ANALYSIS OF THE EARTH CONSTRUCTION'S THERMAL BEHAVIOR – IN SITU MEASUREMENT AND EVALUATION OF THERMAL PERFORMANCE OF THREE RAMMED EARTH CASE STUDIES

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1. **Architectural heritage and earth building techniques. Tradition, innovation and new conservation methods.**

Earth architecture, thermal behavior, in situ measurement.

ABSTRACT

The emergence of the new paradigm of sustainable construction related to the concern of excessive energy consumption of our society, led to the investigation of techniques, materials and construction solutions that could causes less environmental impact. Consequently, the interest given to ancient techniques that dealt with earth constructive solutions aroused, which has captivated the interest of architects, builders and people in general. Although this type of material is associated to a less dignified and poor construction, the search for modern expression in new buildings' design has shown the physical and plastic potential of the usage of earth in modern architecture.

However, the regulation of the constructions' minimum requirements related to materials' mechanical strength and thermal performance (such as the Portuguese Thermal Building Regulation- RCCTE), has been one of the biggest obstacles in spreading and growing the application of this technique. This study intends to increase the knowledge of the thermal behavior of this type of construction.

In this article, the results of in situ measurement campaigns, carried out during the summer and winter periods, are presented. They were performed on three different single-family dwellings located in Abrantes, Portugal. These dwellings were built using the rammed-earth technique, each one having walls with 50-55 cms of thickness. Several experimental measurements were conducted in order to evaluate the rammed-earth wall thermal behavior, such as: the incident global radiation on vertical plane of the facade; indoor and outdoor environment temperatures and moisture; indoor and outdoor surfaces wall temperatures; and heat flows. The experimental results revealed a large thermal inertia of the walls, which led to low indoor temperatures in both seasons. The results demonstrate the need to improve the thermal conductivity of the earth in order to meet the minimum requirements imposed by the Building Regulations.

1. Introduction

The earth construction is known for their large walls and their pleasant inside temperatures during very warm summers which explain the use of this material in hot climates. In Portugal there is a vast heritage, particularly in Alentejo and in the interior of Portugal, where the maximum temperatures in summer can, generally, rise above 40ºC. As a benefit of the large thickness, the earth's walls have a high thermal inertia which is responsible for

the delay of the heat conduction throughout the walls, contributing for mild inside temperatures.
Also, their large mass can accumulate the heat inside the walls and, consequently, it can reduce the use of heating energy once they can function as a heat source. However, the thermal resistance value of earth walls is usually very low and this represents a problem when facing the Building Regulations.
Although the large experience in living in earth's constructions since the remote ages, the concepts of sustainable construction and thermal comfort is relatively new and there is few scientific documentation of earth's construction thermal behavior and about how to improve this solutions so it can be used as a modern material.
This paper presents the results of two in situ measurement campaigns during two different periods, summer and winter, carried out in three dwellings located in the region of Abrantes, Portugal. There were monitoring the vertical global radiation, the indoor and outdoor environment temperatures and moisture; indoor and outdoor surfaces wall temperatures; and heat flows. The performance of the earth walls is examined by analyzing the evolution of the indoor and outdoor heat flow through the walls and the indoor and outdoor temperatures with the influence of the incident solar radiation.

2. Case Studies and Experimental set-up

All the three case studies are located in the region of Abrantes, N39°27′52″; W8°11′52″, Portugal. which characteristically has dry and very warm summers and mild and wet winters.
The outdoor temperatures during both the winter and summer campaigns for the three case studies were summarized in Table 1:

Table 1. Maximum, minimum and average outdoor temperatures during both campaigns in the three case studies: CS1 – case study 1; CS2 – case study 2; CS3 – case study 3. Courtesy of "Hélder Silvano Neves – MeteoAbrantes" for outdoor measurements.

