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Case study

Thermal performance of unfired clay bricks used in construction in the north of France: Case study

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ABSTRACT

The objective of this study is to demonstrate and to study the sustainability and the qualities of the earthen construction in real conditions. A demonstrative building was designed and built with unfired clay bricks, were industrially produced by the factory "Briqueteries du Nord" (BdN). This industrial plant is located in the north of France. This project aims to create conditions for the development of earthen construction techniques in the north of France. Moreover, it aims to prove the benefits of this material on the sanitary quality of the building.

This article is composed of three parts. Firstly, the identification of raw materials was performed in order to study the mains properties of these building materials. The second part of this work presented an experimental study conducted to investigate the dynamic thermal performance of unfired clay bricks.

To complete the tests already carried out in laboratory, an experimental investigation was carried out in situ on a demonstrative building. The hygrothermal performance of building is monitored for two consecutive years. The first analysis of the obtained data proved clearly that the earthen wall reduces the fluctuations of the outside temperature.

1. Introduction

Reducing energy consumption in the building sector is a key policy priority for the industrialized nations. As an illustration, the building sector in France consumes more than 42% of final energy. It generates nearly one-quarter of that country's greenhouse gas emissions (ADEME, French Environment and Energy Management Agency, 2010). Performance requirements to be reached over the next years appear ambitious and were expressed in France through adoption of the new RT 2012 thermal regulation. This new standard promotes the widespread construction of low-energy buildings. The objective consists on reducing the average primary energy consumption in new buildings by two-thirds. The maximum value was fixed at 50 kWh/m^2 per year on average for the five uses of heating, hot water, lighting, cooling and auxiliaries (fans, pumps).

Creating energy savings and reducing CO$_2$ emissions in this sector constitute a major economic and ecological challenge, and encourage the use of sustainable construction materials. Earthen construction presents several advantages that allow it

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to be a current response to energy and climate issues. In fact, it is one of the main building materials used on our planet. It is estimated that almost a third of the world's population lives in some type of earthen dwelling. It is one of the oldest building materials, used in many different ways around the world for centuries. Approximately 50% of the population of developing countries, the majority of rural populations, and at least 20% of urban populations live in earth homes (Houben and Guillaud, 1994).

During the last few years, a growing interest has been considerably appeared for earth as a sustainable material. It has been then studied in the engineering laboratories around the world in the aim of the earth building products certification. Obviously, Earth is an abundant natural and recyclable resource. It is low embodied energy building material, which is in perfect adequacy with the eco-friendly construction and in the field of the sustainable development. Dethier and Eaton (2002) presented earth as the material of future with desirable sustainability attributes, which can produce interesting architecture in modern times.

Several research studies have outlined these benefits, as demonstrated by Pittet and Kotak (2009) in his comparative study between different technologies of construction (earth, concrete, brick and stone). Shukla et al. (2009) showed that construction and maintenance of an adobe house allow to save 370 GJ of energy per year, compared to conventional materials. It can also reduce CO_2 emissions by 101 tonnes per year. Lastly, Morel et al. (2001),Chel and Tiwari (2009) and Zami and Lee (2010) proved the economic benefits of earth construction, by reducing the energy required for the manufacture of these products, as well as reducing the environmental impact.

Furthermore, the thermal storage properties and humidity balancing effects of earth provide the advantages of this ecological material. It contributes to the thermal comfort and to the healthy aspects of buildings. Thus, the earth walls have hygroscopic qualities. They balance the indoor climate by absorbing and releasing moisture as the relative humidity of the air changes. In fact, a high moisture levels affect thermal performance of building and indoor air quality through the development of moulds and bacteria. The recommended relative humidity for humans comfort is between 30 and 60%, as mentioned by most of authors (Balaras et al., 2007; Wolkoff and Kjærgaard, 2007).

The earth walls have the ability to provide an excellent constant internal relative humidity, as shown in the research carried out by Minke (2000, 2006). In other hand, Padfield (1998) has tested the efficiency in buffering the indoor relative humidity of different building materials, using an experimental climate chamber. The buffer performance among the materials tested is given by wood and a specially developed mixture of bentonite with perlite. Further, Lindberg and Akander (2002) made an experiment in a full-scale room with earth walls. They concluded that the high heat and moisture buffering capacity of earth can reduce the need for energy-driven ventilation. Similarly, Morton et al. (2005) and Jaquin et al. (2009) showed the hygroscopic qualities of earth structures.

