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Energy evaluation of rammed earth wall with long term in situ measurments

Lucile Soudani[#*1], Antonin Fabbri[#2], Monika Woloszyn[*3], Anne-Cécile Grillet[*4], Jean-Claude Morel[$5]

[#]LGCB-LTDS, UMR 5513, CNRS, Université de Lyon, Ecole Nationale des Travaux Publics de l'Etat (ENTPE)
Rue Maurice Audin, 69518 Vaulx-en-Velin cedex, FRANCE

[1]lucile.soudani@entpe.fr

[2]antonin.fabbri@entpe.fr

[*]LOCIE, Polytech Annecy-Chambéry, Université Savoie Mont-Blanc
Campus scientifique Savoie Technolac, 73376 Le Bourget-Du-Lac cedex, FRANCE

[3]monika.woloszyn@univ-smb.fr

[4]anne-cecile.grillet@univ-savoie.fr

[$]School of Energy, Construction and Environment, Faculty of Engineering, Environment &Computing, Coventry University
Coventry, UK

[5]jean-claude.morel@coventry.ac.uk

Abstract

Available throughout the world and used in construction for thousand years, earthen materials are known to improve indoor air quality while keeping the internal temperature relatively stable. In Rhône-Alpes, France, the rammed earth technic is the most spread and consists in compacting layers of earth, one by one, within a framework. Current thermal standards, which are mainly based on static performance of the material (and in particular, on its thermal resistance), urge to insulate walls. However, due to its interaction with its environment, and the couplings between heat and moisture transfers, the observed thermal behavior of uninsulated rammed earth is commonly significantly above the expectations. The objective of the paper is to highlight the energy performance of non-insulated rammed earth walls, for different orientations, from in-situ measurements over more than two years. Winter, without or with low energy consumption for heating, and summer, with no cooling device, are studied. The study points out the important role of solar irradiance on the thermal balance of the house, and thus the importance of a good architecture.

Keywords : rammed earth ; in-situ measurments ; energy performance ; solar irradiance

1. Introduction

Rammed earth, and more generally earthen materials, are often promoted as a sustainable building material, based on their low embodied energy [1]. However, they also have a low thermal resistance (R-value), which makes them likely to provide poor thermal performance, as underlined in [2][3]. On the other hand, other works (e.g. [4]) support that the high thermal mass of the material avoid low temperatures in winter and hot temperature in summer. Indeed, when exposed to a heat source (internally with heater or solar radiation), the wall absorbs and stores the heat to release it when the surrounding temperature drops. This effect may be enhanced by the so-called hygrothermal couplings between heat and mass transfers which occur within the earthen walls [7]. The following study will use experimental data from a monitored house composed by non-insulated rammed-earth walls to investigate its energy performance over the seasons.

2. Monitored house

a. Main characteritics

The house studied in this paper is located in Saint-Antoine-l'Abbaye, in Isère, South-Eastern France. It has a living area of 150m², over two floors and lost attics. The house was built in the summer 2011 and its envelope is composed of four non insulated walls in rammed earth (exposed to the South, East and West) of 50cm thick and 3m high and a timber-frame wall filled with straw (mainly North orientation and upper parts of the construction), as it can be seen in **Erreur ! Source du renvoi introuvable.**. The earth used for the wall construction was taken in Roybon, about 10km away from the site. The slab is made out of a mix of cement, lime, straw, sawdust and cellulose wadding, and covered with baked earth tiles.

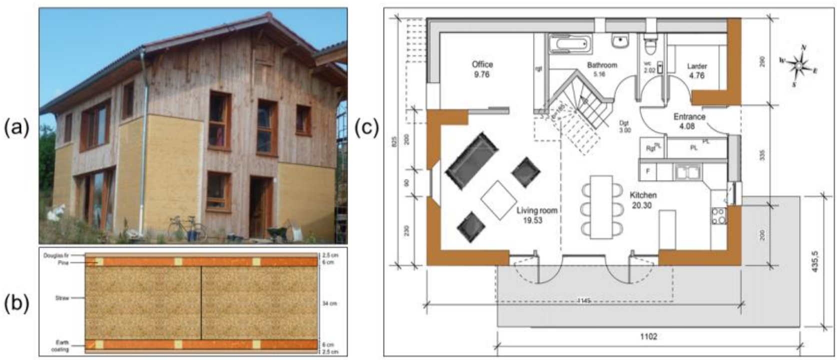

Figure 1 : (a) House in Saint-Antoine-l'Abbaye, 2014; (b) Home plan of the first floor with the four rammed earth walls; (c) Composition of non-rammed earth alls and thicknesses