		Winter	Summer
CS 1	Max	23,37	32,30
	Min	0,37	8,72
	Mean	**10,00**	**16,76**
CS 2	Max	19,23	41,66
	Min	-0,65	12,52
	Mean	**9,96**	**23,08**
CS 3	Max	18,61	-
	Min	1,81	-
	Mean	**11,27**	-

The three dwellings are uninhabited and have doors and windows closed.
During the campaign 2 thermocouples Type T were used to measure surface wall temperatures (Tse and Tsi); PTC sensor for environment temperatures (Te and Ti); and 2 heat flow meters installed on the indoor and outdoor wall surfaces, to measure de heat flow. It was also installed one thermo-hygrometer to measure the indoor relative humidity and temperature, for the outdoor, it was used data from the weather station of Abrantes (courtesy by Hélder Silvano Neves – MeteoAbrantes). Finally, a pyrometer was installed on the façade to measure the vertical global radiation.
A data logger NCE 2520-00 Network Control Engine by Metasys®, with remote transmission, was programmed to take measurements with intervals of 1 in 1 minute and record the average of these values each 10 minutes.

2.1. Case Study 1 (CS1)

The case study 1 is located in Casais de Revelhos, Abrantes, Portugal. The main facade was the monitored one and is facing south. There are no shade elements so the probes are exposed directly to the solar radiation.
Due to the poor conservation along the 100 years of existence, some house components, such as the ceiling and doors are really damage, so the airtightness is not completely assured.
Figures 1 and 2 show a photograph of the dwelling's façade and a sketch of the probes location, respectively.

Fig.1. Monitored façade (South façade).

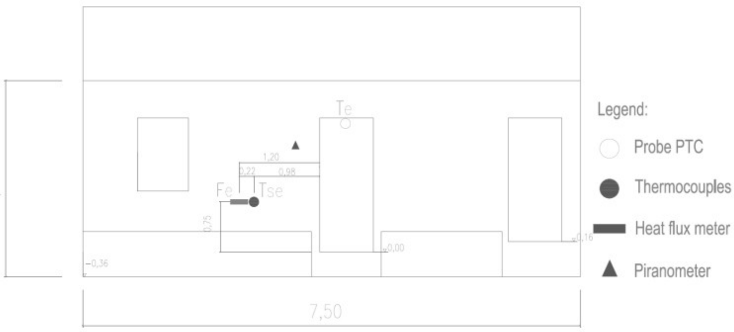


Fig.2. South façade's sketch with probes' location.

2.2. Case Study 2 (CS2)

The case study 2 is located in Pego, Abrantes, Portugal. The main facade is facing north; the monitored façade was the one facing west. Nevertheless, the PTC sensor for the outdoor temperature measurement was installed near the window of the north façade so the solar radiation does not influence the values.
It is not recommended to install the equipment near a thermal bridge, however in this case it wasn't possible to avoid the location of some probes near the corner between the north and the west walls because of the length of the probes' cables.
Figures 3 and 4 show a photograph of the dwelling's north and west façades and figure 5 shows a sketch of the probes location.

Fig.3. North façade.

Fig.4. Monitored façade (West façade).

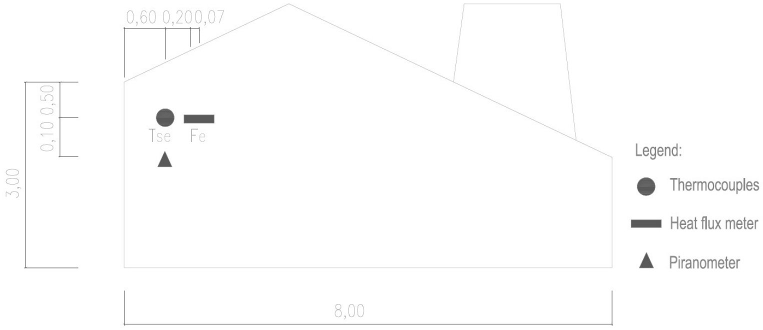


Fig.5. Sketch of the west façade with probes' location.

2.3. Case Study 3 (CS3)

This case study is also located in Pego, Abrantes, Portugal. The main facade was the monitored one and is facing south. There are also no shade elements. Unfortunately, due to some unforeseen contingencies, it was not possible to carried out the summer campaign in this case study.

Fig.6. Monitored façade (South façade).