Moreover, the thermal properties of earth walls can contribute to reach the energy efficient building design requirements. The thermal mass of this material has the capacity to store daytime heat gains and to release the heat during the night. Martin et al. (2010) compared stone, adobe (traditional) and wooden (modern) houses in their investigation of the thermal behavior of existing housing in Spain. They demonstrated that the indoor environment inside the traditional houses could be comfortable with less energy consumption than new buildings. They attribute this result to the thick exterior walls of high thermal inertia.

Nevertheless, despite its qualities, the earthen construction has largely remained unrecognised; this is due to the fascination for modern materials such as concrete, brick or steel. Moreover, the lack of international standards required for the products evaluation leads to this phenomenon. Only some national reference documents and codes are used in the earth construction around the world, as mentioned by Delgado and Guerrero (2007). Orally-transmitted know-how has been lost and project owners are not aware of its advantages. However, it has many features that meet environmental concerns and is in perfect harmony with the environmentally-friendly construction approach. In this context, this study has launched with the Briqueteries du Nord company, intended to create the conditions for developing earthen construction techniques and spreading their use. The main objectives of this project are promoting this type of construction in Northern France, improving the insurability of structures, initiating an integrative approach of active involvement of regional stakeholders in the areas of eco-materials, architecture, construction and land use, and finally, demonstrating the benefits of this material in creating a healthy living environment.

The present work investigates the thermophysical properties of unfired clay bricks at laboratory scale and on situ. These bricks are industrially produced, by the Briqueteries du Nord (a factory located in the north of France), with an extrusion process. Firstly, the characterization of the raw material, used in the production of this building material, is presented. Then, the different thermophysical properties of this brick were determined. Finally, an experimental investigation was carried out in situ on a demonstrative building (20 m^2). The objective is to study and to analyze the characteristics of this material, in real

Table 1
Soil characteristics.

Constituents/properties	Values	Constituents/properties	Values
Textural composition (%wt)		Atterberg limits (%)	
Sand	15	Water content	21
Silt	80	Liquid limit	24
Clay	5	Plastic limit	21

conditions and over time. This building was instrumented by temperature and flow sensors, to characterize the thermal behavior and to study the indoor thermal comfort.

2. Identification of soil properties

A soil sample was collected from a quarry in the north of France. It has been used in the manufacture of unfired clay bricks.

Particle size analysis and the consistency limit tests were carried out to determine the physical and geotechnical properties of the sample. Particle size distribution was determined using a wet sieving and a sedimentation test, according to standard (XP CEN ISO/TS 17892-4, 2005XP CEN ISO/TS 17892-4, 2005). Atterberg limits were determined using a standard method described in NF P94-051 (1993). The results of this work are presented in Table 1.

It can be noted that the soil can be classified as a low plasticity soil (Plasticity index = 3). This is mainly due of the low clay content and the abundance of quartz. This observation is in accordance with the sample microstructure, presented in Fig. 1. This soil microstructure was determined by scanning electron microscopy (SEM). It showed that the soil has a discontinuous structure and an open texture, with the presence of individual plates where the voids are more visible and connected.

Chemical composition tests using X-ray fluorescence (XRF) technique and mineralogical examination based on X-ray diffraction (XRD) were carried out to study the composition of soil sample. The chemical composition, presented in Table 2, shown that the soil contained a significant amount of silica, primarily from the alumina silicates and the quartz, as demonstrated in the mineralogy analysis (Fig. 2). Other trace oxides (Fe, K, Ca, etc.) have been detected in the chemical analysis of the sample.

3. Thermophysical characterisation of unfired clay bricks

The Briqueteries du Nord Company produces unfired clay bricks, using the raw material characterized previously. It is produced according to artisanal techniques. It is shaped using a vertical mixer and a wooden mould (see Fig. 3). The brick surface is smoothed by water. The bricks are then stacked on carts by a robot and conveyed to drying tunnel with controlled air temperature and humidity.

