



HAL
open science

Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings

Emma Stephan, Richard Cantin, Antoine Caucheteux, Sihem Guernouti,
Pierre Michel

► To cite this version:

Emma Stephan, Richard Cantin, Antoine Caucheteux, Sihem Guernouti, Pierre Michel. Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings. *Building and Environment*, 2014, 80, pp.241-248. 10.1016/j.buildenv.2014.05.035 . hal-01819341

HAL Id: hal-01819341

<https://hal.science/hal-01819341v1>

Submitted on 19 Feb 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

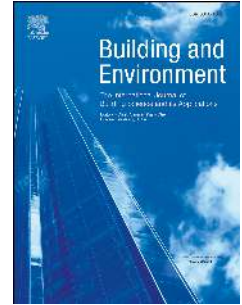


Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Accepted Manuscript

Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings

E. Stéphan, R. Cantin, A. Caucheteux, S. Tasca-Guernouti, P. Michel



PII: S0360-1323(14)00185-1

DOI: [10.1016/j.buildenv.2014.05.035](https://doi.org/10.1016/j.buildenv.2014.05.035)

Reference: BAE 3731

To appear in: *Building and Environment*

Received Date: 26 March 2014

Revised Date: 13 May 2014

Accepted Date: 31 May 2014

Please cite this article as: Stéphan E, Cantin R, Caucheteux A, Tasca-Guernouti S, Michel P, Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings, *Building and Environment* (2014), doi: 10.1016/j.buildenv.2014.05.035.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings

E. Stéphan^{1,2}, R. Cantin², A. Caucheteux¹, S. Tasca-Guernouti³, P. Michel²

¹CEREMA – DterOuest - DLRCa, 23 avenue de l'Amiral Chauvin, 49136 Les Ponts-de-cé, France

²ENTPE – LGCB, Université de Lyon, Rue Maurice Audin, 69518 Vaulx-en-Velin, France

³CEREMA – DterOuest – DVT, Rue René Viviani BP 46223, 44262 Nantes, France

Corresponding author: Emma Stéphan, Tel.: +33 2 41 79 13 17; fax: +33 2 41 44 32 76

E-mail address: emma.stephan@cerema.fr

Abstract

The aim of this paper is to evaluate summer thermal inertia in high porosity limestone old buildings. These buildings have to be retrofitted to save energy. Consequently, this paper focuses on the effects of insulation on this property. Monitoring surveys were carried out in an experimental room and in five single-family houses.

In summer, thermal inertia may vary in a same building according to the localization of the room and the insulation. The analysis of monitoring data before and after insulation of the experimental room allows to highlight the improvement of thermal inertia of the room thanks to insulation: the decrement factor is divided by 10 and the time lag increases by 4 hours. These results are confirmed by single-family houses measurements. The decrement factors of insulated limestone rooms are lower (0.10) than non-insulated ones (0.17) and the time lag increases by 3 hours with insulation.

Insulation of Tuffeau stone rooms does not cause overheating conditions in summer.

These results indicate the benefit of insulation on this passive design. For these buildings, insulation reduces the temperature amplitude in summer and delays the maximum of temperature during the night.

Keywords

Old limestone buildings - Thermal inertia - Insulation

1. Introduction

The current energy and environmental constraints lead governments to be interested in building sector. Indeed, it represents nearly 40% of global energetic consumption and the residential part composes 22% [1]. In France, three main periods of construction characterize the entire housing stock. The first part was built before 1948 [2]. These buildings are presented as old buildings. They are distinguished by a social, historical and cultural heritage. The industrialized buildings submitted to economic constraints compose the second part of the housing stock (1948-1975). The last part represents the buildings which consume less energy. They respect the thermal regulations since 1975.

The annual growth of the building stock in France is around 1% [3]. Therefore, retrofitting of existing stock is a major lever to save energy. The French old buildings represent 10 millions of dwellings. It is a third part of the entire housing stock. They depend on the material available on site and on the local style of construction (wall thickness, floor composition, etc.). Consequently, they are heterogeneous and the characterization of the old building stock is difficult because of this variability. Zhai and al. [4] link the traditional buildings construction to the climate. The global vernacular architecture may be classified according to the main weather conditions in the world [5,6]. For example, Oikomou and al. [5] characterize the architecture of Greek dwellings and underline that these buildings are submitted to environmental aspects as main wind direction, rain direction, etc. All these studies underline that the passive design used on old buildings is an advantage for comfort and energy consumption.

Thermal inertia is a passive design famous in old buildings. It is defined by Ferrari [7] as the heat storage capacity of building structure and its performance to delay the heat transmission. Orosa and al. [8] compare experimental measurements in an old school and in a new one. Their analysis underlines that the design of the old school (heavy structure, high thermal inertia, etc.) gives a better summer thermal comfort than in the new one. Moreover, Martin and al. [9] study two old houses in Spain. They benefit of a good summer comfort without cooling system. The heavy structure of these houses maybe explained these results. Brau and al. [10] have compared the thermal behaviour of a room with heavy construction (concrete walls) to a room with low thermal inertia (wood walls). With the same geometry and the same climate, the room with heavy concrete construction had a better summer comfort than the other. However, heavy structure and high thermal inertia is not only benefiting for

summer comfort but also for heating needs. However, the energy gains due to this phenomenon may be very different from buildings and climate as Aste explained it [11].

Retrofitting solutions may affect the thermal inertia of the buildings. Several studies focus on the compromise between thermal inertia during summer and energy savings in winter. Di Perna and al. [12] analysed the effect of an internal insulation on the thermal behaviour of classrooms. In this case, the thermal inertia of these rooms is degraded with the insulation. Fang and al. precise in [13] that insulation may increase energy consumption for cooling during summer. Stazi and al. [14] compare three different walls and conclude that internal insulation may cause overheating problems. However, the localisation of the insulation and its density affect the thermal inertia of a wall [15]. External insulation seems to be better for summer thermal comfort than internal insulation [16].

In France, 45% of old buildings have been built with stone [17]. Among the diversity of existing stones, limestone represents 20% of the total sedimentary stock. It is used for constructions in sedimentary basins in France. The high porosity limestone was widely used because it was easy to sharpen [18]. For example, Tuffeau stone is a high porosity limestone found in the Loire Valley in France. Its porosity varies from 35% to 45% [19]. This kind of buildings has to be retrofitted but the selection of a retrofitting solution is a complex process. Indeed, it is a compromise between historical preservation, energy consumption improvement, structure degradation risk and occupant behaviour conservation and/or improvement [20,21]. For example, the architectural preservation prevents from some retrofitting actions as external insulation. Moreover, the specific hygrothermal behaviour of old masonry may degrade the thermal performances of internal insulation and the structure of the wall [22].

Consequently, insulation must be analysed according to many criteria in Tuffeau stone building: thermal inertia, thermal performance and wall degradation. The aims of this paper are to assess the summer thermal inertia of Tuffeau stone buildings and to assess the effect of internal insulation on this passive design. Monitoring surveys were achieved out on an experimental room and five Tuffeau stone houses. The experimental room was monitored during two summers before and after internal insulation. Thermal inertia of the wall and of the ambiance is compared before and after insulation

with theoretical indicators. The five buildings have different characteristics and levels of insulation. The thermal behaviour of the cases was analysed according to their retrofitting thermal level.

2. Thermal inertia indicators

Thermal inertia is a passive method to store heat energy and to delay its restitution. This phenomenon is associated with the thermal mass of construction elements. Its characterization used generally two dynamic indicators [23,24]: the decrement factor (f) and the time lag (φ). The decrement factor evaluates the heat storage capacity and the time lag characterizes the heat transmission delay (Figure 1).

Two kinds of thermal inertia may be distinguished: the construction elements and the “building system”. The “Building system” takes into account the construction elements, the interaction with outdoor environment and the use of the building (ventilation, internal loads, and occupancy).

The thermal inertia of the construction elements (walls) depends on the thermal properties of materials [23] (thermal conductivity, specific heat capacity and density). However, other parameters than walls materials may affect the thermal inertia of the building. The air change rate modifies the indoor temperature and consequently the thermal inertia. A high air change rate decreases the thermal inertia as explained by Orosa and al. [8] and Roucoult and al. [25]. The solar irradiation varies according to the orientation and causes differences in boundary surface conditions [26,27]. Thus, thermal inertia is affected by room orientation. Moreover, high internal loads may decrease the thermal inertia of a room thanks to the modification of indoor temperature [12].