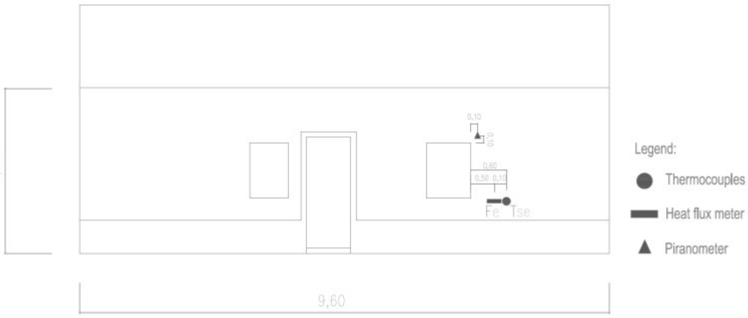


Fig.7. Sketch of the south façade with probes' location.

3. Monitoring Results

In order to have a general perception of the thermal behavior of the earth's construction, two campaigns were taking place in extreme Portuguese climate situations: one during the winter period and another during summer period. Table 2 presents the periods monitoring of each case study:

Table 2. Monitoring periods of each case study.

		CS1	CS2	CS3
Winter	Start	4th February, 12h20	12th February, 15h00	8th March, 14h10
	End	12th February, 10h30	8th March, 11h20	28th March, 12h00
	Duration	**7 days, 22 hours and 10 min.**	**23 days, 20 hours and 20 min.**	**19 days, 21 hours and 50 min.**
Summer	Start	25th May, 12h30	15th June, 14h40	*N.A
	End	15th June, 15h30	4th July, 13h00	*N.A
	Duration	**21 days and 3 hours**	**18 days, 22 hours and 20 min.**	*N.A

*N.A. – not applicable

The results were organized by campaign and it only will be presented the results of the extreme days, such as the coldest and the warmest day for winter and summer, respectively, for each dwelling.

3.1. Winter Campaign

During the winter campaign one façade of each dwelling was monitored (see Chapter 2). The data recorded and the results of the monitoring coldest day in winter campaign are presented in Figures 7-9.

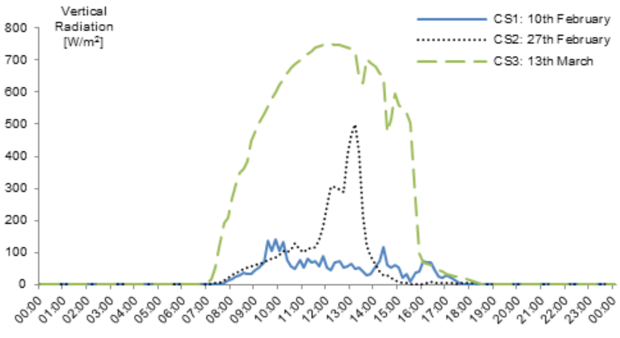
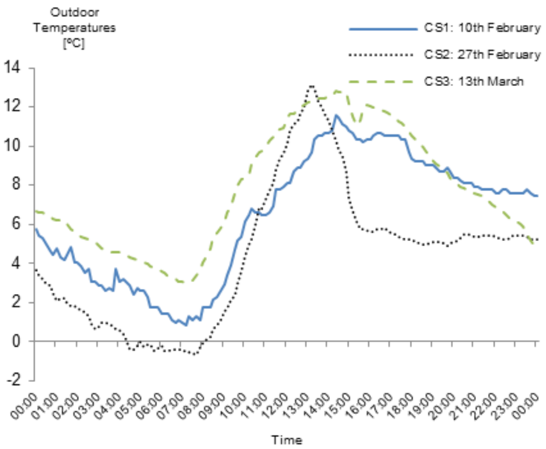


Fig.7. Incident global radiation on the vertical plane of the façades in the coldest winter monitoring day.

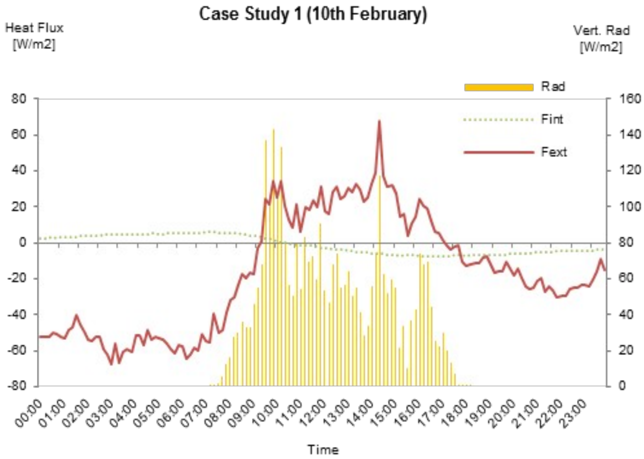


a. b.

