Life Cycle Assessment of alveolar brick construction system incorporating phase change materials (PCM)

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Abstract

An evaluation of the environmental impact of construction systems that are composed of facades based on alveolar bricks and macroencapsulated phase change materials done using Life Cycle Assessment (LCA) is presented. Their energy consumption rates for both heating and cooling have been measured and registered in two experimental cubicles located in Puigverd de Lleida (Spain). This work examines if the reduction of the environmental impact that is reached due to the energy savings achieved during the operational phase of these cubicles compensates the increase of the environmental impact that is induced during the manufacturing phase. Theoretical case studies, such as assuming different climatization and weather conditions, are proposed and studied to determine the most suitable climatic conditions for using the alveolar bricks and PCM technologies. Within the context of the LCA study, it is concluded that the overall benefit of PCM is the highest when summer weather conditions throughout the whole year is theoretically assumed, where for different assumed lifetime periods of the cubicles the reduction of the overall global impact of the cubicle containing PCM ranges from 12 % to 14 % in comparison to the other cubicle without PCM.

Key-words: Life Cycle Assessment (LCA), phase change materials (PCM), thermal energy storage (TES), buildings, energy efficiency.

1. Introduction

The increasing consumption of natural resources during the last years is clearly represented by the high consumption rates of the building sector. For example, the energy demand for cooling and heating in buildings is increasing significantly, and thus, it is contributing largely to the total energy consumption and CO_2 emissions. The contribution of the corresponding energy consumption has been estimated to be around 40 % in Europe [1], demonstrating the huge potential for improving the energy efficiency of buildings. This can be done through modifying the constructive systems by using specific building technologies (such as trombe walls or double skin facades), insulating materials, and a recently applied technology, which is the incorporation of phase change materials into the building structure in order to increase the thermal energy storage capacity of envelopes and floors. The reduction of energy consumption and other natural resources during the operational, manufacturing and disposal (dismantling) phases of buildings can reduce the impact on the environment, achieving a more sustainable and environmentally friendly building sector. The criteria for analyzing the opportunities of achieving the required sustainability can be applied through adopting a Life Cycle Assessment (LCA) approach.

LCA is a tool for evaluating the environmental impact of a product through analyzing the corresponding life cycle phases from cradle to grave. In case of buildings, LCA is mainly used to evaluate the environmental impact during the manufacturing phase, the operational phase and the dismantling phase. For example, LCA has been recently used in order to analyze the energy supply and installations in Spanish buildings [2]. A state of the art regarding the use of LCA in the building sector has been carried out by Zabalza et al. [3]. This research also proposes a simplified criterion for applying LCA in order to overcome the complexity of the analysis and the difficulties related to the energy certification applications. In addition, new methodologies and calculation methods are under research and development [4] and the influence of some simplifications is being investigated [5].

Papadopoulos and Giama [6] have applied LCA in order to examine the buildings environmental performance evaluation through insulation materials selection. In this study, it has been concluded that the use of the environmental performance evaluation in the building sector can help verifying the impact of insulation on energy consumption. Another study conducted by Huberman and Pearlmutter [7] has focused on evaluating the environmental impact of specific building materials showing that the impact of their embodied energy represents about 60% of the over all life cycle energy consumption. Kofoworola and Gheewala [8] have conducted an LCA approach to examine the environmental impact of a typical commercial office building in Thailand, verifying that the operational stage is the predominant one in case of commercial buildings. Moreover, twenty five commercial buildings in Hong Kong have been studied by Chau et al. [9] highlighting the most impacting building materials and building services materials as well. All these studies demonstrate the significance of using LCA in order to examine the construction solutions, and search for alternative ones that achieve the required level of sustainability.

Many constructive systems that encompass different building materials have appeared and have been considered in the recent years in order to improve the thermal behaviour of buildings; some of these solutions are trying to simplify the construction process as well [10]. For example, the use of a simpler construction system based on alveolar bricks instead of the common systems based on conventional bricks, air gap and insulating materials has been introduced in the last years with the aim of reducing the construction process time and complexity, and increasing the thermal inertia of the building walls. This solution has been further improved by embedding phase change materials (PCM) in the building envelope in order to further increase the thermal inertia of the whole system and hence reduce energy demand; this is especially important for reducing the cooling demand as it has been verified experimentally [11,12]. Besides, using the alveolar brick construction system without insulation has been proved to achieve similar energy savings to those accomplished by the conventional brick construction solutions that incorporates insulation materials. This conclusion is attributed to the high thermal inertia provided by the alveolar bricks constructive system [13,14]. However, an LCA is still needed in order to determine the global benefits of such solutions including the contribution of the relevant life cycle phases and taking into consideration the possible burdens shifting from one life cycle phase to another due to the use of such emerging technologies within the construction systems.