In this paper, the wall thermal inertia is characterized by the decrement factor and the time lag between inside surface temperature and outside surface temperature (Equations (1) and (2)) as presented in Figure 1:

$$f^{wall} = \frac{A_{si}}{A_{se}} = \frac{T_{max,int}^s - T_{min,int}^s}{T_{max,ext}^s - T_{min,ext}^s} \quad (1)$$

$$\text{at } t_1 \quad T_{int}^s(t_1) = T_{max,int}^s$$

$$\text{at } t_2 T^s_{ext}(t_2) = T^s_{max,ext}$$

$$\varphi^{wall} = |t_2 - t_1| \quad (2)$$

The building is considered as a volume which separates two environments (indoor and outdoor) as for a wall. The time lag and the decrement factor characterize the thermal inertia of the building. The difference of calculation with the wall indicators is the outdoor temperature: for the wall, it is the outdoor surface temperature, for the ambiance, it is the outdoor air temperature.

The decrement factor for a room is defined by the following equation (3):

$$f^a = \frac{A_i}{A_e} = \frac{T^a_{max,int} - T^a_{min,int}}{T^a_{max,ext} - T^a_{min,ext}} \quad (3)$$

And the time lag for a room (4):

$$\text{at } t_1 T^a_{int}(t_1) = T^a_{max,int}$$

$$\text{at } t_2 T^a_{ext}(t_2) = T^a_{max,ext}$$

$$\varphi^a = |t_2 - t_1| \quad (4)$$

3. Experimental procedure

3.1. Monitoring procedure of an experimental room

In 2012, an experimental room was built in Angers (France, 47°25'00''N – 0°31'23''W). It has a surface area of 15 m² and a height of 3 m. The room is located next to three heating zones so just one wall is in contact with the outdoor. The facade (wall of the room in contact with the outdoor) is made of Tuffeau stone of 0.22 m (wall a in Figure 2) and is oriented south.

To stop the heat and moisture transfers between different zones, the three inner walls (b, c and d in Figure 2) and the ceiling are insulated by 0.10 m of fiberglass and a vapour barrier. The floor is composed of vinyl on concrete slab.

There is no mechanical ventilation. The air exchange is due to the surface leakages. The air change rate (ACH) at 50 Pa of the experimental room has a value of 4.3 h⁻¹. Consequently, this case corresponds to an average tightness level [28]. The room is not occupied.

The hygrothermal conditions of the indoor environment are monitored. The air temperature is measured at 1.80 m in the middle of the room to avoid thermal convective effects of walls. The outer wall is monitored in four points: left and right to take into account the other zones effect at the height of 0.50 m and 2.50 m (Figure 3). Temperature was measured in three depths in Tuffeau stone: 0.05 m from the surfaces to study the boundary effect and in the middle of the stone (0.11 m).

The monitoring was realised during several months from August 1st of 2012 to May 15th, 2013.

During June 2013, the experimental room was insulated by 0.15 m of hemp concrete. The thermal resistance of the wall increases from 0.55 m².K/W to 2.6 m².K/W. The low limit to retrofit wall of R=2 m².K/W is defined in the French thermal regulation for existing buildings [29]. The physical and thermal characteristics of the Tuffeau stone and of the insulation are presented in Table 1 [19], [29].

One sensor was put in the hemp concrete (Figure 4). The monitoring of the insulated room was conducted from July 8th to July 22nd, 2013.

The devices used for monitoring temperature are Rotronic data loggers (HC2 for the ambiance and the wall and AC1913-A for the surface temperature). Their accuracy is $\pm 0.1^{\circ}\text{C}$ for the ambiance and the wall and $\pm 0.15^{\circ}\text{C}$ for the surface temperature sensor. The time step for monitoring is 5 minutes.

A local weather station measures the in situ climatic conditions.

3.2. Monitoring procedure on in situ single-family houses

Five single-family houses were selected for this study. Table 2 presents the characteristics of the five houses.

In each house, some rooms were monitored. Overall, 18 rooms are studied (Table 3).

For the 18 rooms, the indoor hygrothermal conditions were monitored during one month of summer.

For the buildings A to C, the measurements were conducted from August 1st, 2011 to August 31st,

2011, for the building D from August 1st, 2012 to August 31st, 2012 and the building E was monitored from July 1st, 2013 to July 24th, 2013.

The occupancy of the room cases corresponds to an active family. During the week day, people are only presented in the night, during lunches and in the evening. During week-end, people are generally presented during the whole day.

The devices used for monitoring temperature are ONSET data logger with an accuracy of $\pm 0.35^{\circ}\text{C}$.

The time step for monitoring is 10 minutes to preserve the memory storage.

The weather conditions (temperature and relative humidity) were measured by MeteoFrance weather station (The French national weather service) in Beaucouzé near the 5 single-family houses (Lat $47^{\circ}28'42''\text{N}$, Long $0^{\circ}36'48''\text{W}$). The time step for monitoring is one hour.

4. Results and analysis

4.1. Analysis of monitoring results on the experimental room

In this first part, the theoretical values of thermal inertia of the wall are calculated. They are compared to experimental indicators before and after insulation. Then, the thermal ambience behaviour was analysed according to the insulation or non-insulation of the Tuffeau stone wall.

4.1.1. Wall thermal behaviour analysis

The dynamic properties of the non-insulated wall and of the insulated one were evaluated according to the international standard EN ISO 13786 [30]. This method is based on admittance procedure. In this paper, two indicators were calculated: the decrement factor (f) and the time lag (ϕ) for temperature delay. The theoretical results are compared to experimental ones.

The experimental decrement factor and the time lag are calculated for each day of the monitoring periods before and after insulation. Outdoor surface temperature was used for the calculation (Equations (1) and (2)). Table 4 presents the average and the standard deviation of both thermal inertia indicators of each wall points before insulation (from August 1st, 2012 to August 31st, 2012) and after insulation (from July 8th, 2013 to July 22nd, 2013) and the theoretical results for the non-insulated wall and the insulated one.

The standard deviation of the decrement factor is low (from 0.01 to 0.06) and is constant with insulation so the decrement factor does not vary significantly during the monitoring periods. For

example, the minimum of decrement factor is 0.39 and the maximum 0.57 before the insulation for the 0.05 m point.

The standard deviation of the time lag is lower than one hour for the Tuffeau stone point. In the insulation, the time lag varies from 8 hours to 16 hours. The heterogeneity of the hemp concrete could explain the significant variation of time lag during the summer. The heat transfer may be not linear. On the contrary, Tuffeau stone is a homogeneous material [19] and present less variation during the monitoring periods.

In the following part, the analysis is focused on one day of each period. The selected days are the ones with the highest outdoor temperature amplitude: August 18th, 2012 (before the insulation) and July 21st, of 2013 (after the insulation). Table 5 gives the weather conditions of these two days.

Figure 5 and Figure 6 present the decrement factors and the time lags according to the depth before and after insulation of the wall and the theoretical values.

In the Tuffeau stone, the decrement factor is steady with insulation (Figure 5) and the time lag increases about one hour (Figure 6). The dynamic evolution of temperature in the Tuffeau stone is not affected by insulation.

Insulation has a different behaviour than Tuffeau stone: the decrement factor decreases significantly from the Tuffeau stone to the insulation. It is divided by 10. Consequently, the variations of temperature are less important in the insulation. Regarding to the time lag, the difference is less significant: the time lag increases by 3 hours. The thermal conductivity (Table 1) of the insulation (0.07 W/m.K) is lower than that of Tuffeau stone (0.4 W/m.K). Consequently, the heat transfers are braked from the Tuffeau stone to the indoor ambiance by insulation. Moreover, the specific heat of hemp concrete is higher than the Tuffeau stone one (1700 J/kg.K and 1000 J/kg.K for Tuffeau stone). The insulation needs more energy to cause a temperature change.

Theoretical values are different from experimental ones. The experimental measurements underline a better decrement factor than theoretical values. On the contrary, the theoretical time lags are mainly higher than the measured ones. Moreover, the standard results underline a continuous evolution of thermal inertia indicators with the insulation (Figure 5 and Figure 6). This continuity is not observed

experimentally. The differences may be explained by the contact between insulation and Tuffeau stone. Contrary to theoretical hypothesis, the contact is not perfect. Moreover, the EN ISO 13786 procedure considers sinusoidal boundary conditions for the indicators calculation. As explained by Gasparella and al. [31], theoretical thermal inertia indicators may be different from experimental values because of the non-sinusoidal boundary conditions of experimental case.