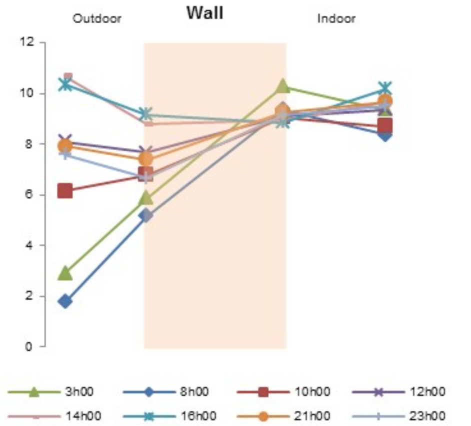
Fig.8. Indoor and outdoor temperatures in the coldest winter monitoring day.

The figures 7-9 show conformity between the outdoor temperatures (Fig.8.) and the solar radiation (Fig.7.) and the values obtain by the probes installed at the dwellings' façades (Fig.9.).
Figures 7 and 8 show that the dwellings were exposed to similar outdoor temperatures values (Fig.8. b.), even if the solar radiation shows very high values, such as in CS3 (Fig.7.). Fig.8.b. shows that the maximum outdoor temperature was between 12 ºC and 14 ºC and the minimum was between -1 ºC and 3 ºC. Also, the indoor temperatures are quite similar and compared to the outdoor temperatures have very small temperature variation (Fig.8.). The outdoor temperatures have almost a temperature variation of 14 ºC, whereas the indoor temperature has less than 2 ºC of delay variation.
Figure 7 shows that the maximum value of solar radiation in CS2 is registered during the afternoon because the monitored façade is west oriented. The other case studies, CS1 and CS3 are south oriented.
The select day of CS3 correspond to an overcast sky condition while the others CS1 and CS3 correspond to a clear sky condition.
On the other hand, Figure 9 presents the indoor and outdoor heat flow with the influence of the solar radiation and the horizontal profiles of temperatures in different hours of the day.

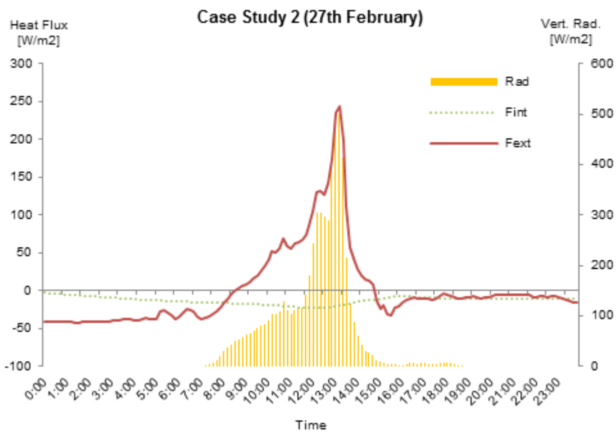
Heat flows are assumed as positive when they take the outdoor-indoor direction. In Figure 9 it is possible to observe that the outdoor heat flow is highly influenced by the incident solar radiation, whereas the indoor heat flow is generally closed to zero. Moreover, Figure 9. a., c., and e. show that the indoor heat flow has, during daytime, an opposite signal to the outdoor one. Therefore the heat flow, in most cases, does not have just one way, which means that the wall is accumulating heat during the daytime.



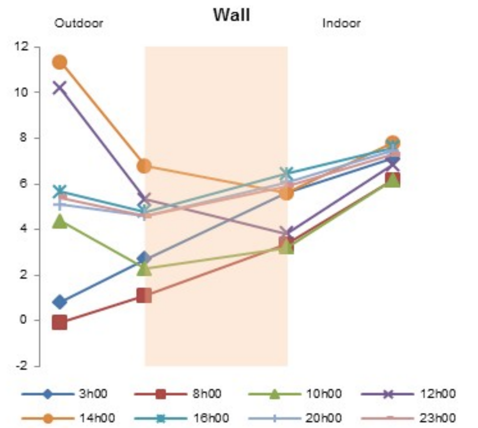
a.