Openings count windows and doors are described: double glazing Argon for South, East and West facades (U=1.70 W.m^{-2}.K^{-1}), triple glazing Argon for North façade (U=1.09 W.m^{-2}.K^{-1}), double glazing for wooden French window (U=2.95 W.m^{-2}.K^{-1}), wood door (U=5.00 W.m^{-2}.K^{-1})[5].

The house is occupied by five persons (two adults and their three children from 10 to 18 years old). The heating system is a wooden stove operated by the occupants and located in the living room. Yearly energy consumption is evaluated at two cubic meters of wood with the stove turned on two hours a day, which corresponds approximately to 3000kWh according to [6], i.e. 20 $kWh.m^{-2}.year^{-1}$. Given the size of the house, such consumption is very low.

During the summer, no cooling system is installed, only natural ventilation is used. Regarding the close environment, a mound of earth is located near the western rammed earth wall.

b. Instrumentation

The house has been monitored from construction until now. 12 sensors were placed inside the South/West wall during the construction, at 6 different positions (in the middle and at 10cm from both surfaces). At each spot, two sensors were placed: a temperature/relative humidity sensor (CS215, Campbell Scientific, Inc., Logan, UT) and a TDR sensor (CS616, Campbell Scientific, Inc., Logan, UT) to evaluate the water content. The sensors were placed at about 2m from the ground. The measure reading is set to every 15min and the mean value over an hour is saved.

7 sensors (EL-USB-2, Lascar electronics, Salisbury, UK) were placed inside the house at different locations: in the living room (near the south-west rammed earth wall), in the kitchen (near the south-east rammed earth house), the WC of the ground floor, and one in each four bedrooms upstairs. A value is saved every hour.

The installed weather station placed near the house was very simple, recording only outdoor temperature and relative humidity. The complementary weather data (solar irradiance) was taken from the most complete station in the region located in Vaulx-en-Velin, France [7]. It provides, every minutes and since 1992, a large amount of measurements related to the temperature, relative humidity, sun (light and energy) and wind. The distance of the station to the house location (about 110 km) should be noticed. Therefore, the Vaulx-en-Velin weather station measurements were compared with those from a non-professional station located in Saint-Marcellin (8 km from the house) and didn't show much difference on the studied periods.

The present study covers the two-year period from March 2013 to June 2015 when the house was occupied.

3. Energy performance

The energy performance is often associated to thermal insulation. Indeed, thermal insulation prevents heat to flow between indoor and outdoor climates so that less heating energy is used in order to maintain constant indoor temperature even for high outdoor temperature variations over days and seasons.

In winter, or more generally when the weather is cold, it is important not only to keep indoor heat but also to capture the maximum amount of outdoor heat during the day so that it can be used during the night when temperature drops. During the summer, on the other hand, the aim is to prevent outdoor heat from entering as well as to expulse indoor heat to refresh the house during the night. In order to keep the indoor temperature at a correct level, these situations often require the use of external equipment such as heater or cooler. In order to minimize energy consumption, these two aspects have to be considered when designing or insulating buildings.

a. General observations

<u>Estimation of the heat fluxes using measured data:</u>

Energy performance can be quite difficult to quantify as it depends not only on building's intrinsic parameters but also on the occupants and their habits. However, a first sight is given with the study of need for heating, calculated from the outgoing flux. As a convention in this paper, a positive flux is considered as a gain whereas a negative flux is considered as a loss.