Thus, the LCA approach in this article is applied to two experimental house-like cubicles that are made of alveolar bricks (with inner dimensions of 2.4x2.4x2.4 m) located in Puigverd de Lleida (Lleida, Spain). The location of the experimental setup represents a typical continental Mediterranean climate that is characterized by cold winters and dry hot summers. The list of the materials used in the cubicles construction process will be used in evaluating the environmental impact of the manufacturing and dismantling phases. The temperature variations and the energy consumption rates of these cubicles have been monitored. The registered energy consumption values of the heating/cooling systems will be used for the operational phase impact evaluation [12]. Also, some theoretical case studies, such as different weather conditions and different heating and cooling methods, are studied in order to determine the most suitable conditions for using these technologies (alveolar bricks and phase change materials).

Finally, these results will be compared to the ones obtained in a previous work [15] for three other cubicles that are built using a typical Mediterranean constructive system based on conventional bricks, air gap and insulation. The inclusion of PCM (Paraffin RT27 with peak melting point of 28 ºC, and salt hydrates SP25 A8 with peak melting point of 26 ºC, both PCMs from Rubitherm) in that type of systems has been examined as well.

2. Methodology

2.1. Construction solutions of the studied cubicles

An LCA study is conducted to evaluate the environmental impact of two house-like cubicles located in Puigverd de Lleida (Lleida, Spain) (Figure 1), both of them with facades built with alveolar bricks; one without PCM (ALV), and the other one with the inclusion of macroencapsulated PCM. The PCM used is salt hydrates SP-25 A8 encapsulated in CSM (Compact Storage Modules) panels from Rubitherm [16] with melting temperature peak of about 28 ºC (ALV+PCM). The PCM panels are installed internally on the south and west walls and the roof. The envelope of the cubicles is composed of walls of alveolar bricks with interior coat of plaster and exterior coat of cement mortar (Figure 2 and Figure 3). The roof structure is based on a concrete precast beam, 5 cm of concrete slab, interior coat of plaster, insulating material (polyurethane), exterior coat of cement mortar and a double asphalt membrane that acts as a water proofing layer.

The LCA results of the two alveolar brick cubicles presented in this work are to be compared to the results of another study that comprises three cubicles built using conventional bricks [15]. Those three cubicles are: a reference cubicle (REF - no insulation is installed on the walls), a polyurethane cubicle

(PU - 5 cm of sprayed polyurethane is installed on the south and west walls and the roof), and a polyurethane with PCM cubicle (PU+PCM – macroencapsulated RT-27 PCM and 5 cm of polyurethane are installed on the south and west walls and the roof). The envelope of each cubicle (described in [15]) is composed of an interior coat of plaster, perforated bricks, air gap, hollow bricks, and an exterior coat of cement mortar. The roof structure is the same as that of the alveolar brick cubicles.

The construction materials of the considered cubicles constitute the inventory list that is needed to perform the impact assessment of the manufacturing and dismantling phases.

2.2. Experimental set-up characteristics

Inside the studied cubicles, the temperatures values and the energy consumption rates are monitored and registered. Pt-100 DIN B probes calibrated with a maximum error of ± 0.3ºC are used for measuring the surface temperatures of the walls and the roofs. A temperature transmitter for HVAC applications (ELEKTRONIK EE21FT6AA21) with accuracy of ± 2 % is used for measuring the internal humidity and air temperature. The energy consumption rates of the HVAC systems (heat pumps and electrical oil radiators) are measured with an electrical network analyser ARDETEM PECA 15. The energy consumption values are required to evaluate the environmental impact of the operational phase of the cubicles in order to quantify the impact induced during that phase.