An experimental study was carried out to investigate the thermal properties of unfired clay bricks. The thermal conductivity (λ) of the bricks was determined based on standard NF EN 12664 (2001). The method consists in simultaneously measuring the heat flow and temperature on both faces of a sample subjected to a temperature gradient generated by two exchanger plates.

Another element that characterises the thermal properties of materials is the specific heat capacity (c). The specific heat capacity is primarily determined based on a material's heat storage process. The measuring apparatus is the same as for measuring conductivity and only the imposed thermal stresses are different. In the initial state, the system is isothermal (the exchanger plates are at a temperature (θ_{initial}) then it is brought to a final heat level (θ_{final}), also isothermal, by changing the setpoints of the bath thermostats. In-between these two states, the sample stores an amount of energy Q, which represents the variation of the material's internal energy, as expressed by the following formula, where C is the capacity (J/K m^2), $\Delta\Phi$ is the difference of the measured flows (W/m^2) and dt is the acquisition time:

$$Q = \int_{t_{\text{ini}}}^{t_{\text{fin}}} \Delta\phi \mathrm{d}t = C(\theta_{\text{final}} - \theta_{\text{initial}}) \left[\mathrm{J/m^2}\right] \quad (1)$$

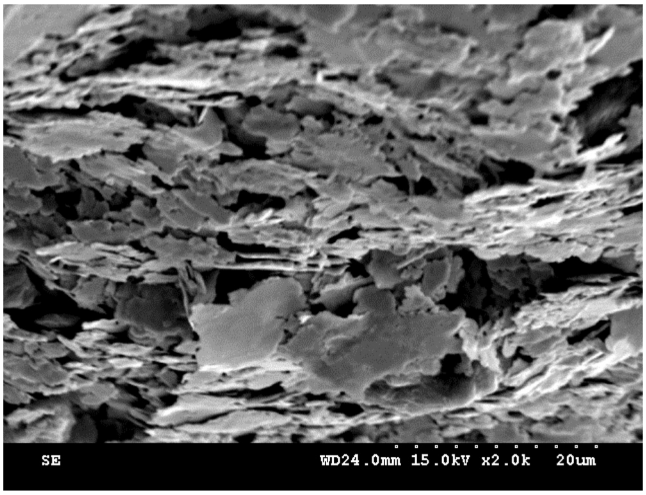


Fig. 1. Soil microstructure by SEM analysis (×2000).

Table 2
Chemical composition of soil sample (%wt).

SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	CaO	Na_2O	TiO_2	LOI
73.97	8.52	3.22	2.00	0.73	4.18	1.01	0.77	6.03

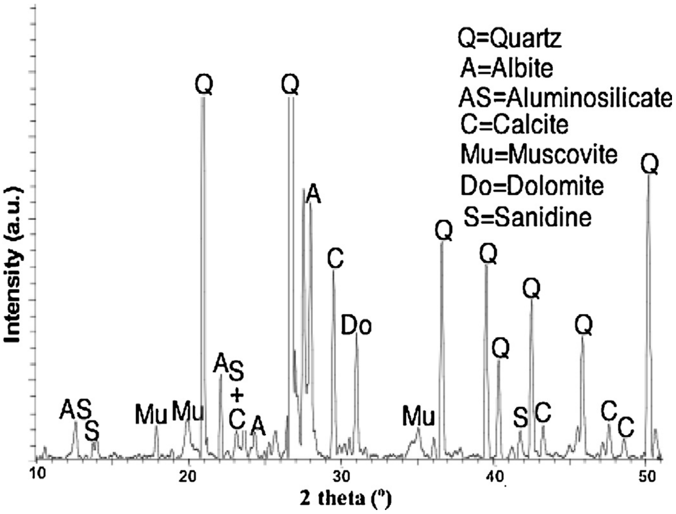


Fig. 2. XRD patterns of soil sample.

Fig. 3. Extrusion of unfired clay bricks.

Heat capacity is evaluated by calculating the integral of the difference of flows from the initial state (θ_{initial}) to the final state (θ_{final}). The specific heat capacity is then derived as follows:

$$c = \frac{C}{\rho e}[\mathrm{J/kgK}] \tag{2}$$

where ρ is the brick density [$\mathrm{kg/m^3}$] and e its thickness [m].