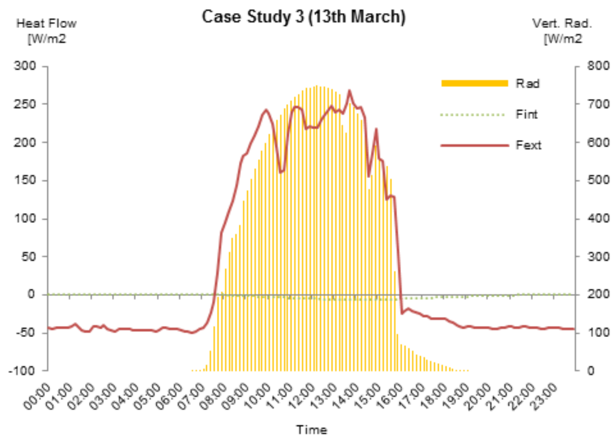
b.



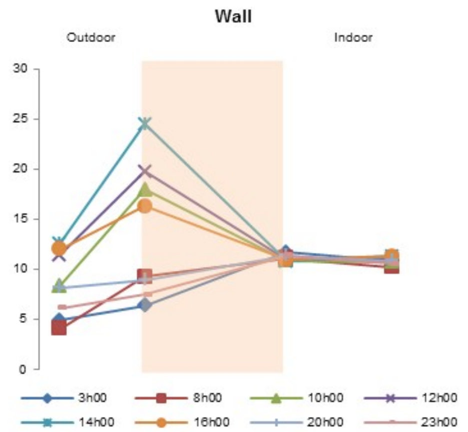
c.



d.



e.



f.

Fig.9. Incident global radiation on the vertical plane of the façade and heat flow through the wall (a., c., e.); horizontal profiles of temperature (b., d., f.) in the coldest winter monitoring day for each case study.

Concerning the temperatures distribution (Figure 9. b., d., and f.) it is noticed that both inside temperatures (indoor temperature and indoor surface temperature on the wall) are very stable while the opposite occurs to outdoor temperatures (outdoor temperature and outdoor surface temperature on the wall). Furthermore, notice that both surface temperatures set out the heat capacity of the earth construction, as the outdoor temperature has the highest temperature variation. This last fact excludes CS3 (Fig. 9. f.) where the outdoor surface temperature, is always higher than the outdoor temperature, which can be due to an overheating of the thermocouple as it is directly exposed to the solar radiation.

3.2. Summer Campaign

During the summer campaign it was monitored the façades of the two first dwellings, CS1 and CS2. The corresponding data recorded and the results of the monitoring warmest day are presented in Figures 10-12.

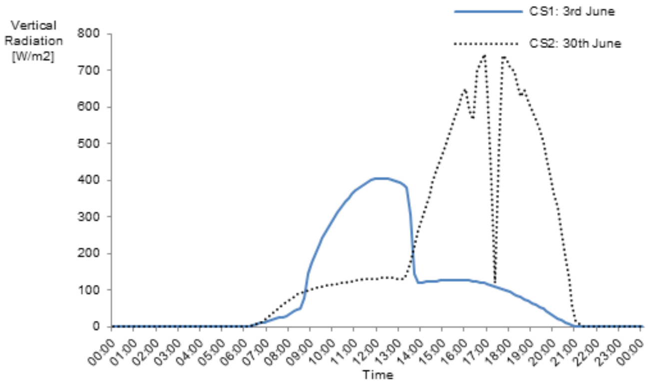
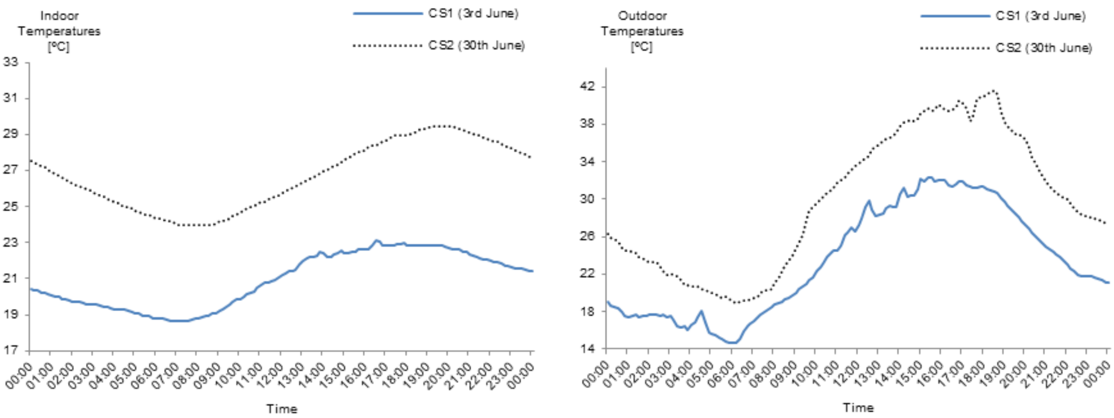