4.1.2. Volume thermal behaviour analysis

The effect of the insulation on the thermal inertia of the room (volume) is analysed. As for the experimental room, both thermal inertia indicators are calculated on the days with the highest outdoor temperature amplitude. The indoor and outdoor temperature evolutions are presented before and after insulation in Figure 7 and Figure 8.

The average temperatures are equivalent for these two days: 27.5°C. In both cases, indoor temperatures suffer fewer variations than outdoor temperature. The indoor amplitude is 2.3°C before insulation and inferior to 1°C after insulation instead of outdoor amplitude superior to 14°C before and after insulation (Table 5). The maximum of outdoor temperature are not reached at the same time the August 18th, 2012 (16:00) and July 21st, of 2013 (14:00). In August 18th, 2012, the maximum was reached at 21:00 contrary to 23:00 in July 21st, 2013. .

Table 6 gives the decrement factor and the time lag of the room before and after insulation for the wall and for the volume. The decrement factor of the volume is divided by 2.6. Consequently, the insulation has reduced the temperature variation in the room. The time lag has significantly increased (5 hours to 9 hours).

Thermal inertia indicators of the volume are different from the wall (Table 6). Other parameters than walls affect the volume.

4.2 Analysis of in situ monitoring in 5 single-family houses

The thermal inertia of the 18 rooms in single-family houses is analysed. The rooms are classified in four categories according to their localisation in the building (attic spaces or not) and their insulation (Figure 9, Figure 10 and Figure 11):

- Non-insulated attic spaces (1 case)
- Insulated attic spaces (4 cases)
- Non insulated Tuffeau stone rooms (4 cases)
- Insulated Tuffeau stone rooms (9 cases)

The results on the experimental room underline few variations of the thermal inertia indicators with the weather conditions (Table 4). Thus, the decrement factor and the time lag of the 18 cases are calculated during the day with the highest outdoor temperature variation of the monitoring periods. The attic spaces have the highest decrement factors (Figure 9). They vary from 0.25 to 0.55 for the insulated attic rooms. Consequently, these rooms have high indoor temperature variations during the day. This low thermal inertia may be explained by the solar absorption coefficient and the incidence of solar irradiance. Indeed, Kontoleon et al. [32] explain that darker the outer material is, lower the thermal inertia is. Moreover, the orientation affects the received solar irradiance. The roof is composed of slate (black material) contrary to the Tuffeau stone (white stone).

The Tuffeau stone rooms have a better decrement factor when they are insulated. Indeed, the average of decrement factor for the four non-insulated Tuffeau stone rooms is 0.17 and it is 0.10 for the insulated ones (Figure 9). As for the experimental room, the insulation may reduce the indoor temperature variations in Tuffeau stone rooms.

The time lags of attic spaces and non-insulated Tuffeau stone rooms are close (Figure 10). The average is 4.3 hours for both categories.. The insulation increases the time lag of Tuffeau stone rooms. The average is increased by 3 hours. For a maximum of outdoor temperature at 14:00, the indoor temperature reaches its maximum at 22:00 instead of 18:00. Consequently, as for the experimental room, the insulation permits to reduce temperature variation and to delay the restitution of heating during the night.

Thermal inertia is generally associated to summer thermal comfort. Insulation improves thermal inertia in these cases but it may cause overheating. The average temperatures during monitoring periods vary from 21.5°C to 23.9°C for the 18 cases. These temperatures are comfortable however the variations may be large. Consequently, the percentage of time when indoor temperature is higher to 27°C is calculated during one month of summer (Figure 11). The temperature limit has been selected according to the French thermal regulation [29].

The warmest rooms are the attic spaces with an average of 10% for the percentage of time with a temperature superior to 27°C. The other rooms rarely exceed 27°C. The relation between thermal inertia and summer comfort underlines the benefits of high thermal inertia for indoor thermal comfort (Figure 12). High decrement factors cause more overheated temperatures in the rooms. Insulation does not cause warmer conditions in the Tuffeau stone rooms.

In a same building and a same category, the thermal behaviour may be different. Parameters presented in paragraph 2 may explain the differences. The following analysis focuses on cases with specific thermal inertia which highlight variable behaviour.

For example, for the building E, the non-insulated Tuffeau stone rooms E_3 and E_4 have respectively a decrement factor of 0.24 and 0.07. Three reasons may explain this difference as presented in paragraph 2. The thickness of the wall is 0.22 m for the case E_3 and varies from 0.50 to 0.70 m for the case E_4. The thermal inertia of the elements is different for both cases. Moreover, the orientation of these rooms is different: North, South and West for the case E_3 and North/South for the case E_4. The case E_3 benefits from more solar radiation which may cause higher temperature variations (amplitude of 3.9°C) than E_4 (1.1°C of temperature amplitude). Finally, the case E_3 represents kitchen behaviour with high internal loads during mealtimes.

The case A_2 in the category of insulated attic spaces present some differences with the other cases of this category. Its percentage of overheated room is really low (2%) and it is the case with the better decrement factor in this category. The comparison of the theoretical decrement factor of the element of attic spaces (Table 7) underlines the low decrement factor of the roof of case A_2 (0.11). On the

contrary, the roof decrement factor is from 0.88 to 0.98 for the other attics spaces. The low experimental decrement factor of this room may be explained by the coating made of lime and hemp used for roof insulation.

5. Conclusions

The main objective of this paper consisted in assessing the thermal inertia of old limestone buildings in summer and determining the impact of a retrofitting solution on thermal behaviour of these buildings.

Two monitoring surveys were achieved out on an experimental room and five Tuffeau buildings. In summer, thermal inertia may vary in a same building according to the localisation of the room (attic or not) and according to the material (thickness, insulation, etc.). The decrement factor of occupied Tuffeau stone buildings vary from 0.07 to 0.54 and the time lags from 3 to 8 hours. Moreover, Tuffeau stone rooms are comfortable during summer. Indeed, the percentage of time with overheating conditions does not exceed 13% of summer in these cases.

Analysis of monitoring data on the experimental room before and after insulation underlines that internal insulation with hemp concrete improves thermal inertia of the room in summer. The decrement factor is divided by 10 and the time lag is increased by 4 hours in the room. These results are confirmed by in situ monitoring. The decrement factor of in situ rooms is 0.17 for non-insulated Tuffeau stone rooms and is 0.10 for insulated Tuffeau stone rooms. The time lag increases by 3 hours. Insulation allows a decrease of the indoor temperature variations and delays the maximum of indoor temperature.

The attic spaces have a lower thermal inertia than the Tuffeau stone rooms: their decrement factor is 0.37 and their average time lag is 4.3 hours.

These experimental results underline the advantages of insulation for thermal inertia on Tuffeau stone buildings. However, the decision of a retrofitting solution is a complex process and these actions have to be analysed on other criteria as thermal comfort or energy savings.

6. References

- [1] IEA, AEO2014 Early Release Overview, 2014.
[http://www.eia.gov/forecasts/aeo/er/pdf/0383er\(2014\).pdf](http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2014).pdf) (accessed on 24.02.14).
- [2] Cantin R., Burgholzer J., Guarracino G., Moujalled B., Tamelikecht S., Royet B.G., Field assessment of thermal behavior of historical dwellings in France, *Building and Environment* 45 (2010) 473-484.
- [3] INSEE, TEF Edition 2014, 2014. <http://www.insee.fr/fr/publications-et-services/default.asp?page=collections-nationales.htm> (accessed on 24.02.14)
- [4] Zhai Z., Previtali J., Ancient vernacular architecture: characteristics categorization and energy performance, *Energy and Buildings* 42 (2010) 357-365.
- [5] Oikonomou A., Bougiatioti F., Architectural structure and environmental performance of the traditional buildings in Florina, NW Greece, *Building and Environment* 46 (2011) 669-689.
- [6] Sözen M. S., Gedik G. Z., Evaluation of traditional architecture in terms of building physics: Old Diyarbakır houses, *Building and Environment* 42 (2007), 1810-1816.
- [7] Ferrari S., Building envelope and heat capacity: re-discovering the thermal mass for winter energy savings, 28th AIVC Conference, 2007, Greece.
- [8] Orosa JA, Oliveira AC, A field study on building inertia and its effects on indoor thermal environment, *Renewable Energy* 37 (2012) 89-96.
- [9] Martin S., Mazarrón F. R., Cañas I., Study of thermal environment inside rural houses of Navapalos (Spain): The advantages of reuse buildings of high thermal inertia, *Construction and Building Materials* 24 (2010) 666-676.
- [10] Brau J., Depecker P., Yezou R., Influence de l'inertie thermique sur les consommations d'énergie et de confort. *Comportement thermique dynamique des bâtiments*, 1984.
- [11] Aste N., Angelotti A., Buzzetti M., The influence of the external walls thermal inertia on the energy performance of well insulated buildings, *Energy and Buildings* 41 (2009) 1181-1187.
- [12] Di Perna C., Stazi F., UrsiniCasalena A., D'Orozi M., Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads, *Energy and Buildings* 43 (2011) 200-206.