Based on the thermal conductivity (λ) and the specific heat capacity (c), the thermal diffusivity (D) and thermal effusivity (E) were determined, which are both essential features for non-steady thermal conditions. These two parameters are important characteristics for the building comfort. They are calculated according to the following formulas:

$$D = \frac{\lambda}{\rho c}[\mathrm{m}^2/s] \tag{3}$$

$$E = \sqrt{\lambda \rho c}\left[\mathrm{JK}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1/2}\right] \tag{4}$$

The dynamic thermal behaviour of the tested bricks were determined based on the NF EN ISO 13786 (2008) standard. It are described by these parameters:

- The thermal capacity of the inner surface: it describes the capacity of a wall to absorb, store and restore calories. Essentially, it characterizes the internal thermal inertia.

- The decrement factor: this is the ratio between the temperature amplitude at position x to the amplitude of the excitation temperature.

- The thermal lag: this is the time between the maximum excitation and the maximum response to the excitation at a given position x.

The decrement factor and the thermal lag primarily characterise the thermal transmission inertia of the total thickness of the wall, which absorbs and phase shifts of temperature variations between the inside and outside. The thermophysical characteristics of studied brick were determined at a constant temperature ($T = 23\,^{\circ}\mathrm{C}$) and at a relative humidity (RH = 60%). It were presented in Table 3.

The results showed that the thermal conductivity of this brick is around 0.9 W/mK. This building material is not intended for thermal insulation.

Concerning the dynamic thermal characteristics, the calculated values showed that the thickness of the material has a significant effect on decrement factor and on thermal lag. Thus, the brick with a 104 mm thickness has a decrement factor equal to 0.94 and a thermal lag of only 2.51 h. This means that indoor temperature fluctuations will be great, as temperature peaks will be rapidly transmitted to the interior of the building.

In general, a day/night thermal lag is sought, corresponding to thermal lag values of 10–12 h. To reach this objective, a study of the dynamic thermal characteristics of unfired clay bricks as a function of the wall thickness was conducted. It is found that the optimum thickness of earthen wall is equal to 400 mm. It enables to achieve the optimum values of thermal inertia. It ensures the greatest heat capacity (66 kJ/m^2 K) and a thermal lag of 10 h, taking into account the quantity of bricks necessary for the wall construction and the habitable area.

4. Thermal performance of the experimental building

To complete the tests already carried out in laboratory scale and to study the impact of environment on the unfired clay bricks, a building was mainly built with these bricks. The surface of the building was limited to 20 m^2 in order to simplify formalities (no need to request a building permit).

The objective of the construction of this demonstrative building is to assess the suitability of such bricks. Their use could demonstrate the sustainability and the qualities of the earthen construction in real conditions.

The design building was optimized according to the urban planning code. Indeed, the building was oriented to the south, with glazed window openings in order to trap and to store heat within the building elements and then effectively contributed to the comfort and energy saving. The construction process depends on weather conditions. Though, the protection of the implantation site and fresh walls from rainfall is essential. During the construction phase, the building was protected against bad weather.

To safeguard their technical performance, extended eaves and raised footings were provided in the building design to protect walls from water. After the foundations were laid, the first two rows of walls were built using brickworks intended to protect the raw earth walls from capillary rise.

Table 3
Thermophysical properties of unfired clay bricks.

Properties	Values	Dynamic thermal characteristics	Values
Dimensions L x l x h (mm)	222 × 104 × 60	Inner surface heat capacity (kJ/m^2 K)	32.84
Density (kg/m^3)	1788		
Thermal conductivity (W/m K)	0.9	Decrement factor	0.94
Specific heat capacity (J/kg K)	545	Thermal lag (h)	2.51
Thermal diffusivity (10^{-7} m^2/s)	9.23		
Thermal effusivity ($\mathrm{J\,K}^{-1}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1/2}$)	936.49		

Foundations Thick walls made of unfired clay bricks

Quoins Nubian vault built without formwork

External protection Demonstrative building

Fig. 4. Photographs illustrating the construction phases.