The heat flux through the wall can be calculated using the well-known Fourier's law:

$$\phi = -\lambda \, grad(T) \tag{1}$$

In steady conditions, the heat flow is constant throughout the wall. In unsteady, i.e. real conditions, it varies because of the heat storage within the materials. Consequently, at a given time heat flow value can be different in the middle of the wall as well as at the external and internal surfaces. In the present work, we are interested in the value of heat flux exchanged between indoor air and the wall as it impacts directly heating needs. This heat flux is estimated using temperatures measured in the air (one of the USB sensor placed near the wall) and in the wall at 10 cm from the indoor surface:

$$\phi_{gain} = \left(\frac{e}{\lambda} + \frac{1}{h_i}\right)^{-1} \cdot (T_{ins} - T_{Xint\_wall}) \tag{2}$$

with

T_{ins} [°C]: temperature inside the house

T_{Xint_wall} [°C]: temperature inside the wall, (here at 10 cm from the internal surface). X = S for the southern wall and W for the western wall

e [m]: thickness of the layer between the sensor and the surface, i.e. 10 cm

λ [W.m^{-1}.K^{-1}]: thermal conductivity of the layer between the sensor and the surface, (here taken equal to 1 W.m^{-1}.K^{-1} according to [8])

h_i [W.m^{-2}.K^{-1}]: surface heat transfer coefficient for indoor surface, taken equal to 8 W.m^{-2}.K^{-1} according to [9].

Negative value of heat gain flux (when indoor air temperature is higher than wall temperature) means that the heat exchanged between the air and the wall is a loss for the room.

<u>Boundary conditions:</u>

The heat fluxes through the wall depend mainly on indoor and outdoor temperatures as well as on solar irradiance.

In **Figure 2** are reported interior and exterior temperatures for the entire period from April 2013 to June 2015. These temperatures are, for each month, the mean value of measurements collected every hour. Is also reported the direct horizontal irradiance of the sun. For each month, it corresponds to the mean value of data collected every minute.

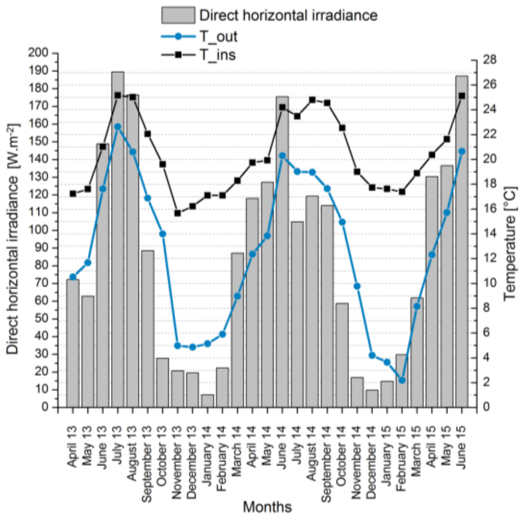

Figure 2 : Outside and inside temperatures and direct horizontal irradiance

As expected, it can be noticed that the maximal solar radiation reaches the house in summer and the minimal in winter. However, even for the same season, solar radiation can be different (e.g. July in 2013 and 2014) and this, even if the mean temperature is the same (e.g. October 2013 and May 2014). Solar radiation thus provides an additional information to temperatures. These observatiaons lead to consider, for the different season, period with "good weather" (understood as high direct horizontal irradiance) and "bad weather" (understood as low direct horizontal irradiance).

Information provided in Figure 2 gives an interesting overview, however it is not sufficient to study several specific phenomena such as daily variations. For example, as mean values are considered, the inside temperature of summer months is always higher than the outside temperature, the latter not going above 25°C, as well as the winter outside temperature not going below 2°C. To carry out a deeper analysis, the following parts focus on the winter and summer thermal balances, dealing more in details with data just introduced.

b. Thermal balance in winter

First of all, the study of the whole season provides the main tendency. In Figure 3, the thermal balances of both western and southern walls are illustrated, for two winters 13/14 and 14/15 (from December 21st to March 20th). The "heat gain", respectively "heat loss", corresponds to the mean hourly value of negative, respectively positive, integral in the season, multiplied by the number of hours in a year, so that the flux can be expressed in $kWh.m^{-2}.year^{-1}$. This enables to avoid differences due to the different number of days considered for each period. The "mean" value takes into account both negative and positive values of the integral.