Fig.10. Incident radiation on the vertical plane of the façades in the warmest summer monitoring day.



a. b.

Fig.11. Indoor and outdoor temperatures in the warmest summer monitoring day.

In the summer campaign the recorded data shows conformity between the outdoor temperatures conditions and the solar radiation. By Figures 10 and 11 it is possible to observe that CS2 was exposed to very high temperatures during all day and a high solar radiation incidence. As referred before, the monitored façade in CS2 was the west side one, which explains the highest values during the afternoon. Figure 10 a. shows that the solar radiation in CS1 has a big crush in the middle of the daylight that could be explained by a cloudy afternoon.

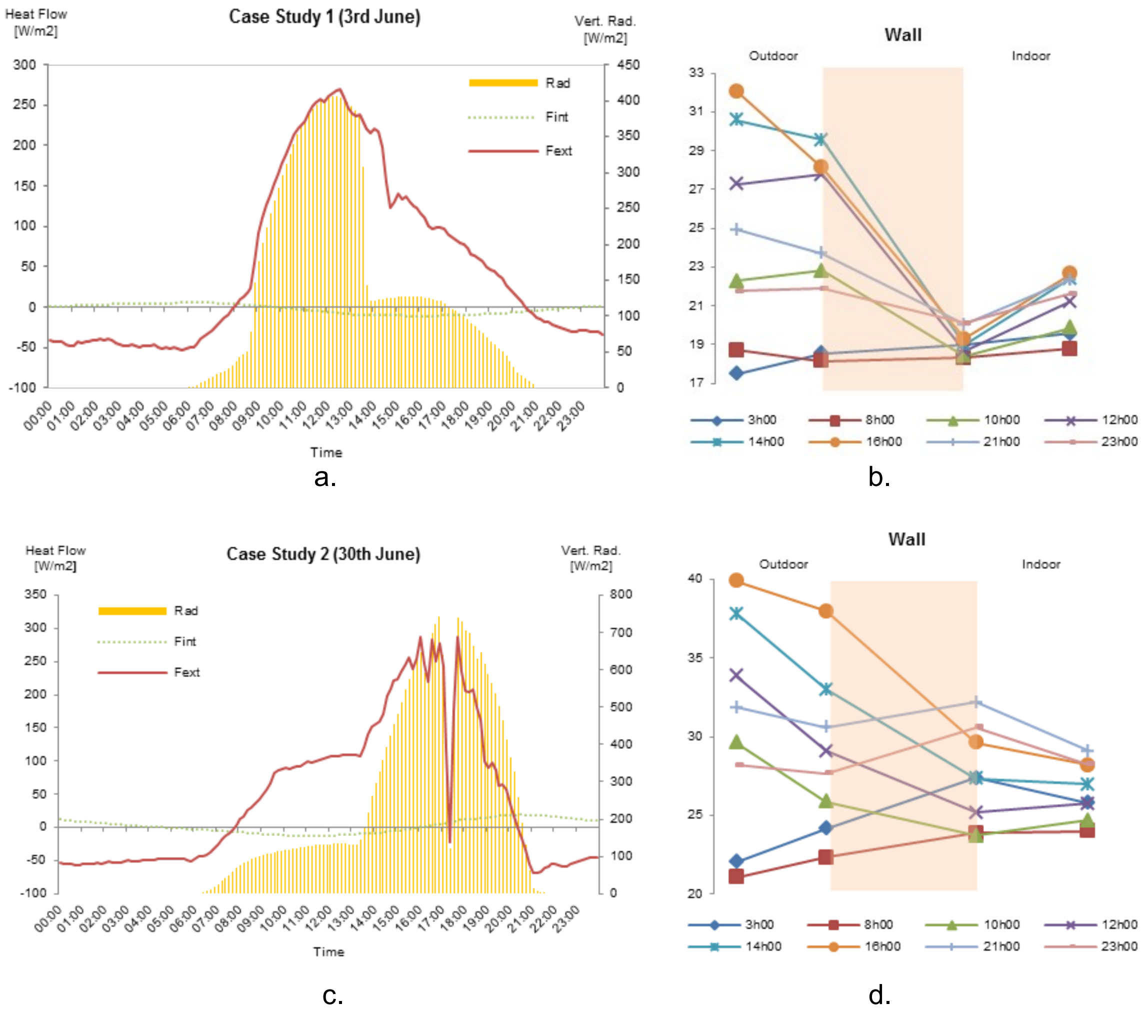


Fig.12. Incident radiation on the vertical plane of the façade and heat flow through the wall (a., c.); horizontal profiles of temperature (b., d.) in the warmest summer monitoring day.

In this campaign, the maximum outdoor temperature (Figure 11 b.) was between 30 ºC (in CS1) and 42 ºC (in CS2) and the minimum was between 14 ºC (in CS1) and 20 ºC (in CS2). This means that the outdoor temperature variation reaches 22 ºC in CS2. Once again, the indoor temperatures are quite similar and compared to the outdoor temperatures have very small temperature variation.

Figure 12 a. and c. shows very high values of the outdoor heat flows (with outdoor-indoor direction) clearly influenced by solar radiation, where the maximum values of the heat flow coincide with the maximum value of the incident solar radiation. As in the winter campaign, the indoor heat flow is almost null, which indicated that the solar radiation is absorbed and the heat accumulated in the walls during the daytime.

The indoor heat flow, in most of the cases, has an opposite signal to the outdoor heat flow. When the outdoor heat flow reaches its highest value, the indoor heat flow reaches its lowest value. Almost at the same time, it is registered the highest value for the indoor environment. As we can see in Figure 12 b., the indoor surface temperature almost doesn't have any variation and, however, the indoor temperature has a bigger variation. As so, it's possible to conclude that the variation of the indoor temperature is due to the heat conduction throw the ceiling, door and windows and not throw the earth walls. This explains the negative signal of the indoor heat flow.