Given the sensitivity of raw earth to water and precipitation, the external surfaces of walls were protected; some of them were rendered with lime and covered with natural clay plaster. An external skin of wood has been used to protect other walls. However, internal surfaces have been left uncovered. Fig. 4 illustrates several construction phases and a general view of the building.

The thickness of earthen walls varied from 460 mm to 600 mm. The mortar used was a mixing of earth material with a flax shives, used to strengthen the adherence of the mixture. The choice of the wall thickness of 460 mm was actually based on the results of the study of dynamic thermal characteristics of unfired clay bricks. It had demonstrated that a thickness of

400 mm has very good thermal performance. The additional six centimetres were due to the layout of the bricks within the wall and the thickness of the mortar joints. The 600 mm thick wall was selected to serve as a support structure for the construction of a Nubian vault.

To focus the study on the vertical earthen brick walls, the floor and ceiling were heavily insulated. The walls were outfitted with temperature sensors in order to characterise the thermal behaviour of unfired clay bricks under real conditions and to study the indoor thermal comfort. The Fig. 5 shows main photo of the implementation of the sensors.

In order to monitor the thermal behaviour of the envelope, the measurement tests were carried out on two different facades, i.e., the northeast façade, 460 mm thick, and the southeast facade, 600 mm thick. The sensors were installed both in the bulk of the wall and on surfaces. Two flow meters were place on each side of the wall.

The building was monitored for a full year. Data acquisition was performed by reading and recording the tensions provided by each of the sensors, every 5 min. Measurements were taken from 26 July 2012 to 12 July 2013. Fig. 6 shows several elements based on the measurements taken on the two walls.

The results show that the external temperatures of 460 mm walls had more significant values than the 600 mm wall. This was due to the fact that the sensors in the 460 mm wall were directly exposed to the weather, while the sensors in the 600 mm wall were placed under wooden cladding. The external temperatures had fairly large fluctuations.

An analysis of the variation of indoor temperatures showed that during the hottest periods of the monitored year, i.e., from 11 to 21 August 2012, and from 2 to 12 July 2013, that the earth material reduces the fluctuations of the outside temperature, as shown in detail in Fig. 7 for the 460 mm thick wall. Indeed, the measurement results demonstrate that the indoor temperature remained quite stable over the two periods. Its range of variation did not exceed 3 °C, even though the outdoor temperature could vary by as much as 16 °C in the course of one day. The decrement factor, representing the ratio between the range of variation of the indoor temperature and the range of variation of the outdoor temperature was about 0.2. This result highlights the thermal inertia of unfired clay bricks, which is sufficient so that building occupants do not to feel the fluctuations of the external heat flow.

Furthermore, the thermal lag is defined as the time separating the peaks of the outdoor and indoor temperature in the course of one day, which, in this case, it is about 10 h. It corresponds to the desired thermal lag (daytime/night time) to reduce building's overheating.

During the hottest periods of the monitored year, the outdoor temperature may reach levels above 35 °C. However, the indoor temperature did not exceed 26 °C for both the 460 mm and the 600 mm walls, except for several points in the period 26 July–21 September 2012 for the 460 mm wall, as shown in Figs. 8 and 9. The points represent measurements taken every 5 min.

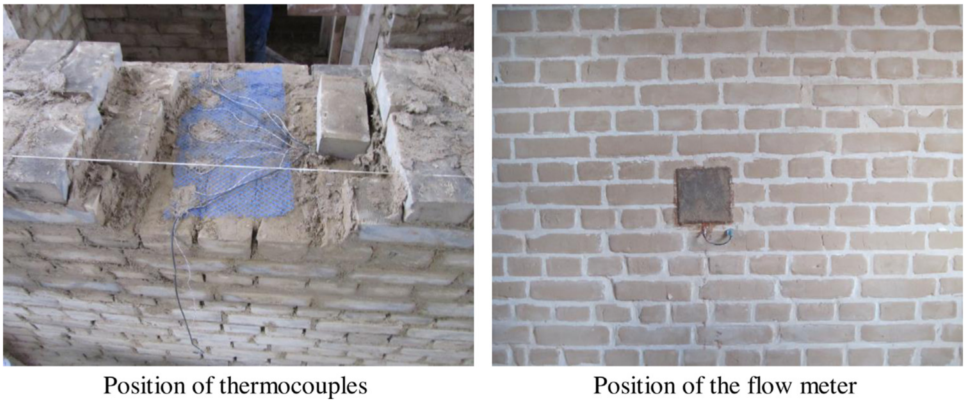
A change in the thermal behaviour of the earthen material was also observed when comparing the behaviour of the wall at the beginning and at the end of the measurement period. The drying masonry and the thermal inertia of unfired clay bricks caused a decrease in the indoor temperature by an approximately 3 °C, which created an increased feeling of comfort.