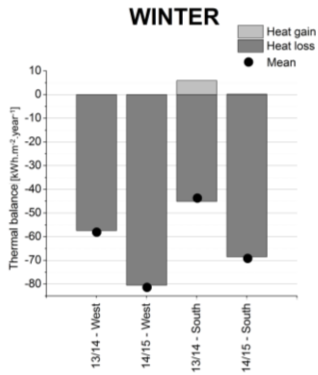

Figure 3 : Thermal balance of West and South walls in winters 2013/14 and 2014/15

The first observation is the majority of heat losses in both orientations and years. Indeed, the temperature is higher inside the house than outside, thus driving out the heat through the wall. This phenomenon is increased by the heater. But the losses are lower for the southern wall than for the western: the solar radiations heat the wall, which leads to lower the gap between outside and inside temperature, consequently lowering the heat flux. As the southern wall is exposed to the solar radiation earlier in the morning and longer in the daytime, this observation remains intuitive. A difference is also noticeable between the two winters: the losses are globally more important in 14/15 than in 13/14. This can be explained by the mean weather of each winter, the first being milder than the second. Indeed, looking at Figure 2, the mean monthly irradiance value of winter 13/14 (/per month) is equal to 38.9 W.m^{-2} whereas it is 35.5 W.m^{-2} for winter 14/15. What's more, although the internal mean temperature is quite similar (17.5°C for winter 13/14 and 17.9°C for winter 14/15), the outside temperature is lower for winter 14/15 (4.7°C) than for winter 13/14 (6.7°C).

At last, the presence of heat gains through the southern wall for both winters can be noticed, even if they are almost equal to zero in winter 14/15. The heat gains reach around 13% of the amount of heat losses over the winter 13/14 for the southern wall. It means, that despite lower outside temperature, heat can go from the wall to the inside of the house.

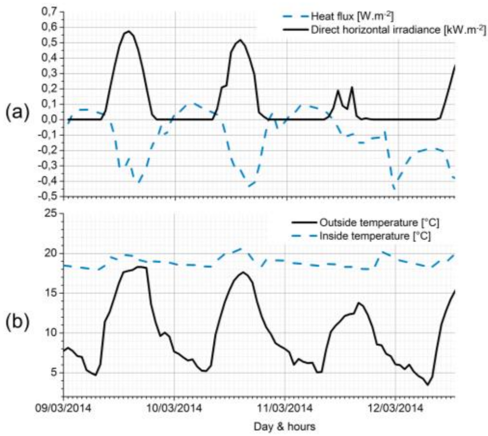

Figure 4 : (a) Heat flux in the southern wall against solar irradiance for March 2014; (b) Inside and outside temperature for March 2014

To carry out a deeper investigation, let us focus on three days, among others, when the reversed heat flux occurred, e.g. from March the 9th to March the 12th of 2014. In Figure 4a are represented the hourly total heat flux (positive being heat gain and negative being heat loss) in the southern wall, as well as the direct horizontal irradiance over the same period of time.

It can be noticed that the peak of the maximal flux (i.e. the maximal heat gain) always occurs around 4 a.m., whereas the maximum solar irradiance occur around noon. As soon as the sun goes down (i.e. when the solar irradiance is equal to 0 in this case), the heat flux becomes positive. More precisely, the heat gain seems to be proportional to the intensity of the solar irradiance of the daytime before (e.g. on the 9th and 10th, the irradiance is high, so is the heat gain, whereas on the 11th, the irradiance is low and there is no heat gain the night after). This means that the drop of temperature due to the sunset leads to a positive flux within the house: the heat is stored during the day and released during the night.

In Figure 4b, outside and inside temperatures over the same period are represented. It is easily remarkable how the outside temperature is related to the direct horizontal irradiance. On the other hand, the inside temperature remains stable, with the exception of slight increasing which might correspond to owners coming back home and starting the heater and is not related to the solar irradiance peak.

These analyses reveal the good energy performance of the house during the cold season. Indeed, it counts comfortable inside temperatures, low heating consumption, a good thermal mass allowing interesting phase shift of solar gains and an overall good insulation of the house despite the non-insulated rammed-earth walls.

c. Thermal balance in summer

The other aspect to be kept in mind regarding energy performance of building envelope is the summer comfort, understood here as indoor thermal comfort when outside temperatures are high.

First of all, an overview of heat fluxes in summer is shown in Figure 5b.

