Floor	Reinforced concrete slab	100	2.3	2400	1000	0.442
	Expanded polystyrene	100	0.050	10	1450	
	Fine gravel	50	2	1800	1000	
	Sand	50	2	1800	1000	
Ceiling	Plasterboard	13	0.25	900	1000	0.293
	Concrete entre vous	200	1.33	1500	1000	
	Glass wool	150	0.047	14	1030	
	Reinforced concrete slab	100	2.3	2400	1000	

The Cob house with the same architecture as the conventional house, uses the French Cob materials (fibre-soil mixture) as showed in Table 4. Thermo-physical properties of the Cob house materials are measured experimentally as described above. The walls of the Cob house are a succession of lime (1.5 cm), cob insulation (30cm), cob structure (40cm) and Coated raw earth (1.5cm). Its transmission coefficient is about 0.291 W/m<sup>2</sup>.K. The ceiling of the Cob house consists of cob structure (30cm), cob entrevous (7cm) and coated raw earth (1.5cm) with 0.390 W/m<sup>2</sup>K transmission coefficient. The used thicknesses of Cob house walls already accomplish the strength and compression criteria. In this study, doors with light wood of 4 cm thickness and 2.29 W/(m<sup>2</sup>K) heat transmission coefficient, and two types of windows, simple and double glazing are considered as described in Table 5. The building is occupied all over the year according to the schedule given in Figure 6. The internal heat loads are presented by table 6.

Table 4 : Thermo-physical properties and size of the Cob house building materials

Building component	Composition	Thickness (mm)	Thermal conductivity (W/m.K)	Density (kg/m <sup>3</sup> )	Thermal capacity (J/kg.K)	U-Value (W/m <sup>2</sup> .K)
External wall	Lime	15	1.98	1400	850	0.291
	Cob insulation	300	0.19	625	1408	
	Cob structure	400	0.24	1145	1121	

	Coated raw earth	15	0.75	1500	900	
Floor	fired earth	20	0.22	700	1000	0.271
	slab of lime	120	1.98	1400	850	
	Expanded clay balls	300	0.09	330	1000	
Ceiling	Cob insulation	300	0.19	625	1408	0.390
	Cob structure	120	0.24	1145	1121	
	Cob Entrevous	70	0.24	1145	1121	
	Coated raw earth	15	0.75	1500	900	

Table 5 : Windows characteristics

Windows	Material	Thickness	U-value (W/m <sup>2</sup> .K)	G-value (%)
Simple glazing	Ordinary glass	2.5	5.74	0.84
Double glazing	Glass/air/glass	2.5/12.7/2.5	2.95	0.777

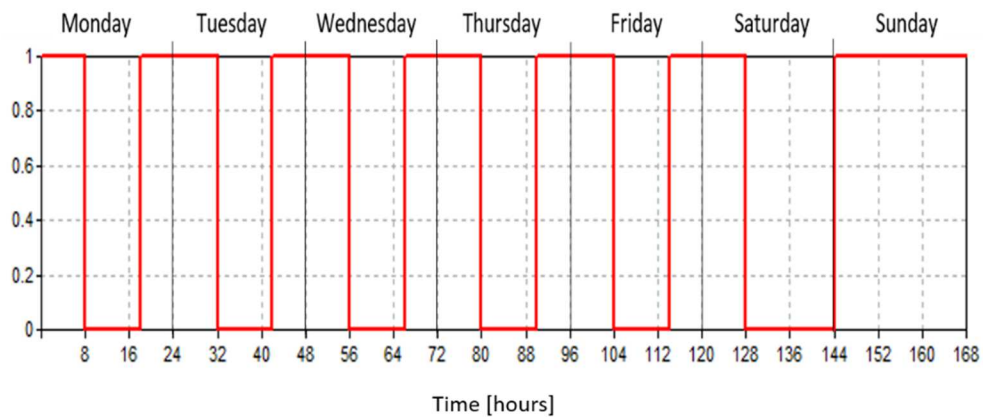


Figure 6 : weekly occupation scenarios.

Table 6 : Internal heat gains.

Types	Sensible power	Duration
Persons	65W per person (seated) ASHRAE 2013.	See Figure
Appliances	Kitchen Appliances 200 W ; SIA 2024	2 hours/day
Light	6 W/m <sup>2</sup>	On : L<120 W/m <sup>2</sup> Off : L>200 W/m <sup>2</sup>

### 3.2. Climatic context

French's climate varies widely according to eight climatic zones as shown in Figure 7. It can be seen from Figure 8, that according to French regulation RT2012, the lowest energy demand is 40 kWh/m<sup>2</sup>/year for the H3 zone and the highest is 65 kWh/m<sup>2</sup>/year for the H1b zone. Figure 9 shows the hourly variation of ambient temperature for a typical meteorological year of the eight French climatic zones. It is clearly seen that there is a significant variability in the climatic conditions of each zone, which means that is necessary to investigate the thermal performance of both conventional and cob houses with respect to each zone.