During the cold period, the indoor wall temperature could reach −5 °C, which shows that unfired clay bricks is not a good insulating material.

This experimental building has highlighted the qualities of earthen construction and their contribution to create summer comfort by providing an almost stable indoor temperature with shifted phases of daytime peak temperatures.

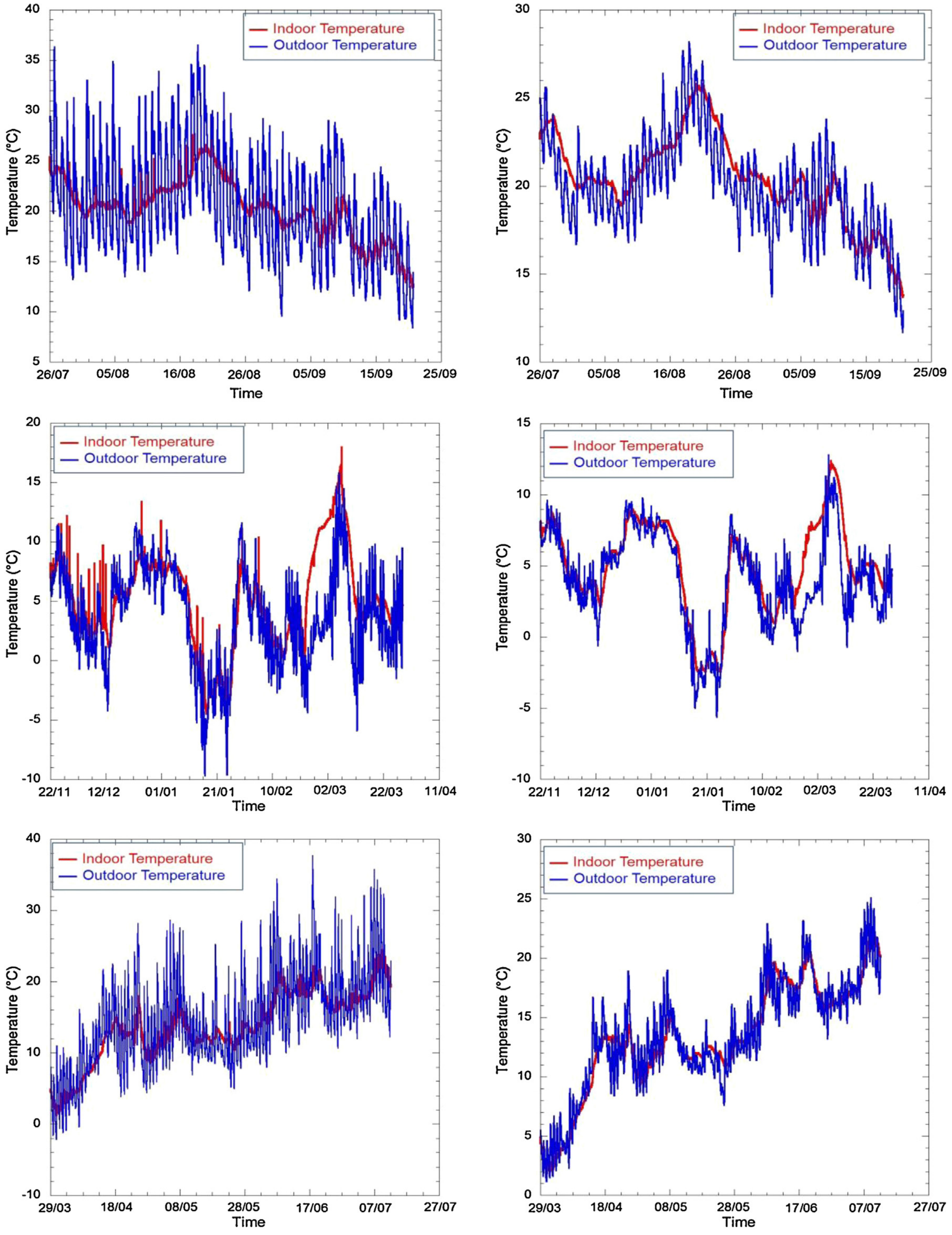
5. Conclusion

The dynamic thermal characterization of unfired clay bricks showed that the optimum thickness of earthen