- [13] Fang Z., Li N., Li B., Luo G., Huang Y., The effect of building envelope insulation on cooling energy consumption in summer, *Energy and Buildings* 77 (2014) 197-205.
- [14] Stazi F., Veglio A., Di Perna C., Munafo P., Retrofitting using a dynamic envelope to ensure thermal comfort, energy savings and low environmental impact in Mediterranean climates, *Energy and Buildings* 54 (2012) 350-362.
- [15] Kontoleon K.J., Theodosiou Th. G., Tsikaloudaki K.G., The influence of concrete density and conductivity on wall's thermal inertia parameters under a variety of masonry and insulation placement, *Applied Energy* 112 (2013) 325-337.
- [16] Al-Sanea S. A., Zedan M. F., Al-Hussain S. N., Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential, *Applied Energy* 89 (2012) 430-442.
- [17] Stéphan E., Caucheteux A., Cantin R., Michel P., Tasca S., 2013. « The diversity of limestone and the implication for energy efficiency of buildings”, 7th Annual International Symposium on Environment, Athens, Greece.
- [18] Smith B., Gomez-heras M., Viles H., Underlying issues on the selection, use and conservation of building limestone, Geological society, London 2010.
- [19] Beck K., Al-Mukthar M., Rozenbaum O., Rautureau M., Characterization, water transfer properties and deterioration in Tuffeau: building material in the Loire Valley – France, *Building and Environment* 38 (2003) 1151-1162.
- [20] Ferretti V., Bottero M., Monidini G., Decision making and cultural heritage: An application of the Multi-Attribute Value Theory for the reuse of historical buildings, *Journal of Cultural Heritage* (2014), <http://dx.doi.org/10.1016/j.culher.2013.12.007>.
- [21] Hall M., Casey S., Loveday D., Gillott M., Analysis of UK domestic retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential, *Building and Environment* 70 (2013) 48-59.
- [22] Moradias P.A., D. Silva P., Castro-Gomes J.P., Salazar M.V., Pires L., Experimental study on hygrothermal behaviour of retrofit solutions applied to old building walls, *Construction and Buildings Materials* 35 (2012) 864-873.

- [23] Gagliano A., Patania F., Nocera F., Signorello C., Assessment of the dynamic thermal performance of massive buildings, *Energy and Buildings* (2014)
<http://dx.doi.org/10.1016/j.enbuild.2013.12.060>
- [24] Ulgen K, Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor, *Energy and Building* 34 (2002) 273-278.
- [25] Roucoult J.-M., Douzane O., Langlet T., Incorporation of thermal inertia in the aim of installing a natural nighttime ventilation system in buildings, *Energy and Buildings* 29 (1999) 129-133.
- [26] Mavromatidis L., El Mankibi M., Michel P., Santamouris M., Numerical estimation of time lags and decrement factors for wall complexes including Multilayer Thermal Insulation, in two different climatic zones, *Applied Energy* 92 (2012) 480-491.
- [27] Kontoleon K. J., Eumorfopoulou E. A., The influence of wall orientation and exterior surface solar absorptivity on time lag and decrement factor in the Greek region, *Renewable Energy* 33 (2008) 1652-1664.
- [28] NF EN ISO 13789:2008, Thermal performance of buildings – Transmission and ventilation heat transfer coefficients – Calculation methods. 2008.
- [29] Arrêté du 28 Décembre 2012 relatif aux caractéristiques thermiques et aux exigences de performances énergétiques des bâtiments nouveaux, *JORF* , (2013).
- [30] NF EN ISO 13786:2008, Thermal performance of building components – Dynamic thermal characteristics – Calculation methods. 2008.
- [31] Gasparella A., Pernigotto G., Baratieri M., Baggio P., Thermal dynamic transfer properties of the opaque envelope: Analytical and numerical tools for the assessment of the response to summer outdoor conditions, *Energy and Buildings* 43 (2011) 2509-2517.
- [32] Kontoleon K. J., Bikas D. K., The effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations, *Energy and Buildings* 39 (2007) 1011-1018.

Tables

Table 1: Thermal characteristics of Tuffeau stone and insulation

	Tuffeau stone	Insulation (Hemp concrete)
Thickness (m)	0.22	0.15
Density (kg/m ³)	1400	300
Specific heat (J.kg ⁻¹ .K ⁻¹)	1000	1700
Thermal conductivity (W/m.K)	0.4	0.07

Table 2: Single-family houses characteristics






Building	A	B	C	D	E
Pictures					
Latitude	47°15'38''N	47°35'47''N	47°08'07''N	47°24'34''N	47°19'31''
Longitude	00°24'23''E	00°10'51''W	00°07'19''E	00°19'10''W	00°03'19''
Ventilation	Natural	Natural	Dual flow	Natural	Natural
Occupancy	2 people	4 people	Variable (accommodation)	2 people	2 people during weeks, 4 people during week-ends
Number of monitored rooms	2	3	5	4	4

Table 3: Room cases characteristics

Room cases	Date	Use	Attic space	Element	Building components	Thermal transmittance (W/m.K)	Orientation
A_1	16 th c.	No use	Yes	Roof	Slate	16.7	North/South
				Wall	0.55 m of Tuffeau stone	0.73	
A_2	16 th c.	Bedroom	Yes	Roof	Slate 0.26 m of coating made of lime and hemp	0.63	North/South
				Wall	0.55 m of Tuffeau stone	0.73	
B_1	16 th c.	Kitchen	No	Wall	0.65 m of Tuffeau stone 0.06 m of coating of lime and hemp	0.51	East/West
B_2	19 th c.	Library	No	Wall	0.22 m of Tuffeau stone 0.06 m of coating of lime and hemp	1.11	East/West
B_3	19 th c.	Living	No	Wall	0.22 m of Tuffeau	1.11	East/West

		room			stone 0.06 m of coating of lime and hemp		
C_1	16 th c.	Bedroom	No	Wall	0.50 m of Tuffeau stone 0.15 m of plasterwork bricks and chenevotte	0.29	West
C_2	16 th c.	Bedroom	No	Wall	0.50 m of Tuffeau stone	0.80	East
C_3	16 th c.	Bedroom	Yes	Roof	Slate Thin multilayer insulation	3.84	East/West
				Wall	0.50 m of Tuffeau stone 0.15 m of plasterwork bricks and chenevotte	0.29	
C_4	16 th c.	Bedroom	No	Wall	0.50 m of Tuffeau stone 0.15 m of plasterwork bricks and chenevotte	0.29	East
C_5	16 th c.	Living room, kitchen	No	Wall	0.50 m of Tuffeau stone	0.8	West
D_1	18 th c.	Bathroom	No	Wall	0.22 m of Tuffeau stone 0.20 m of wood wool Vapour barrier	0.16	North
D_2	18 th c.	Corridor	No	Wall	0.22 m of Tuffeau stone 0.20 m of wood wool Vapour barrier	0.16	South
D_3	18 th c.	Kitchen	No	Wall	0.22 m of Tuffeau stone 0.20 m of wood wool Vapour barrier	0.16	North/South
D_4	18 th c.	Living room	No	Wall	0.22 m of Tuffeau stone 0.20 m of wood wool Vapour barrier	0.16	North/South
E_1	19 th c.	Bathroom	Yes	Roof	Slate 0.10 m of fiberglass Vapour barrier	0.26	South
				Wall	0.22 m of Tuffeau stone	1.81	
E_2	16 th c.	Bedroom	Yes	Roof	Slate 0.10 m of fiberglass Vapour barrier	0.26	North/South
				Wall	From 0.50 m to 0.70 m of Tuffeau stone	0.57 - 0.8	
E_3	19 th c.	Kitchen	No	Wall	0.22 m of Tuffeau stone	1.81	North/West/S outh
E_4	16 th c.	Living room	No	Wall	From 0.50 m to 0.70 m of Tuffeau stone	0.57 - 0.8	North/South