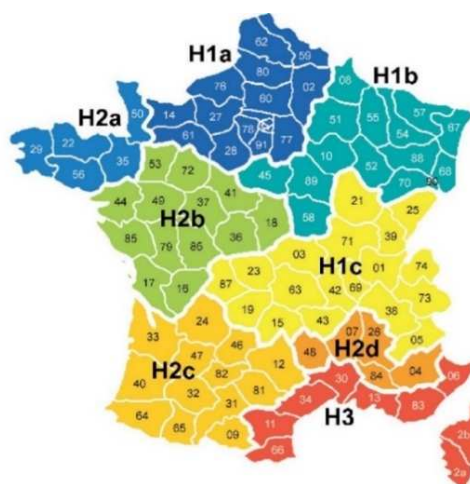


Figure 7: Map of climatic zones according to RT2012 : zones code.

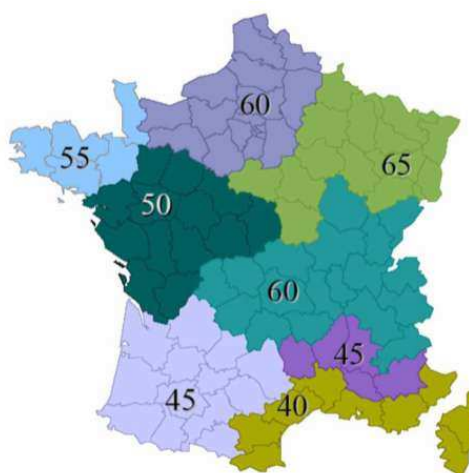
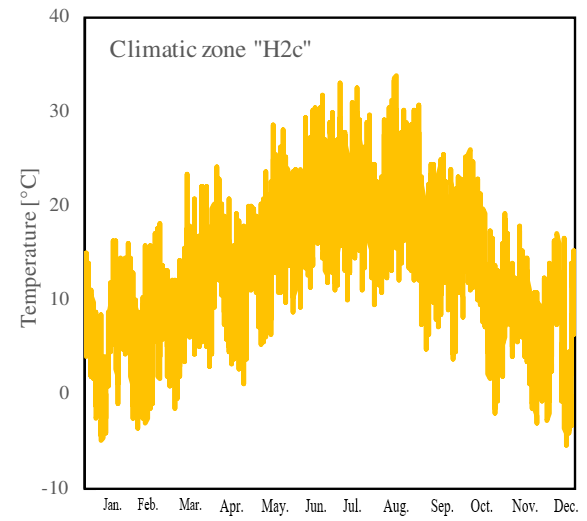
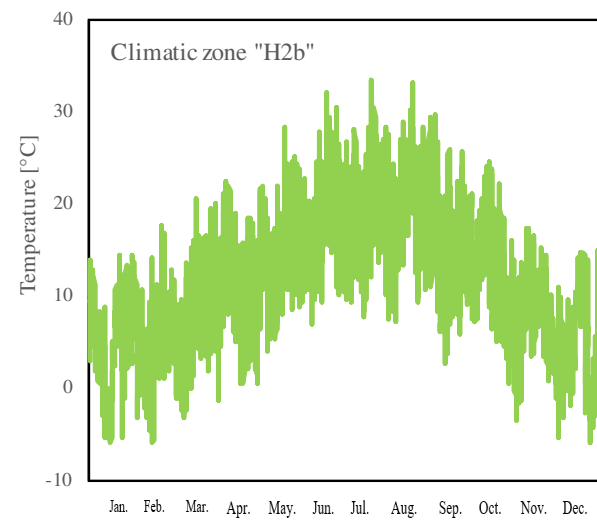
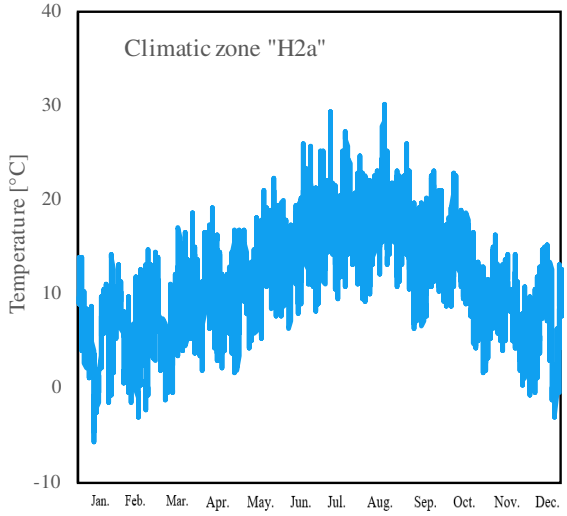
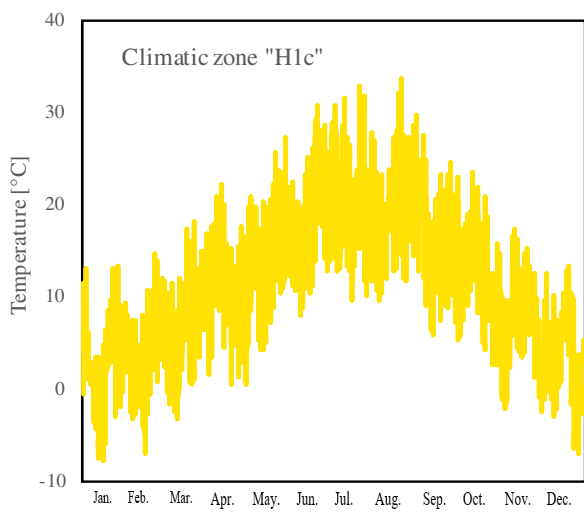
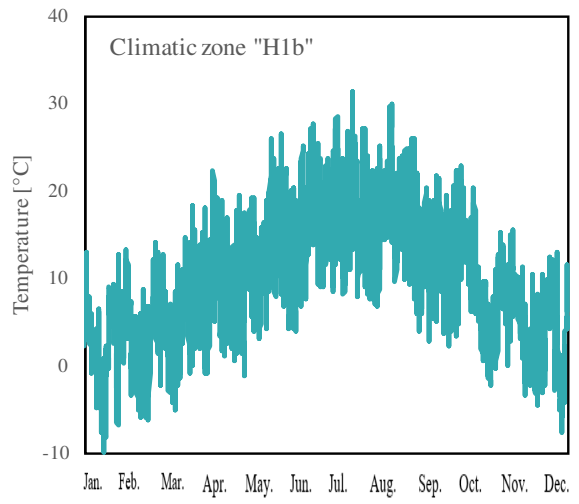
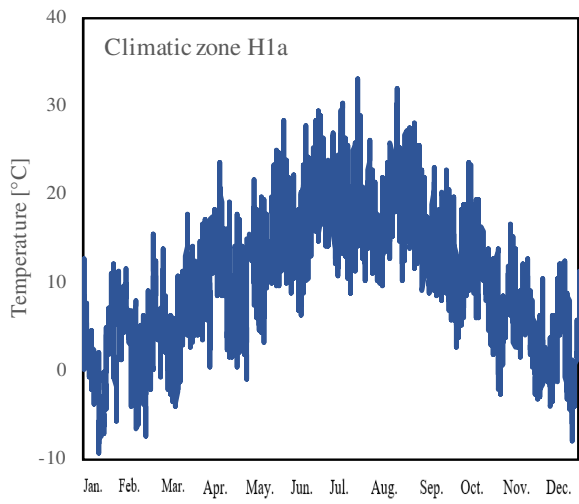