wall is equal to 400 mm. It enables to achieve the optimum values of thermal inertia, with a significant impact on the damping factor and


Position of thermocouples

Position of the flow meter

Fig. 5. Measuring instruments installed on walls.



(a) 460 mm wall

(b) 600 mm wall

Fig. 6. Variation of outdoor and indoor temperatures for the two walls during the periods: 26/07/2012–25/09/2012, 22/11/2012–11/04/2013 and 29/03/2013–27/07/2013.

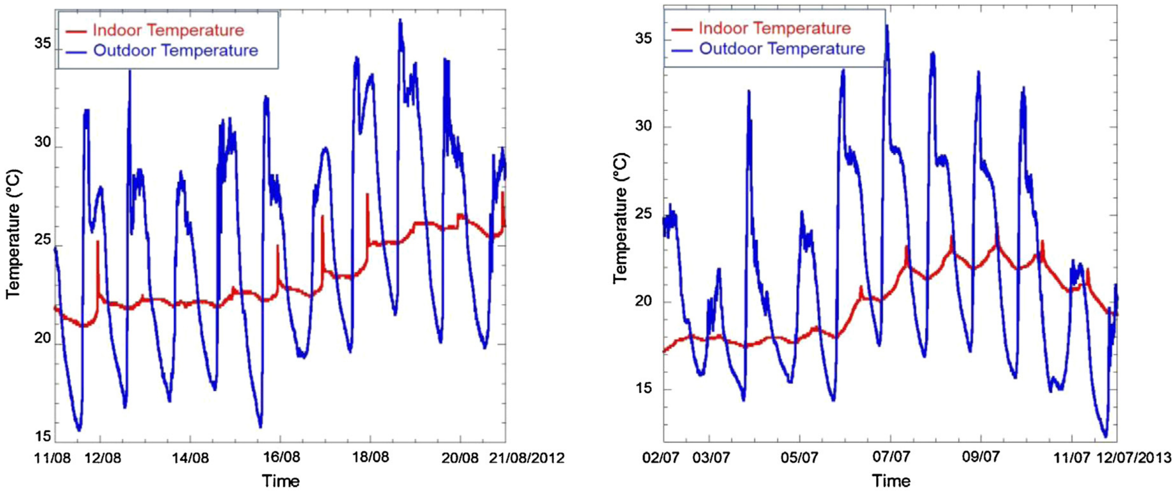
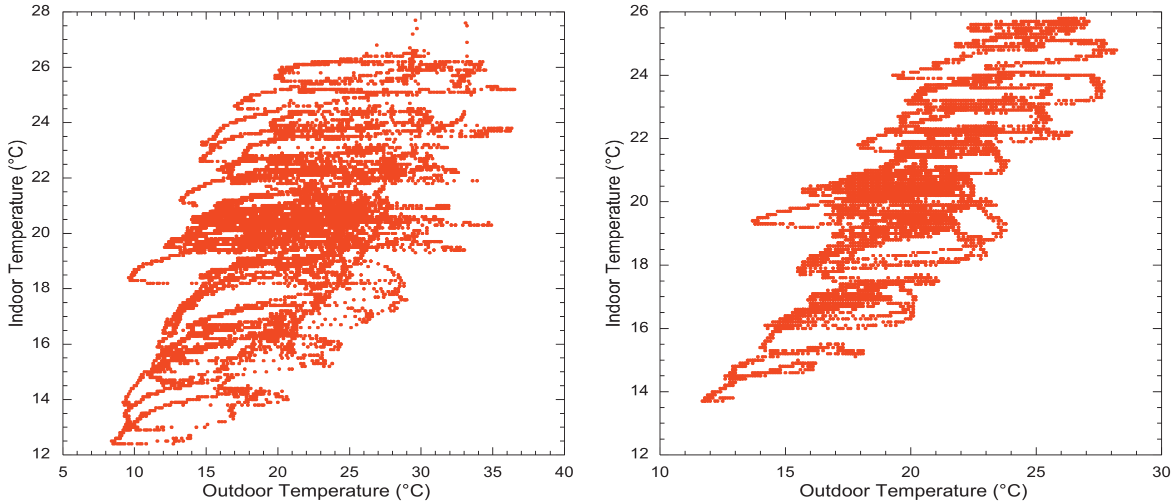