Table 4: Average and standard deviation of the decrement factor and the time lag before and after insulation for each wall point

Wall measurements point	Before insulation				After insulation				Theoretical values	
	f (-)		ϕ (h)		f(-)		ϕ (h)		f	ϕ (h)
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation		
0.05 m	0.51	0.05	1.5	0.7	0.50	0.03	2.2	0.6	0.97	1.9
0.11 m	0.34	0.05	3.4	0.6	0.35	0.03	4.8	0.6	0.80	5.2
0.17 m	0.26	0.05	4.7	0.8	0.29	0.05	6.0	0.6	0.55	7.9
0.22 m	0.23	0.05	5.5	0.7	0.29	0.06	6.6	0.7	0.38	10.1
0.295 m					0.03	0.01	13.2	2.1	0.16	14.6
0.37 m									0.08	20.0

Table 5: Weather conditions during the 18th August of 2012 (before insulation) and the 21st July of 2013 (after insulation)

	Before insulation	After insulation
	18 th August, 2012	21 st July, 2013
Daily average temperature (°C)	27.5	27.0
Maximum temperature (°C)	36.8	34.9
Minimum temperature (°C)	17.8	20.7
Maximum horizontal solar irradiance(W/m ²)	774	778
Horizontal solar irradiation on the day (kWh/m ²)	6.4	6.4
Daily average wind speed (km/h)	2.0	2.8
Maximum wind speed (km/h)	8.0	12.9
Minimum wind speed (km/h)	0.0	0.0

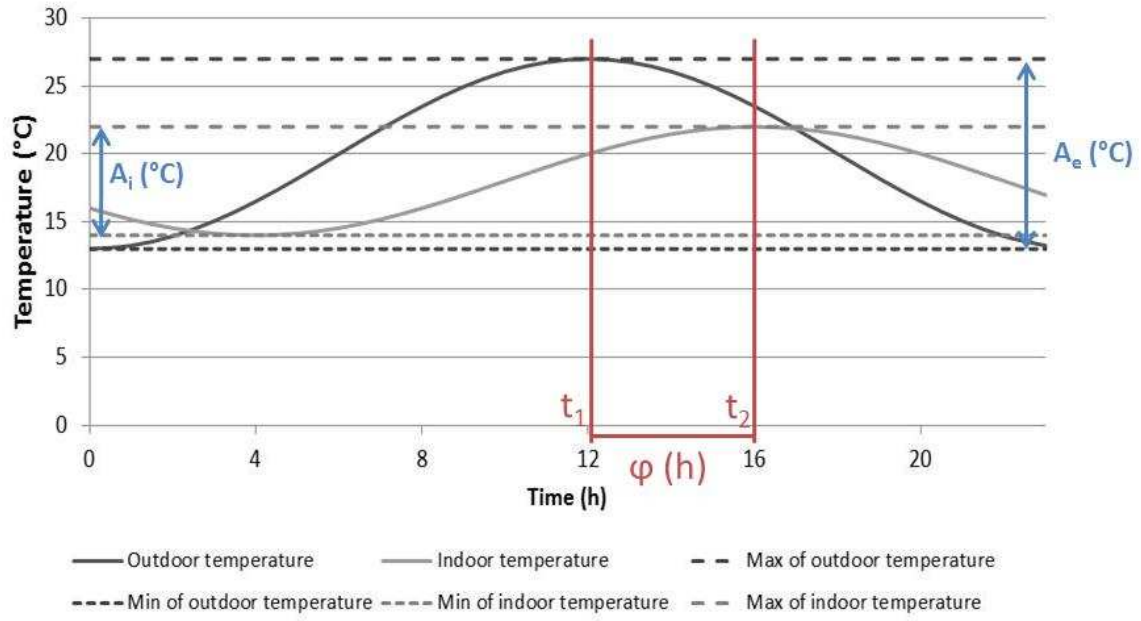
Table 6: Ambient thermal inertia indicators of the experimental room before and after insulation

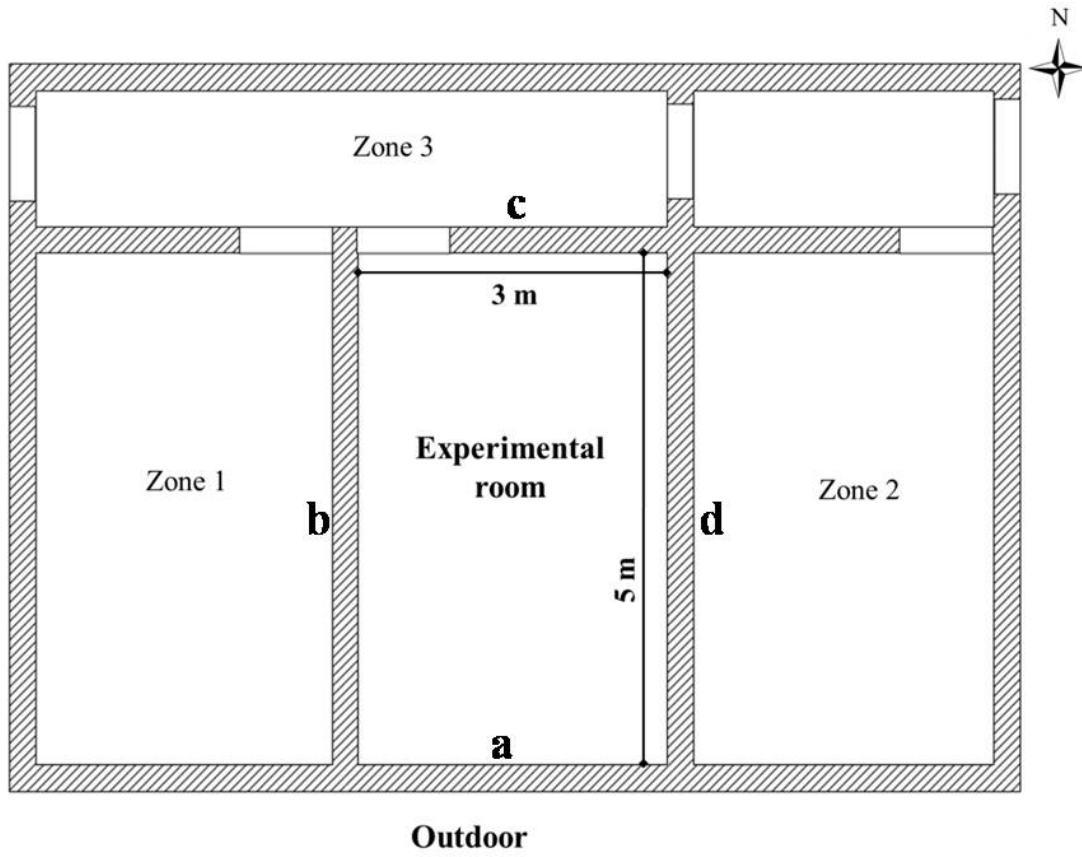
	Volume		Wall	
	Before insulation (18 th August, 2012)	After insulation (21 st July, 2013)	Before insulation (18 th August, 2012)	After insulation (21 st July, 2013)
Time lag (h)	5	9	5	10
Decrement factor (-)	0.12	0.05	0.24	0.03