Figure 8 : Maximal energy demand of BBC house.



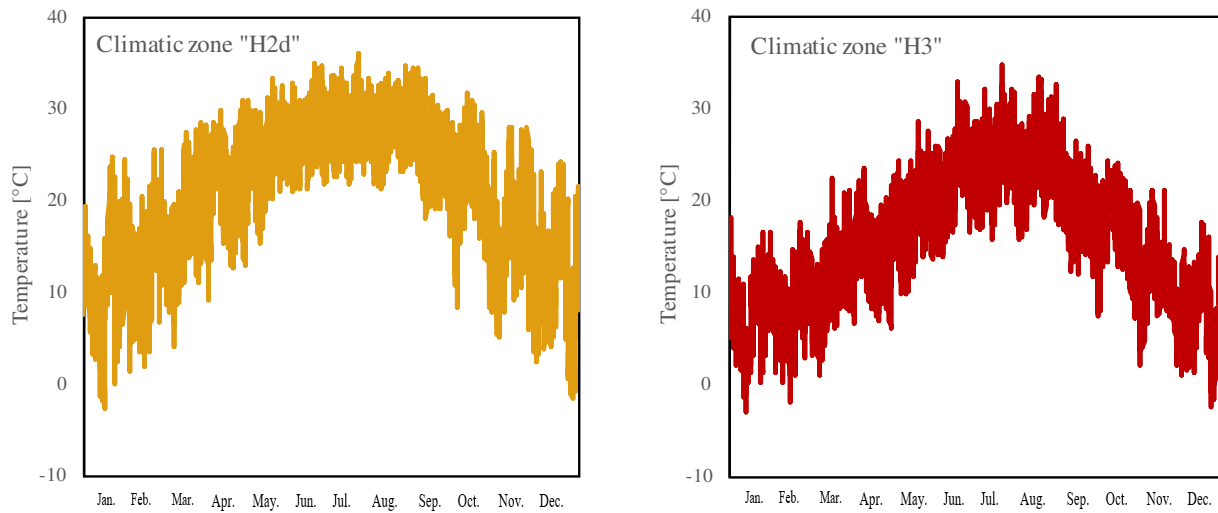
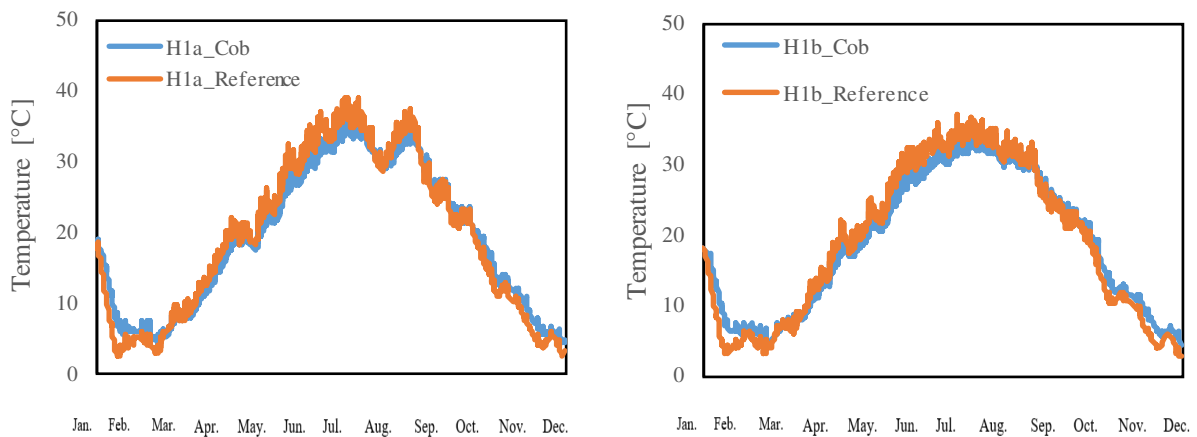