2.3. Life Cycle Assessment (LCA)

According to the ISO 14040-43 standard series [17-20] that are specified for LCA, recommended steps are suggested in order to perform an LCA study efficiently:

- Definition of goal and scope
- Inventory analysis
- Impact assessment
- Interpretation of results

The impact assessment step is the most data intensive within an LCA study; it is considered as a critical step because of the involvement of complex environmental modelling that result in transforming the inventory list into impact categories that express the potential impact on the environment represented by the final indicators. Thus, several impact assessment methodologies have been developed in order to resolve this complexity, saving time and effort for the LCA practitioners and reducing the uncertainties in the data and environmental models. These methodologies are also called Life Cycle Impact Assessment (LCIA) methodologies [21,22]. The methodology used for performing the LCA study in this article is based on the impact assessment methodology Eco-Indicator 99 (EI99) [23] using the database EcoInvent 2009 [24]. More information about the EI99 methodology will be detailed in the following subsections. This is the same impact assessment methodology that has been used in [15] so that the results of both articles can be compared. The LCA steps recommended by the ISO 14040-43 standard series are to be applied in the following subsections.

2.3.1. Goal and scope definition

The aim of this study is to apply the LCA concept in order to examine the environmental impact of two house-like experimental cubicles that are mainly built using alveolar bricks and include phase change materials (Salt hydrates SP-25 A8 from Rubitherm). Furthermore, the results of this assessment are to be compared to the results of a previous work [15] regarding three cubicles of the same experimental set-up. The life cycle phases considered are the manufacturing, dismantling and operational phases. Based on [5], the construction of the cubicles is not taken into account since it has little impact and can be omitted.

The general conditions assumed for applying the LCA in the two studied cubicles are as follows:

- The considered lifetime for a cubicle is 50 years.
- In order to simplify the analysis and to be consistent with the assumptions set for the previous study [15], the maintenance operations of the cubicles and the HVAC systems are considered equal for the ALV and PCM cubicles. Hence it does not produce any difference in the overall global impact. Notice that the cubicles structures are similar and the aim of the work is to compare between relative differences, this assumption will not significantly affect the results.
- The electricity used considers the production mix corresponding to the Spanish energy production system.
- No data is available in the EcoInvent database about the disposal of salt hydrates. Its value is estimated considering the same percentage for all the other used components to the total impact.

This estimation method is also used in [15] to calculate the disposal impact of PCM and does not affect significantly in the LCA study, since the disposal of both PCM (paraffins and salts hydrates) represents less than the 0.01% of the impact during the manufacturing and dismantling phase.

- In order to compare the results of this article with those obtained in [15], the results of the manufacturing and dismantling phases are aggregated into one phase (Manufacturing/dismantling phase).
- As detailed in subsection 2.2, to evaluate the operational phase impact, the measured energy consumption values from the cubicles are used (Table 2). Within this context, three different periods per year are defined:
    - Winter period: 4 months with similar heating demand to the third week of February 2009. Comfort conditions are achieved using an electrical oil radiator with a set point of 24 ºC [25].
    - Summer period: 4 months with similar cooling demand to the fourth week of August 2009. Comfort conditions are achieved using a heat pump with a set point of 24 ºC [25].
    - No controlled temperature: 4 months without temperature control.

LCA is accomplished for the following three theoretical case studies:

1. Heat pump case study: a heat pump is used instead of the electrical oil radiator during the winter period to reduce the energy consumption for heating. This reduction is evaluated by the Coefficient of Performance of the heat pump (COP considered as 3).
2. Summer weather conditions case study: since the selected PCM melts/solidifies around 28ºC, then, in Mediterranean weather conditions, it only operates during the summer season. In order to increase its cycling throughout the year summer weather conditions are assumed to be predominant during the whole year (summer period of 12 months). This scenario might be used to study the environmental impact of using PCM in the building envelopes in a location with these constant hot environmental conditions over the year.
3. Extension of the cubicles lifetime: some studies consider buildings lifetime to be between 50 and 100 years 0~~[26]~~, 0~~[27]~~. Therefore, a parametric study considering 75 and 100 years lifetime for the cubicles is also presented.

2.3.2. Inventory analysis

In this step, the inventory list of all the materials used in the manufacturing/dismantling phase of the cubicles is shown. The energy consumption rates of the studied cubicles are quantified as well. The correlation between the cubicle components used in the manufacturing/dismantling phase and the EcoInvent data base is shown in Table 1. The measured energy consumption values for heating and cooling are shown in Table 2.