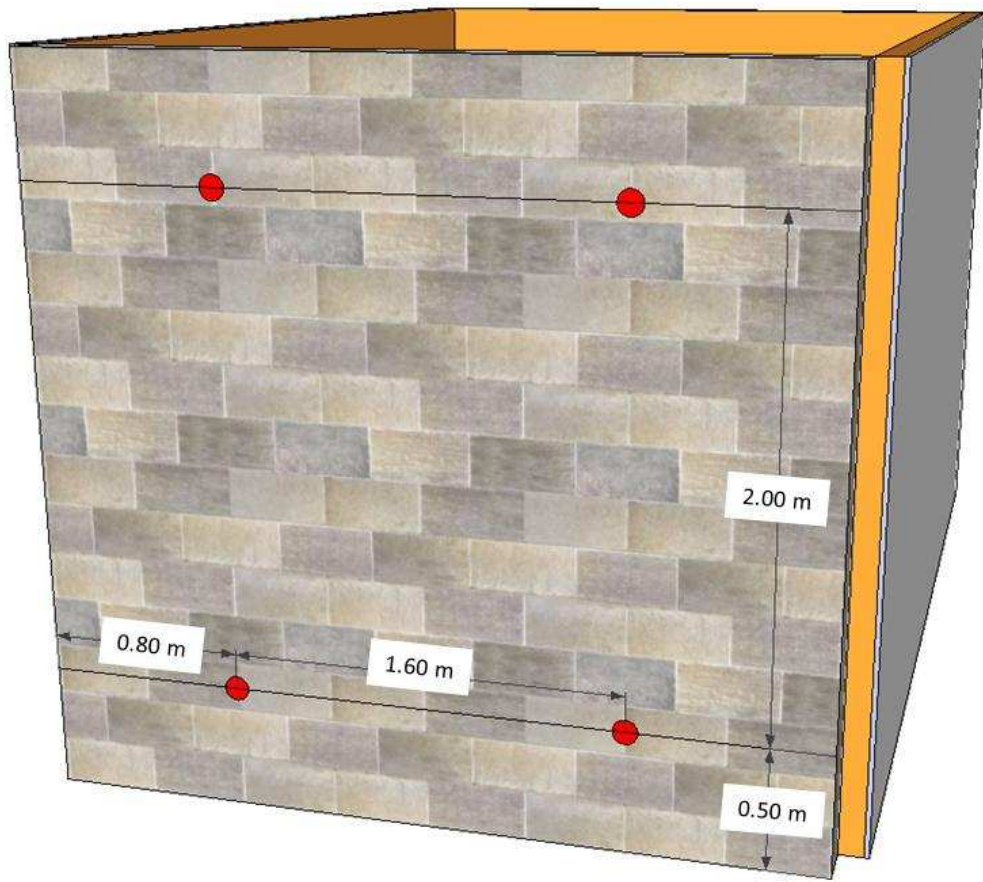
Table 7: Comparison between theoretical decrement factor of element and experimental decrement factor of volume in attic spaces

Room cases	Elements	Theoretical decrement factor of element	Experimental decrement factor of room cases
A_1	Roof	0.99	0.91
	Wall	0.02	
A_2	Roof	0.11	0.25
	Wall	0.02	
C_3	Roof	0.98	0.55
	Wall	0.006	
E_1	Roof	0.88	0.33
	Wall	0.08	
E_2	Roof	0.88	0.35
	Wall	0.03 - 0.0045	

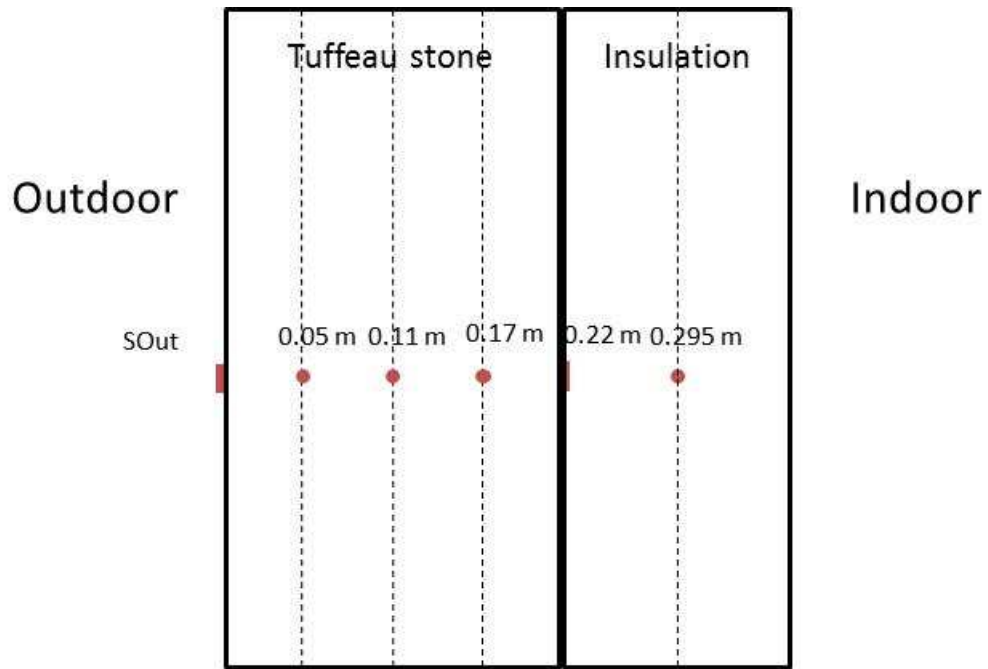
Figures**Figure 1: Thermal inertia indicators****Figure 2: Scheme of the experimental room****Figure 3: View of the four measurements points of the Tuffeau wall****Figure 4: Cross section of the measurements points in the Tuffeau wall and the insulation****Figure 5: Decrement factor of the measurement points in the wall before and after insulation****Figure 6: Time lag of the measurement points in the wall before and after insulation****Figure 7: Outdoor and indoor temperature variations before insulation (18th August of 2012)****Figure 8: Outdoor and indoor temperature variations after insulation (21st July of 2013)****Figure 9: Decrement factor of 18 room cases****Figure 10: Time lag of 18 room cases****Figure 11: Percentage of time with indoor temperature superior to 27°C****Figure 12: Correlation between thermal inertia and indoor summer comfort**