Figure 9 : Hourly temperature profile in the eight French climatic zones for a typical meteorological year.

#### 4. Results and discussion

##### 4.1. Building thermal performance

Thermal behavior of the Cob and conventional houses is analyzed in terms of indoor air temperature for the same climatic zone and the same hourly ambient temperature. The composition and thermo-physical properties of the two houses are presented in Table 3 and 4. Indeed, the climatic conditions of the eight climatic zones of France are taken from the Typical Meteorological Year (TMY) as used in this study [30]. Figure 10 shows the hourly variation of indoor air temperature profile for both houses and for the eight climatic zones. It is shown that the indoor air temperature of the cob house has a low oscillation for all zones, this occurs because of the high thermal inertia of the Cob house. Table 7 presents the temperature difference between the Cob and conventional house for a winter and summer day.







15 <sup>th</sup> Jan.	4.82	4.61	4.51	4.28	4.44	4	2.9	3.59
15 <sup>th</sup> Jul.	-2.7	-2.7	-2.5	-2.5	-1.7	-2.3	-1.8	-2.7

For the winter day, the maximum temperature difference is obtained for the H1a climatic zone (i.e. 4.82°C) although the minimum difference is showed for the H2d climatic zone (i.e. 2.9 °C). For the summer day, the maximum temperature difference (i.e. -2.7 °C) is showed for the H1a, H1b and H3 zones, while the minimum difference is occurred in H2b climatic zone. Furthermore, the air temperature inside the Cob and Reference house strongly depends on climatic zones. For all zones, January and December are the coldest months, although the maximum temperature occurs in July. This temperature difference between the Cob house and the conventional house will affect the heat loads, which will be investigated in the next section according to each climatic zone.

## 4.2. Energy performance

### 4.2.1. Cob house

In this section, the inside air temperature of each zone and for the Cob and conventional houses is kept at set points according to the Figure 11 for heating period in order to compute the annual thermal loads for heating. For the weekdays, the indoor air temperature is kept at 18°C from 00h to 08h and from 18h to 00h, which corresponds to the occupancy period, while it is kept at 12°C from 08h to 18h when the house is unoccupied. Figure 12 shows a comparison of annual heating loads of each zone of the two houses for H1a climatic zone. A clear reduction on heating loads is performed by Cob house. The total heating loads related to whole house are 30.2 and 22.8 kWh/m<sup>2</sup>/year, respectively for the conventional and Cob houses.

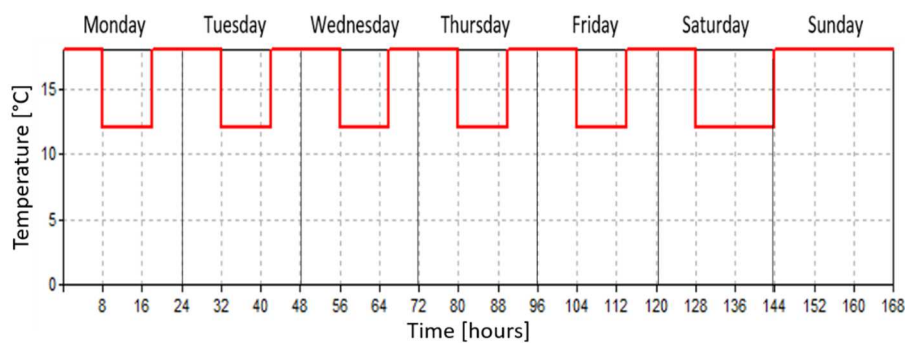


Figure 11 : Hourly indoor set point temperature for heating period.