2.3.3. Impact assessment

According to the EI99 methodology and the requirements of this study, the environmental impact is evaluated and expressed through ten damage categories (Acidification & eutrophication, ecotoxicity, land occupation, carcinogenics, climate change, ionising radiation, ozone layer depletion, respiratory effects, fossil fuels, and mineral extraction). Those damage categories are further aggregated into three areas of protection that express the main aspects of environmental and societal concern: Human health, Eco system quality and natural resources. After extracting the inventory data needed from the data base, each damage category is evaluated according to equation (1):

$$IMP_j = \sum_k d_{k,j} \cdot LCI_k \quad (1)$$

Where IMP_j is the j damage category, d_{kj} is the coefficient of damage extracted from the considered database [23] associated with the component k and damage j, and finally the LCI_k is the life cycle inventory entry (i.e. kg of polyurethane). The results of equation (1) are single score indicators representing the potential impact on the environment through different damage categories. The coefficient of damage for the natural resources damage category is expressed in MJ of surplus energy needed for future extraction. For the ecosystem quality damage category, the coefficient of damage stands for the loss of species over a certain area, during a certain time (% plant, species / $m^2 \cdot$year). Finally, the damage to human health is expressed as the number of years life lost and the number of years lived disabled (disability adjusted life years, DALYs).

The absolute value of these points is not very relevant as the main purpose is to compare relative differences between products. Lower impact score results mean lower impact on the environment and hence mean that the product associated with the results is more environmentally sound. These single score indicators from the EI99 methodology are convenient for the case studies of this article, as the impact of the cubicles and their relevant components on the environment can be easily interpreted and demonstrated [28].

3. Results and discussion

In this section, the results of the impact assessment phase are interpreted and the environmental impacts caused by the studied cubicles and their components are evaluated. This is considered to be the fourth and last step within an LCA.

3.1. Life Cycle Assessment of the real case study

3.1.1. Manufacturing/dismantling phase

A list of all the materials used in the construction of the studied cubicles and their environmental impact during the manufacturing/ dismantling phase is shown in Table 3.

The component with the highest impact is the alveolar brick, with an impact around 66 % and 61% from the total in the ALV and ALV+PCM cubicles, respectively. In the ALV+PCM cubicle, PCM and aluminium represent about 4 % and 3.7 % of the total impact, respectively.

The impact of each damage category during the manufacturing/dismantling phase is shown in row A of Table 4. The inclusion of macro-encapsulated PCM increases the environmental impact by 8% during the manufacturing/dismantling phase.

3.1.2. Operational phase

The measured energy consumption values for heating and cooling (Table 2) are used to determine the impact during the operational phase of the cubicles. The impact of each damage category during the operational phase for the real case is shown in rows B and D of Table 4.

For the winter period (row B of Table 4), no difference can be observed between the cubicles due to the addition of PCM, since in cold weather conditions, temperatures do not reach the melting point of the PCM; hence no energy savings are achieved [12].

For summer period (row D of Table 4), the addition of PCM to the alveolar cubicle reduces the operational environmental impact by about 17 %. However, as it has been proved in previous experimental results [12], the rates of electrical energy consumption during the winter period are more than ten times higher than those during the summer period for the two cubicles. Thus, the effect of PCM, which is only effective under summer weather conditions, remains small. Those findings are represented by the year-round results of the operational impact of the ALV+PCM cubicle, which is only 1.3 % lower than that of the ALV cubicle.

3.1.3. Global results

Table 5 and Figure 4 show the results of the manufacturing/dismantling phase combined together with the operational phase for the real case. As expected, the cubicle with PCM presents the highest impact during the manufacturing/dismantling phase and the lowest impact during the operational phase. The inclusion of the PCM does not affect significantly the overall global impact (reduction percentage of about 0.8 %). Thus, this insignificant difference in the global impact points can be attributed to the following reasons:

- The impact reduced during the operational phase is balanced out with the high impact induced during the manufacturing phase of the cubicle.
- The energy consumption needed for heating is about ten times higher than that required for cooling.

- The operation period of the PCM is short, since it is active only during summer period, and hence the energy savings and the reduced impact on the environment are benefitted from during a short period.

In the considered life cycle phases, it is noticed that the damage categories that contribute significantly to the total impact points are the fossil fuels and the respiratory effects.

3.2. Life Cycle Assessment for the theoretical case studies

3.2.1. First theoretical case study: heat pump

In this case study, the electrical oil radiator is replaced by a heat pump as a heating system, reducing the operational impact of the cubicles during winter to one third due to a much higher efficiency (COP considered as 3). Row C of Table 4 and Figure 4 present the results for this case study. The important reduction of the operational impact during winter helps in highlighting the behaviour of the PCM during summer.