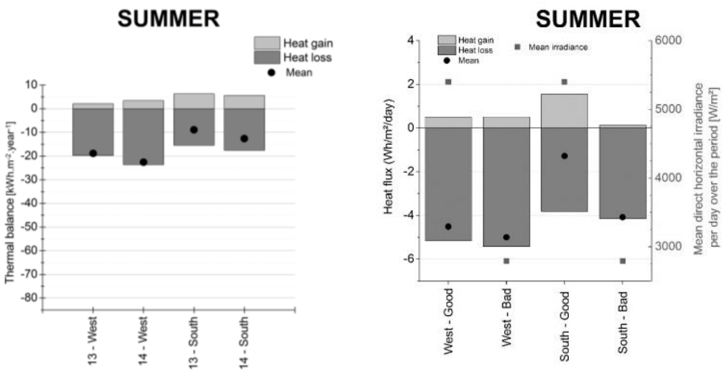

Figure 5 : (a) Thermal balance of West and South walls in summer 2013/14 and 2014/15 ; (b) Daily thermal balance for good (GW) and bad (BW) weathers of West and South walls in summer 2013

As the same scale is kept for both Figure 3 and Figure 5, it can easily be noticed that the heat losses are far lower in summer than in winter, and gains are higher. Losses are lower and gains higher, for the southern wall than the western wall, for the same reasons as previously detailed. A slight difference in both losses and gains between the two summers can be explained by a more sunny summer 2013. Indeed, looking back at Figure 2, the mean solar irradiance is 151.6 W/m² in 2013 against 112.7 W/m² in 2014.

The heat gains could have been expected to be higher as no other cooling system than natural ventilation was used. In order to study more in detail heat fluxes at daily scale, two periods were selected during summer 2013, one qualified as “good weather” (July 20th to 27th) and the other as “bad weather” (June 24th to 30th).

The Figure 5b focuses on the thermal balance of western and southern walls during these two periods. For both orientations, the losses are higher than the heat gains, consequently to higher indoor than outdoor temperatures. For the southern wall, the solar irradiance seems to have a noticeable effect on the heat gain as it is 12 times higher (0.13 $W.m^{-2}.day^{-1}$ for the “bad weather” against 1.56 $W.m^{-2}.day^{-1}$ for the “good weather” whereas the mean direct solar irradiances were respectively equal to 2,8 and 5,4 $kW.m^{-2}.day^{-1}$). On the other hand, the western wall seems to be less impacted by the decrease of solar irradiance. Indeed, the heat gains are almost the same for both bad and good weathers. This can be due to the presence of a mount of earth near the western part of the house, as thus preventing it from receiving a part of the sun irradiance. This raises the importance of the rammed earth walls location to ensure its optimal behavior.

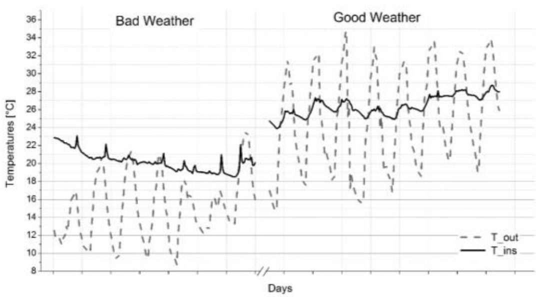

Figure 6 : Inside and outside temperatures for the two weeks referenced as "bad" and "good" weather during summer 2013

The Figure 6 provides the inside and outside temperatures for the two periods mentioned above. First of all, for both periods, the inside remains at a comfortable level, regarding the outside temperature. Indeed, whereas the outside temperature reaches 35°C, the inside temperature doesn’t increase above 28°C. During the “bad weather” week, the inside temperature decreases slightly from 23°C to 19°C in seven days whereas the outside temperatures fall beyond 10°C. This highlights the very good thermal mass of rammed earth and the rather good insulation of the house.

The results clearly show excellent stability of indoor temperatures: daily variations are lower than 2°C. Such stable indoor climate in an occupied dwelling is clearly an advantage of the house and demonstrates its high thermal mass.

4. Conclusion

This study focuses on the energy evaluation of the house through the seasons and compares wall orientations. The house provides a good comfort in summer, judging with regards to the temperatures, and offers a good energy performance in winter as the temperature remains comfortable with a very low heating load, a good thermal mass of the studied walls and an apparent good insulation. The impact of the orientation is also discussed, thus highlighting the importance of architecture for rammed earth houses.

However, the thermal parameters of usual building materials are rather constant, thus making its behavior easier to predict. In the case of rammed earth, the thermal parameters are function of the amount of water located in the porous media. A study of the influence of the water content on the thermal behavior of the rammed earth walls is to be conducted so that the hygrothermal couplings can be an additional tools to predict the thermal behavior, and more generally the energy performance, of the house.

Acknowledgment

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