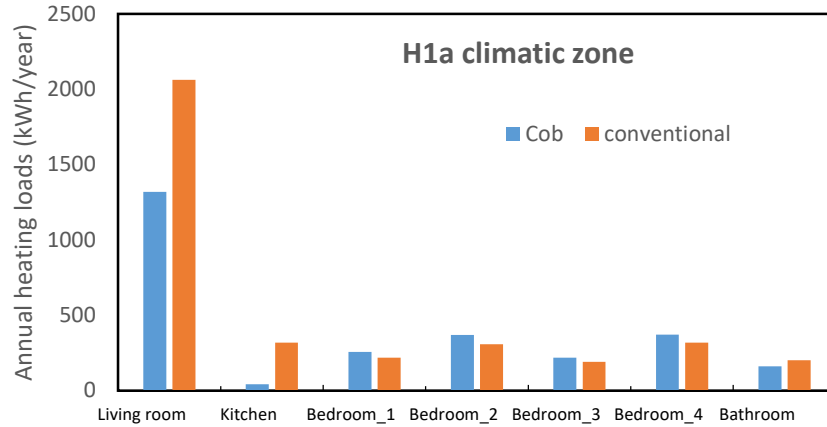


Figure 12 : Heating loads of the Cob and conventional house according to the H2a zone.

Figure 13 shows a comparison of the annual heating loads of the cob and conventional houses according to the eight climatic zones. For all zones, the Cob house performed a low heating loads compared to the conventional house. This occurs due to the temperature difference between the two houses showed in the thermal performance section. The climatic zones H1a and H1b performed the same heating loads; the same observation is valid for the climatic zones H2a and H2b.

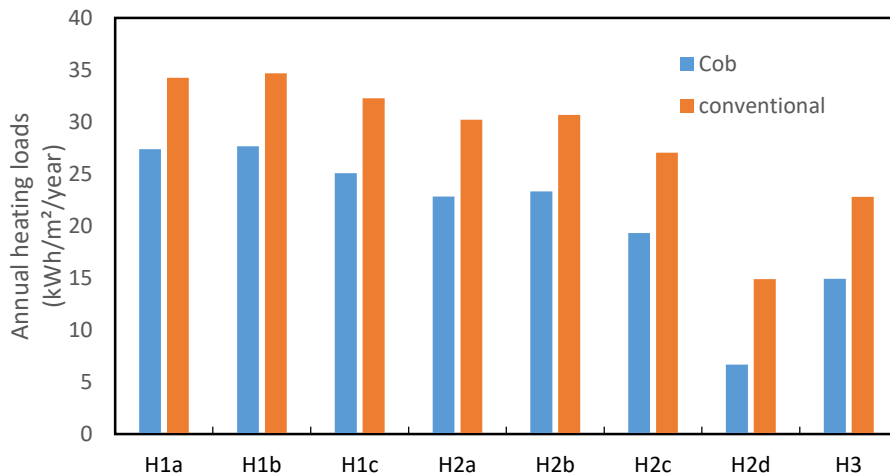


Figure 13 : Annual heating loads of the Cob and conventional house for the eighth zones.

The thickness effect of the insulation wall and the structural wall on heating loads is investigated in order to determine the optimal thicknesses for which the Cob house is competitive to the conventional one respecting the regulation RT2012. Figure 14 shows the effect of cob insulation wall thickness on heating loads for the eight

climatic zones, while the thickness of cob structural wall is kept at 40 cm. It is showed from the figure that, when increasing thickness of cob insulation material, heating loads decreases accordingly for the eight curves. When insulation thickness increases from 10 to 30 cm, the heating loads decreases from 34 to 27, 35 to 27, 32 to 25, 29 to 22, 29 to 23, 24 to 19, 8 to 6 and 19 to 14 kWh/m<sup>2</sup>/year respectively for H1a, H1b, H1c, H2a, H2b, H2c, H2d and H3. The effect of thermal insulation is remarkable in the climatic zone with high heating loads (e.g. H1a) although this effect of thermal insulation is almost negligible for the climatic zone with low heating loads (e.g. H2d).

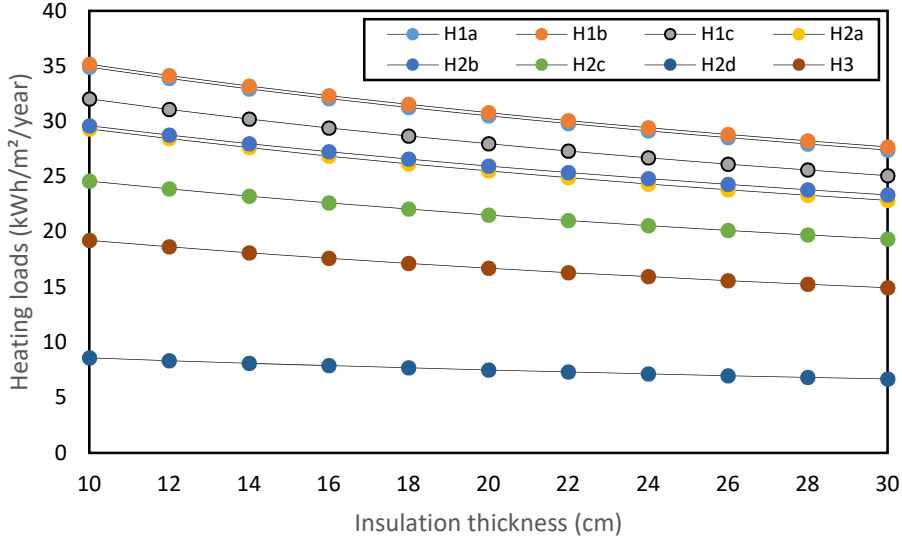


Figure 14 : Effect of cob insulation wall thickness on heating loads for different zones.