3.2.2. Second theoretical case study: summer weather conditions throughout the whole year

Previous experimental results [12] show that the use of PCM reduces the energy consumption and hence the environmental impact during summer since the PCM only works under these conditions. Therefore, the use of this technology in regions where summer weather conditions are predominant throughout the whole year is expected to achieve much better results regarding the energy savings and hence the environmental impact reduction.

Row E of Table 4 shows the operational impact results of the two studied cubicles in these conditions where 50 years of lifetime is assumed. Considering the global results for this case study, as shown in Figure 4, the addition of PCM to the ALV cubicle reduces the impact by about 12 % (ALV+PCM), which is considered the best case study regarding the impact reduction achieved as a result of using PCM.

3.2.3. Third theoretical case study: extension of the cubicles lifetime to 75 and 100 years

As it has been previously discussed, the use of PCM reduces the environmental impact during the operational phase but increases it during the manufacturing phase. Therefore, a longer lifetime operation of buildings will result in a reduction of the global impact when using PCM. Depending on some studies [26,27], different lifetime periods are estimated for buildings. Here, the environmental impact of the cubicles is evaluated considering 75 and 100 years of lifetime in order to analyze the payback time of applying the suggested construction system.

This case study is considered as a two-layer theoretical case study, where the first layer is extending the lifetime of the cubicles to 75 and 100 years, and the second layer evaluates each scenario, which are: using electrical oil radiator (as in the real case study), using a heat pump (the first theoretical case study) and assuming summer weather conditions throughout the whole year (the second theoretical case study).

As it is expected, results show that when the lifetime of the cubicles is extended and PCM is extensively used (summer conditions), slight increments in the global impact reduction are noticed between the two cubicles. In the case of 50 years life time, the ALV+PCM cubicle impact score points is about 12% lower than that of the ALV cubicle, while in case of 75 and 100 years life time, this difference is increased to be around 14% (Only 2% more of impact reduction) (Figure 4 to Figure 6).

3.3. Comparison of the results of the alveolar brick cubicles with the conventional brick ones

In a previous work, an LCA study was applied for three monitored cubicles with a construction system based on conventional bricks [15]. In that study, and specifically for the real case study (based on experimental results) of using an electrical oil radiator during winter and assuming a lifetime of 50 years for the cubicles, an impact reduction in the global impact of about 37% is recognized when PU is added to the reference cubicle. This reduction is achieved due to the decrease of the energy consumption in the operational phase for the cubicle insulated with PU, since the thermal transmittance of its walls has become much lower after adding the PU insulation. Besides, it was concluded that the addition of PCM does not lead to significant variations in the global impact results (only 0.4%) because the impact savings achieved during the operational phase are balanced out with the high impact generated during the manufacturing phase. Besides, it is important to highlight that PCM is not working during winter season, which means that no energy savings are achieved during winter. Moreover, as it has been verified experimentally, the energy consumption required for heating is about ten times higher than that required for cooling. These facts have to be taken into consideration when observing the insignificant variation that may occur in the global results.

A wider comparison that includes the real case study and the theoretical case studies between both construction systems (conventional and alveolar brick) with and without the inclusion of PCM can be done. It must be considered that real construction systems are studied and therefore the different facades do not present the same thermal transmittance in steady-state. The comparisons are highlighted as follows:

- For the real case study, the reference cubicle presents the highest impact due to the lack of thermal insulation; this lack of insulation causes more heat flux through the cubicle envelopes and consequently leads to higher energy consumption rates for both heating and cooling demands. On the other hand, the lowest impact score is achieved by the PU and PU+CM cubicles (impact reduction of about 37% compared to the reference cubicle). However, the PU and the PU+PCM cubicle and all the other cubicles present very similar global impact results, with maximum differences of 2 % (Table 5). These results show that both insulated conventional bricks and alveolar bricks construction systems are comparable for Mediterranean continental climate conditions.
- Also, the reference cubicle presents the highest impact for all the different damage categories. This is due to the higher energy consumption of this cubicle during the operational phase. Since the most of the electrical energy production is mainly based on fossil fuels, it strongly affects all the damage categories, especially fossil fuels and respiratory effects. On the other hand, the energy consumption rates for the other 4 cubicles (PU, PU+PCM, ALV, and ALV+PCM) are very similar.
- For summer weather conditions throughout the whole year (the best case study for the PCM regarding the global impact reduction), and by excluding the reference cubicle from the comparison, it is found that the ALV cubicle represents the highest global impact points among all the cubicles. The global impact of the PU cubicle is about 13.5 % lower than that of the ALV cubicle. Only by using PCM within the alveolar construction system (ALV+PCM) the global

impact is reduced to a similar value to that of the PU cubicle. However, the PU+PCM cubicle further reduces the global impact (Figure 4). Therefore, in case of predominant summer weather conditions, the use of insulated conventional brick systems is much better than alveolar brick ones. Besides, the use of PCM in both construction systems presents similar reductions in the global impact (within the range of 10-12 %).