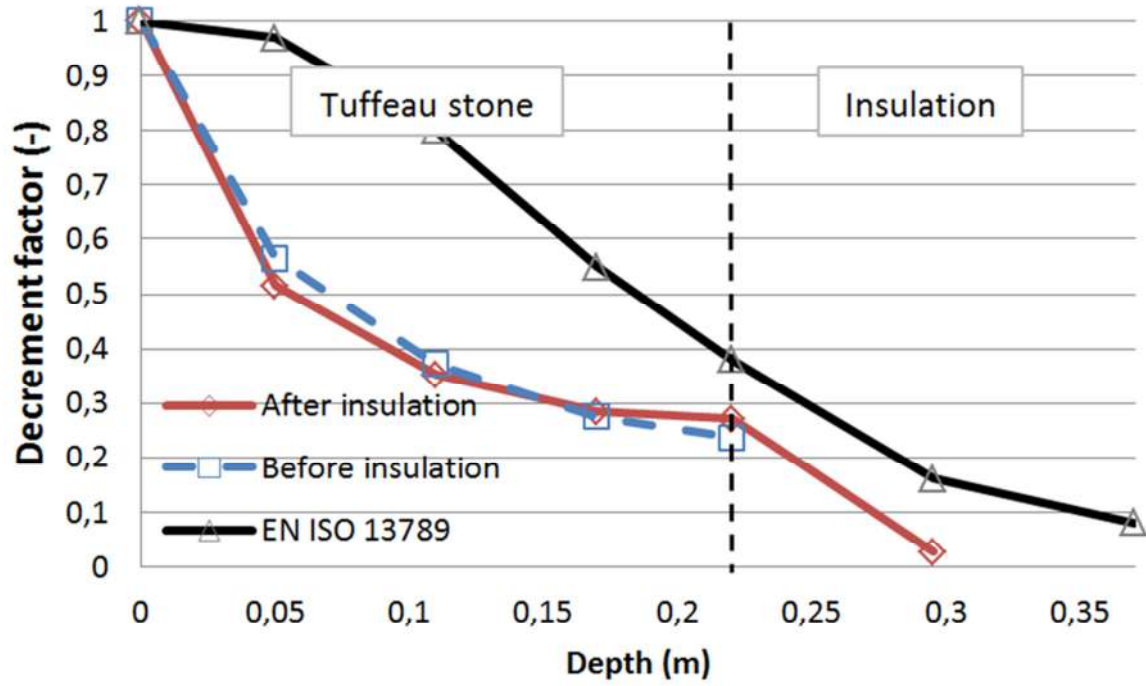


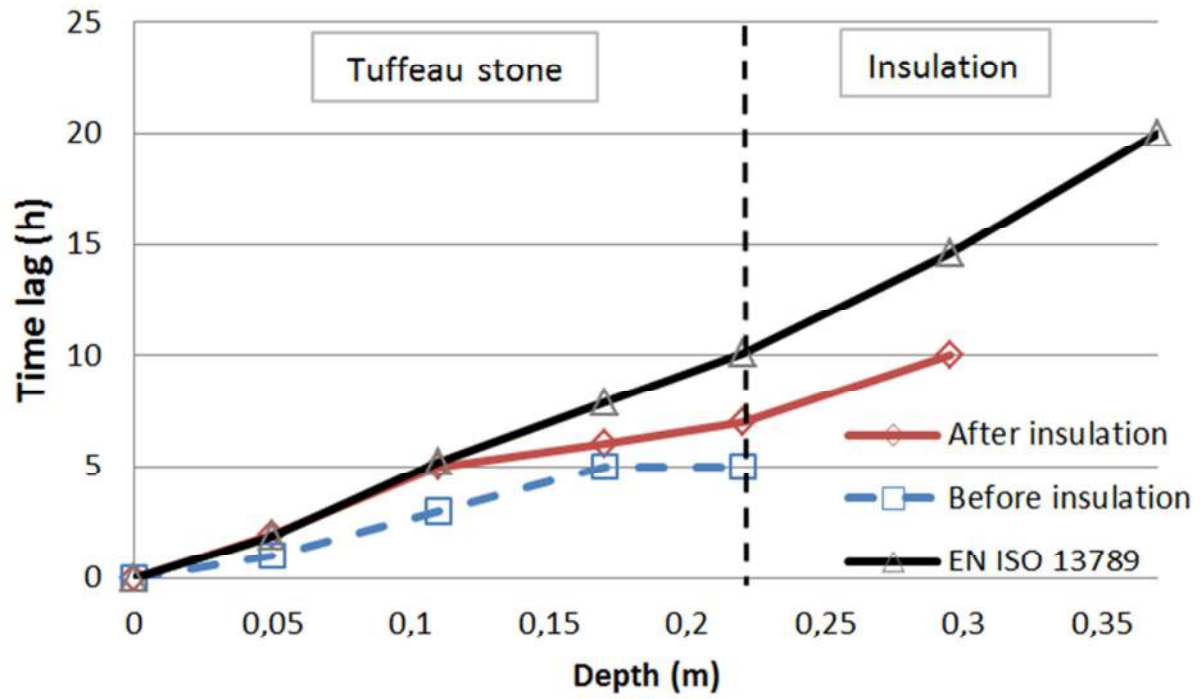


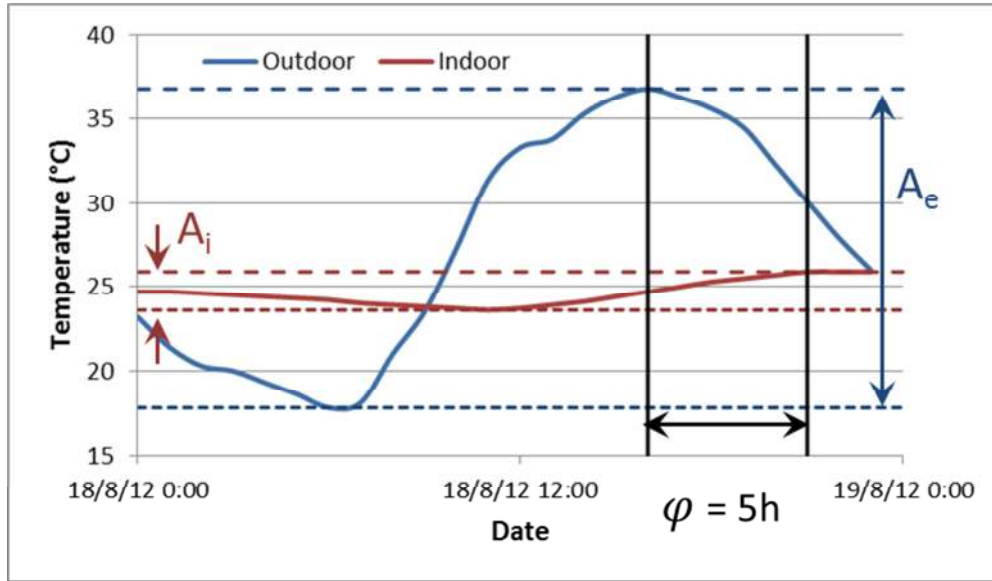


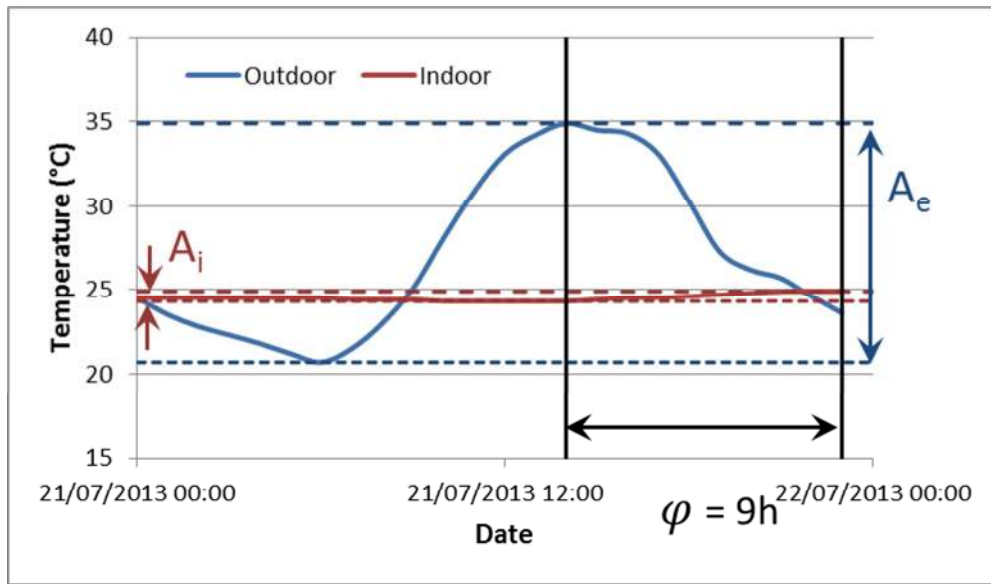
ACCEPTED

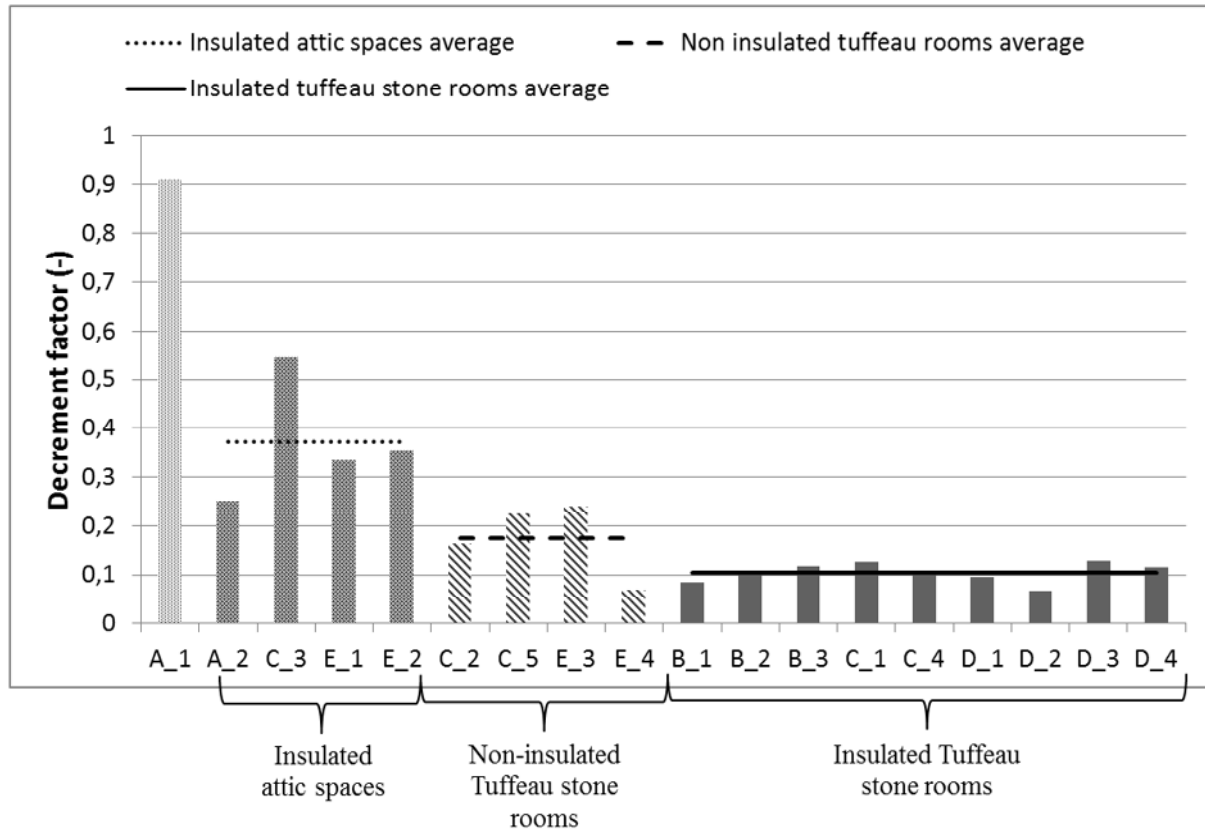


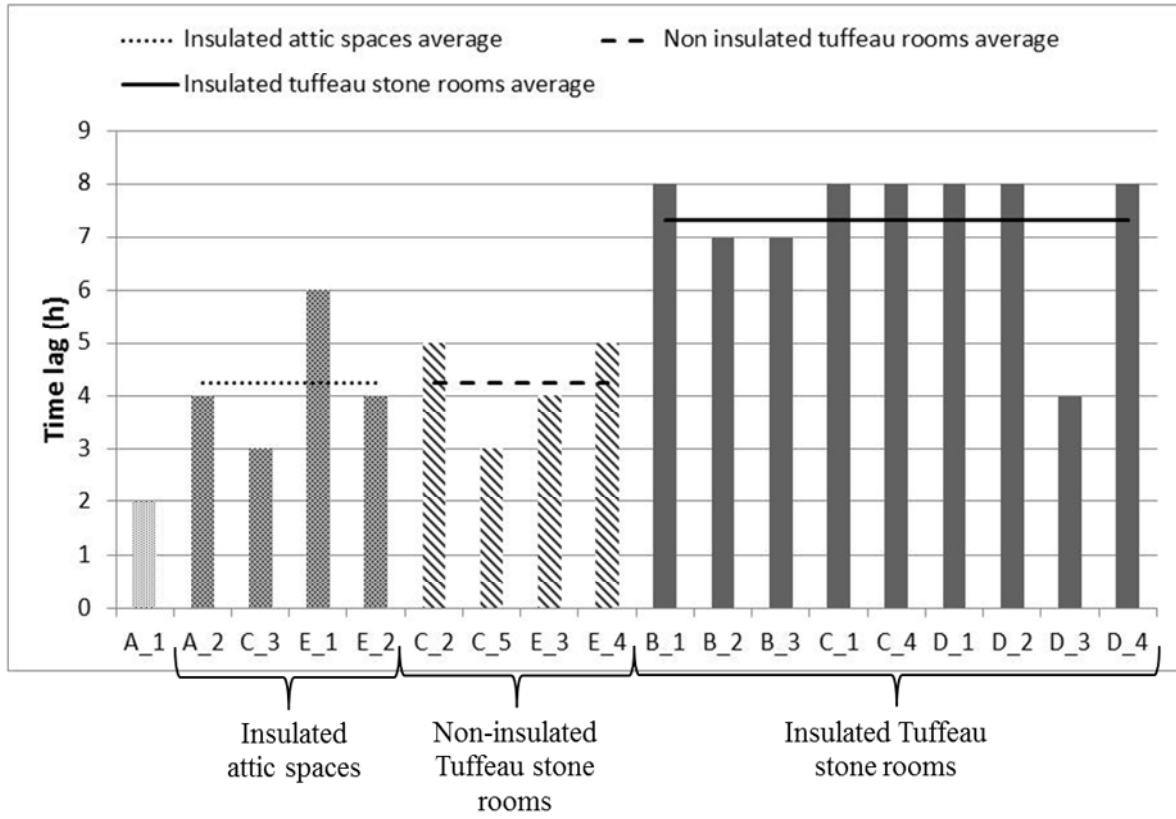


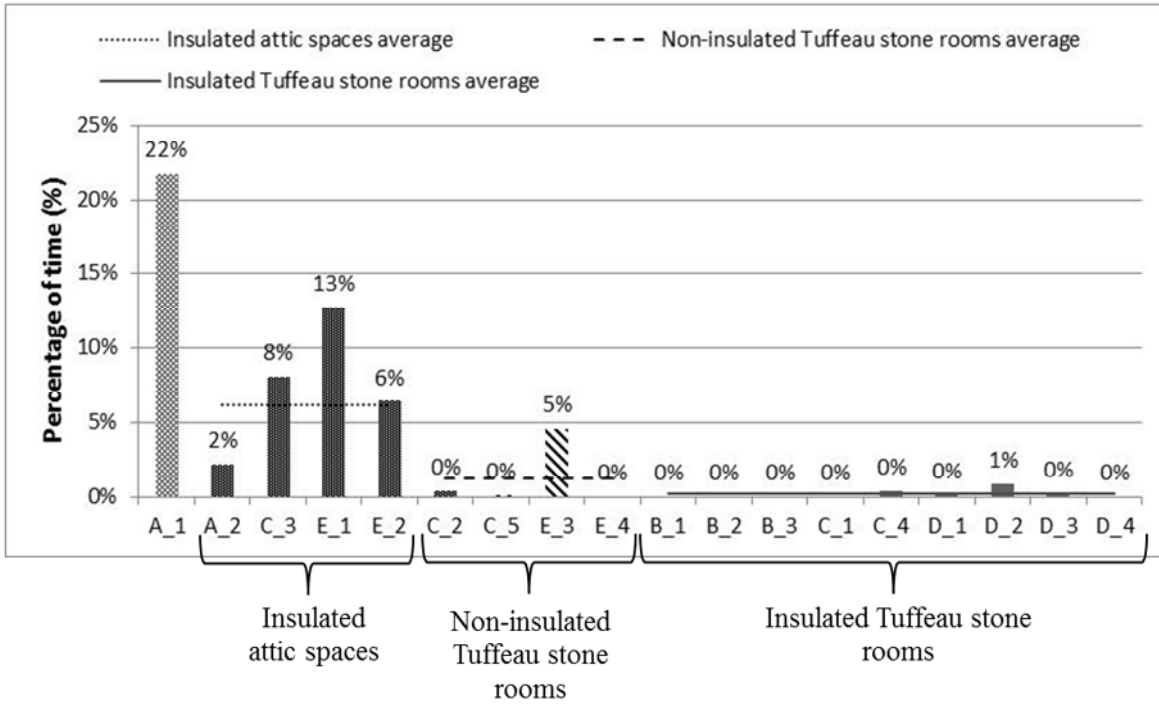