Figure 15 presents the effect of cob structural material thickness on heating loads for the eight climatic zones. Here, the thickness of cob insulation is kept at 30cm. The heating loads decrease with thickness of cob structural material also some climatic zones have the same heating loads. It is noticed according to this analyze that with thicknesses below 30cm and 40cm respectively for structural and insulation cob walls, we can get the requirement of the BBC house described by French regulation RT2012. However, for the mechanical criteria consideration, in the following section, the thicknesses that will be adopted are those presented in Table 3 and 4.

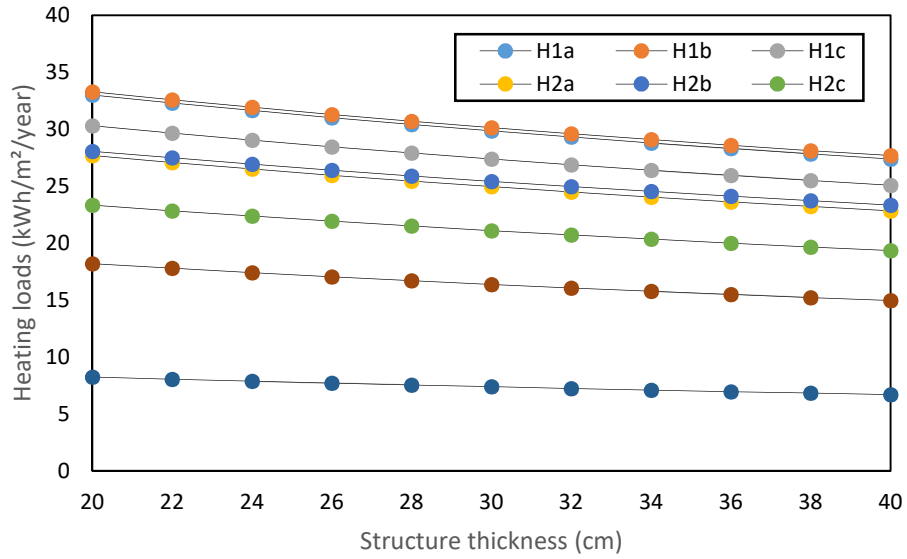


Figure 15: Effect of cob structural wall thickness on heating loads for two thicknesses of cob insulation material.

#### 4.2.2. Cob house enhanced PCM

In this section, a new PCM layer is incorporated into the cob house external walls to enhance its thermal inertia compared to the conventional house. Simulation is conducted using the studied cob house walls defined from the internal to external side as 15mm Lime, 5mm PCM layer, 300mm cob insulation material, 400mm cob structural material, and 12mm coated raw earth. For the six climatic French zones, Figure 16 presents comparison of the thermal performance of the cob house incorporated PCM layer, Cob house without PCM, and conventional house. This comparison is conducted for three houses with the same plans, dimensions, location, orientation, and ambient temperature.

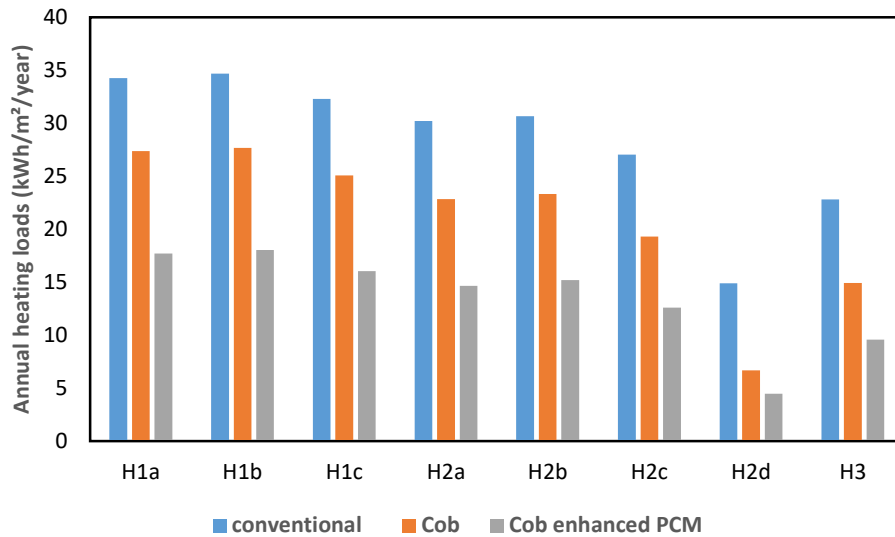


Figure 16: Annual heating loads for the conventional, Cob and Cob integrated PCM house for the eighth zones.