Fig. 7. Variation of outdoor and indoor temperatures for the 460 mm wall during the hottest periods of the following year.



(a) 460 mm wall

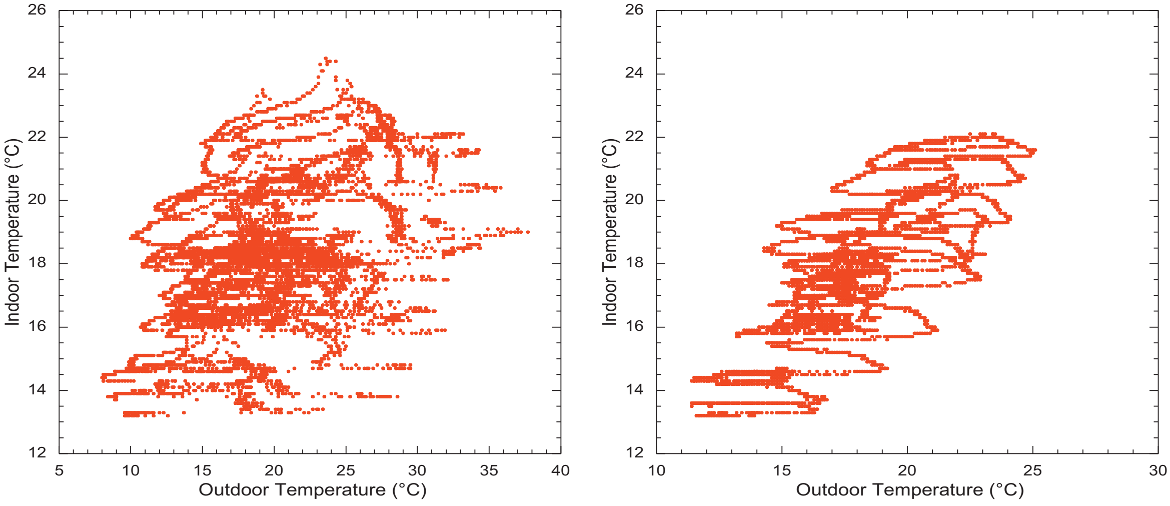
(b) 600 mm wall

Fig. 8. Variation of the indoor temperature as a function of the outdoor temperature in the period 26 July–21 September 2012.

on the thermal lag. It ensures a reduction of the fluctuations of the outdoor temperature and a limitation of the risk of overheating the building.

The demonstrative building enabled the study of unfired clay bricks under real life conditions and over time. The campaign of measurement tests performed on the two walls of this experimental building has confirmed the role of earthen materials in mitigating the fluctuations of outdoor temperatures. This experimental construction has received several visits intended to promote the earthen construction in northern France and initiate an integrative approach of active involvement of regional stakeholders. The laboratory scale and on-site tests have demonstrated the thermal performance of unfired clay bricks and their contribution in creating thermal comfort in buildings. Earthen construction has a promising future and is fully compatible with sustainable development aspirations.

A correlation between the two test results at laboratory scale and in situ will be more developed, gradually with the results obtained of the building thermal performance.



(a) 460 mm wall

(b) 600 mm wall

Fig. 9. Variation of the indoor temperature as a function of the outdoor temperature in the period 1 June–12 July 2013.

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