The outdoor heat flow has positive signal while is registered values of the solar radiation. Without its incidence, the outdoor heat flow could be near to zero as the indoor heat flow. Observing figure 3.6, case study 2, heat flow and solar radiation variation graphic, there was a moment, around 17h30, where the solar radiation crushed abruptly and, as a consequence of this crushed the outdoor heat flow reached a negative value.
Concerning the temperatures distribution (Figure 12 b. and d.), it's possible to observe higher temperature variation for the outdoor parameters (outdoor temperature and outdoor surface temperature).
There is a considered delay between the outdoor and the indoor temperatures maximum values. At 16h00 it was registered the highest outdoor temperature for CS2, whereas the highest indoor environment temperature was only reached at 21h00.
In general, the summer monitoring campaign results are coherent with the ones obtained during the winter campaign.

4. Discussion and conclusions

By the records presented before it is possible to conclude:

- The indoor thermal comfort of the earth's constructions is not achieved during the winter extreme conditions.
- However, during summer extreme conditions its behavior is very satisfactory.
- The temperatures difference between indoor and outdoor environments is very high due to the high thermal inertia of the earth walls.
- Although the high outdoor temperature variation (almost 22 ºC in CS2 during summer campaign) the indoor temperature variation in very small.
- The outdoor heat flow is highly influenced by the incident solar radiation.
- The opposite signals for the outdoor and indoor heat flows during the daytime indicate that the solar radiation is being observed by the wall and the heat is accumulated. This is enhanced by the high thermal inertia of the wall.
- There is a considered delay between the outdoor and the indoor temperatures maximum values which is also due to the high thermal inertia of the wall.
- The experimental results revealed a large thermal inertia of the walls, which led to low indoor temperatures in both seasons.
- The results demonstrate the need to improve the thermal conductivity of the earth in order to meet the minimum requirements imposed by the Building Regulations.

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