As shown by Figure 16, a great reduction of the annual heating loads is achieved by integration of a PCM layer. The results show that for the three tested houses and for the all French climatic zones, the maximal annual energy demand is low than 50 kWh/m<sup>2</sup>. The requirement of the thermal regulation RT2012 for a BBC house is then respected. It can be seen that for Cob house, the maximum annual energy need is about 28kWh/m<sup>2</sup> obtained for H1a climatic zone. In this case 20% of energy saving is obtained by using cob building house. The maximum energy saving is about 50%, obtained for H2d climatic zone where a very largely period of year is at ambient temperature higher than 18°C compared to H1a. For the Cob house integrated a PCM layer and for all the studied climatic zones, the annual energy load is even more reduced by approximately 35% comparing with cob house without PCM. More annual energy is saved for the colds climatic zones than for the hot climatic zones where the energy need is low. This enhancement thermal energy saving is due to latent energy stored by the phase change material layer. The PCM phase change temperature is close to the external ambient temperature of various climatic zones considered in this work. More phase change temperature is close to the ambient temperature, better is energy saving and lower is house energy load. It is well known that for latent heat storage, energy storage occurred at melting temperature, is high. For the case where the case where the ambient temperature is higher than phase change temperature (22°C), PCM layer fully melting occurs inducing sensible heat transfer in the PCM layer. Otherwise, if the ambient temperature became lower than the freezing temperature (18°C), a solid layer occurs inducing a generating sensible heat transfer part. For both cases, sensible heat storage (or generation) is lower than latent heat storage (or generation) because PCM heat capacity is low. Add to that, thermal conductivity of the PCM (about 0.18 W/mK for liquid phase and 0.22 W/m for solid

phase) is low because in the PCM panel, solidification and melting processes occur inside micro spheres containing paraffin, where heat is then transferred from the paraffin to the ambient through spheres surface. In general, enhancing PCM thermal conductivity by including nanoparticles or a metallic matrix, increases heat transfer inside the PCM layer. Therefore, phase change could be occurring evenly inside the PCM layer and increases heat storage efficiently.

### 4.3. Thermo-economic analysis

In this section, the competitiveness of the Cob house is judged in terms of total cost. For this motive, we used the life cycle cost analysis, which include the cost of investment and energy cost for heating, which is calculated as [31]:

$$C_{\text{tot}} = C_{\text{enr}} \text{PVF} + C_{\text{invst}} \quad (6)$$

$C_{\text{invst}}$  is the investment cost, which includes the cost labor force, and material cost calculated as follows:

$$C_{\text{invst}} = C_{\text{lb}} + C_{\text{m}} \quad (7)$$

Tables 8-10 present the cost labor force and material for the two houses based on analyze done by Laestander [32].

$C_{\text{enr}}$  is the energy cost of heating which depends on annual heating loads determined in the previous section, the cost of LPG and its calorific value and the performance of the heat pump used as heat production system. The numerical values of these parameters are given in Table 10.

$$C_{\text{enr}} = \frac{C_f Q_h}{H_u \eta} \quad (8)$$

PVF is the Present Value Function, which depends on the discount rate ( $r$ ), for the lifetime of  $N$  years which is given in Table 10.

$$\text{PVF} = \frac{(1+r)^N - 1}{r(1+r)^N} \quad (9)$$

Where

$$r = \frac{i - g}{1 + i} \quad (10)$$

Figure 17 presents the comparison between the studied conventional house, cob house and cob enhanced PCM house in terms of investment, energy cost and their sum according to the eight climatic zones. It is observed that the investment cost of cob is much higher than that of conventional house by about 2052 Eur/m<sup>2</sup>. However, when

dividing these costs on expected lifespan the investment cost of Cob house became much lower than that of conventional house. Indeed, the energy cost of the Cob house is lower than that of reference house for all zones due to minimum heating loads obtained for the Cob house compared to the conventional one. When integrating the PCM layer to the cob house, a reduction of the heating loads, which translate to energy cost, is observed but the investment cost is increased. It is observed that the total cost of the cob enhanced PCM house is comparable to that of Cob house with a few reductions in the favor of the cob enhanced PCM.

Table 8: Costs labor force cob and conventional [32]

	Persons working	Hours of work/person	Total work time (hours)	Time/m <sup>2</sup>	Cost per m <sup>2</sup>
Cob	8	4 608	36864	307.2	3028.9
Conventional	7	1 572	11004	91.7	904.1

Table 8 : Material cost [32]

	Sum materials (Eur)	Sum materials (Eur/m <sup>2</sup> )
Cob	5 356	44.6
Conventional	14 096	117.5
PCM layer	12325	102,71

Table 9 : The cost per m<sup>2</sup> per year of estimated lifetime for cob [32]

Building technique	Cost/m <sup>2</sup> (Eur)	Expected lifespan (years)	Cost/m <sup>2</sup> per year (Eur)
Cob	3073.6	400	7.6
Conventional	1021.7	100	10.2
PCM layer	102.71	100	1.03

Table 10 : Input parameters [33].