- For the case study of extending the lifetime of the cubicles to 75 and 100 years, the reference cubicle, as expected, presents the highest impact. In case of assuming summer weather conditions throughout all the year, the PU cubicle achieves a reduction in the global impact with respect to the ALV cubicle of about 16%. This reduction value is further increased to 26% in case of adding PCM (PU+PCM cubicle). Adding PCM to the ALV cubicle decrease the impact points to a value that is similar to that of the PU cubicle. (Figure 5 and Figure 6).

4. Conclusions and recommendations

The environmental impact of alveolar brick construction systems with and without phase change materials (salt hydrates SP-25 A8 from Rubitherm) is analyzed using an LCA approach based on the Eco-Indicator 99 methodology (EI99). The study is applied to real monitored cubicles; other theoretical case studies as well are investigated concerning different weather and operating conditions.

The use of PCM did not significantly reduce the overall environmental impact under the experimental conditions considered. However, for some theoretical scenarios, the environmental benefits achieved by the PCM are enhanced (12-14% reduction in comparison with no PCM).

From this work, some recommendations about the use of PCM in buildings can be drawn:

- A higher storage capacity of the PCM may result in higher energy savings and therefore in a larger reduction of the environmental impact during the operational phase.
- Developing phase change materials with lower embodied energy can help achieving sustainability within the life cycle of buildings by reducing the impact on the environment while avoiding the possible shifting of burdens of the operational phase to the manufacturing phase.

- Locations with weather conditions (and with daily temperatures around the phase change temperature of the PCM) that ensure a much longer operation of the PCM will increase the environmental impact reduction during the operational phase.
- Long term operation of buildings will also reduce the environmental impact when using PCM, as shown in the case studies with extended lifetime for the cubicles (75 and 100 years). However the improvements were low (difference about 1-2 % compared to that of the case studies assuming 50 years lifetime).
- The use of PCM that melts/solidifies within suitable temperature range during winter periods presents a huge potential to reduce the energy consumption, since the energy demand for heating is more than ten times higher than that for cooling.
- For Mediterranean continental climate, the global impact induced by insulated conventional brick and alveolar brick construction systems is comparable. On the other hand, for summer predominant weather conditions, the use of insulated conventional brick construction system is better than the alveolar brick
- Increasing the dependency of energy supplies on renewable energy resources can reduce significantly the impact related to the fossil fuels and respiratory effects damage categories. And consequently, within the different LCIA methodologies and the associated databases, considering the environmental impact using independent on-site renewable energy resources for manufacturing of building materials will be a necessity in this case.

Moreover, new materials with lower environmental impact must be developed. This requires a new perspective when defining the desired properties and producing the materials. Nowadays only the technical specifications are considered, but in the future also the environmental ones should be included. For phase change materials, the improvement of the PCM and also its encapsulation must be considered.

Acknowledgments

The work was partially funded by the Spanish government (projects ENE2008-06687-C02-01/CON and DPI2008-04099) and the European Union (COST Action COST TU0802), in collaboration with the company Hyspalit and City hall of Puigverd de Lleida. The authors would like to thank the Catalan

Government for the quality accreditation given to their research group (2009 SGR 534). Lídia Rincón would like to thank the University of Lleida for her research fellowship.

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Figure captions

Figure 1. Experimental cubicles in Puigverd de Lleida (Lleida, Spain).

Figure 2. Construction system of the Alveolar brick cubicle.

Figure 3. Construction system of the Alveolar brick +PCM cubicle.

Figure 4. Impact results for each cubicle and studied scenario for a lifetime of 50 years. Comparison between conventional (De Gracia et al. 2010) 0~~[15]~~ and alveolar construction system.

Figure 5. Impact results for each cubicle and studied scenario for a lifetime of 75 years. Comparison between conventional (De Gracia et al. 2010) 0~~[15]~~ and alveolar construction system.

Figure 6. Impact results for each cubicle and studied scenario for a lifetime of 100 years. Comparison between conventional (De Gracia et al. 2010) 0~~[15]~~ and alveolar construction system.