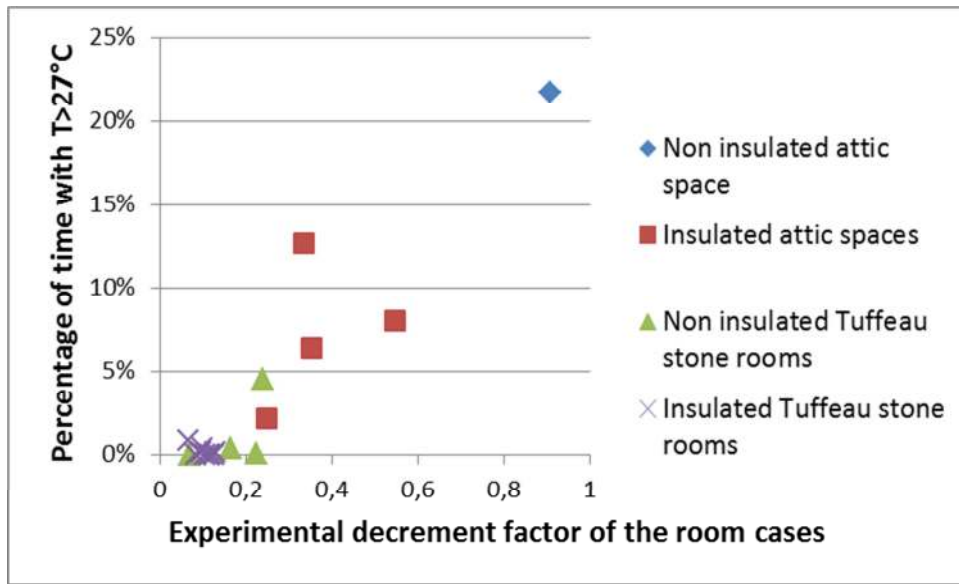












Highlights

Temperatures have been monitored in 5 old limestone buildings.

Thermal inertias of these cases have been calculated.

Internal insulation improves thermal inertia indicators in old limestone buildings.

There are not overheating conditions in non-insulated and insulated limestone rooms.