Parameter	Value
LPG for heating	
Cost, Cf (Eur/kg)	1.75
Lower heating value, Hu (kWh/kg)	12.9
Condensing boiler	
Efficiency, $\eta$	0.98
Economic input	
Average interest rate, i	0.86

Average inflation rate, g	1.6
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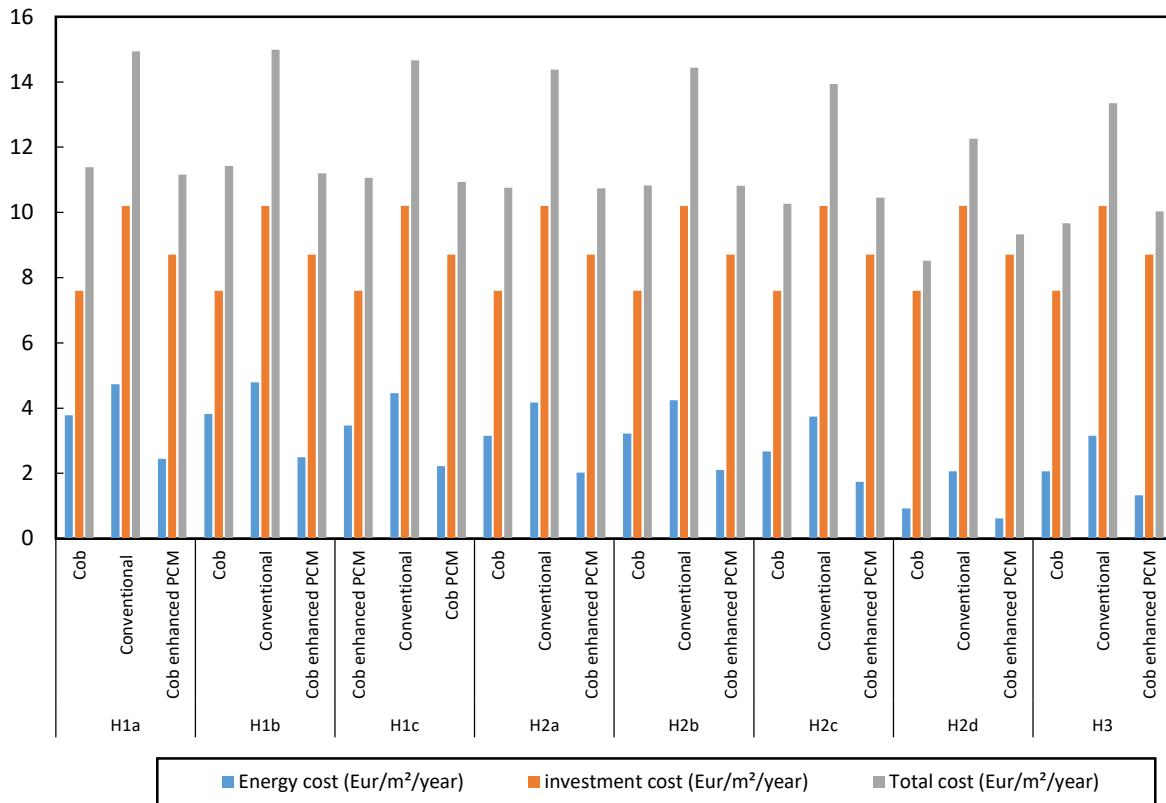


Figure 17: Competitiveness of Cob versus conventional house in terms of total cost for different climatic zones.

## Conclusion

Recently, the new thermal insulations based on bio-sourced materials have taken great attention due to their thermal building insulator performances, their low cost production and their low environmental impact. This paper gives a contribution to the knowledge of these materials, by attempting to describe and assess their thermo-physical properties (i.e. Density, thermal conductivity and thermal diffusivity) in-situ. The impacts of these new materials equipped in a residential house on heating loads and the indoor comfort are analyzed by means of dynamic simulation using TRNSYS software considering a Typical Meteorological Year (TMY) of eight French cities referring to the representative zones of the RT2012. Thermal performance of these materials is assessed by comparison to a conventional house identical to the Cob house but built with conventional materials widely used in French construction. The results show that the bio-sourced materials have a remarkable effect on the indoor air temperature, thermal comfort and thermal load of the house compared to the conventional house. The integration of the Cob materials to the building, leads to better thermal comfort



conditions compared to the conventional case. Moreover, the minimum of the indoor air temperature in Cob house is up to 4°C higher than that of the conventional house in winter, while its maximum is reduced by up to 2.5°C in summer compared to the conventional house. Furthermore, the Cob house performs between 20% and 50%, depending on the climatic zone, reduction of the annual thermal load compared to the conventional case. In the second part of the paper, we integrated a PCM layer into the external wall of the cob house. The integration of the PCM affected significantly the heating loads by storing the heat coming from internal gain and solar radiation. Finally, a thermo-economic study is performed to compare the proposed solution (cob and PCM) to the conventional house in terms of total cost which include the energy cost as well as the cost of labor force and materials.

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