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Reduction of the energy consumption of buildings by acting in the building envelope: materials and passive construction systems

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Universitat de Lleida

TESI DOCTORAL

"Reduction of the energy consumption of buildings by acting in the building envelope: materials and passive construction systems"

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Que la memòria “Reduction of the energy consumption of buildings by acting in the building envelope: materials and passive construction systems” presentada per Susana Serrano Rodríguez per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

Lleida, Agost de 2016

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Resum

Les emissions de gasos d'efecte hivernacle i el consum energètic dels edificis han anat incrementant de forma constant durant els últims quaranta anys, representant al 2010 el 25% de les emissions totals i el 32% del consum energètic a nivell global. Les institucions internacionals preveuen que aquestes emissions poden arribar a duplicar-se o inclús triplicar-se al 2050. Per tant, és necessari reduir el consum energètic dels edificis i els gasos d'efecte hivernacle per mitigar el canvi climàtic. Un dels objectius d'aquesta tesi és estudiar la tendència del consum energètic dels edificis residencials a Europa durant els últims vint anys i els principals condicionants que afecten aquest consum mitjançant la metodologia Kaya.

La Agència Internacional de la Energia recomana millorar l'envolvent de l'edifici amb materials i sistemes constructius apropiats com a principal acció per reduir el seu consum energètic. Per aquest motiu, aquesta tesi està enfocada principalment en millorar les propietats tèrmiques dels materials que formen l'envolvent mitjançant l'ús de materials de canvi de fase per l'emmagatzematge d'energia tèrmica en sistemes passius i/o materials sostenibles.

Per una banda, s'estudien les propietats en estat fresc i endurit de diferents tipus de guix amb materials de canvi de fase per a revestiments interiors. El fet d'afegir materials de canvi de fase pot fer variar les propietats d'aquests i, per tant, poden condicionar la seva implementació en l'edifici.

Per altra banda, s'estudien materials tradicionals a base de terra a escala de laboratori i a escala real. Adaptar aquest tipus de materials als requeriments actuals del edificis poden esdevenir una interesant solució per reduir el consum energètic dels edificis i el seu impacte degut a que són materials sostenibles, amb baix impacte ambiental i de baix cost econòmic.

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Resumen

Las emisiones de gases invernadero y el consumo energético de los edificios han crecido constantemente durante las últimas cuatro décadas, representando en 2010 el 25% de las emisiones totales y el 32% del consumo energético a nivel global. Las instituciones internacionales prevén que estas emisiones pueden llegar a duplicarse e incluso triplicarse en el año 2050. Por lo tanto, es necesario reducir el consumo energético de los edificios y los gases de efecto invernadero emitidos para poder reducir y mitigar el cambio climático. Uno de los objetivos de esta tesis es estudiar las tendencias del consumo energético de los edificios residenciales en Europa en las últimas dos décadas y los principales condicionantes que afectan a este consumo siguiendo la metodología Kaya.

La Agencia Internacional de la Energía recomienda mejorar la envolvente de los edificios con materiales y sistemas constructivos apropiados como principal acción para reducir su consumo energético. Por este motivo, esta tesis está principalmente enfocada a mejorar las propiedades térmicas de los materiales que conforman la envolvente mediante el uso de materiales de cambio de fase para el almacenamiento térmico de energía en sistemas pasivos y/o materiales sostenibles.

Por un lado, se estudian las propiedades en estado fresco y endurecido de diferentes tipos de yeso con materiales de cambio de fase para revestimientos interiores. La adición de estos materiales puede hacer variar las propiedades del yeso y, por lo tanto, condicionar su implementación en los edificios.

Por otro lado, se estudian a escala de laboratorio y real materiales compuestos a base de tierra. La adaptación de este tipo de materiales a las construcciones actuales puede ser una solución interesante para reducir el impacto ambiental y el consumo energético de los edificios ya que son materiales sostenibles, de bajo impacto ambiental y de bajo coste.

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Summary

Greenhouse gases emissions and energy consumption in buildings were constantly increasing the last 4 decades, representing 25% of total emissions and 32% of global final energy consumption in 2010. These emissions are expected to double or even triple by 2050 according to international institutions projections. Therefore, the reduction of greenhouse gases emissions and energy consumption becomes a necessity to encompass pollution and climate change mitigation. One of the objectives of this PhD thesis is to analyse the trends of the energy consumption of European residential buildings and the main drivers that conditioned heating and cooling energy use the last two decades following the Kaya identity approach.

The main action recommended by the International Energy Agency to reduce significantly the energy consumption in buildings is to improve their envelopes with appropriate materials and construction systems. For this reason, this PhD thesis is focused on materials with thermal properties improved using phase change materials (PCM) for latent thermal energy storage in passive systems and/or sustainable materials to be placed in building envelopes.

On the one hand, different methods to include PCM into common gypsum (all of them with no presence of leakage) are used to place gypsum PCM as interior coatings. A deep characterization regarding fresh and hardened state properties is done. Moreover, different parameters that could condition the implementation of these materials in the building site are also evaluated.

On the other hand, sustainable, low embodied energy and low cost earth-based materials are studied at laboratory and pilot plant scale. The adaptation of earth-based materials to current building requirements becomes interesting solution to reduce the energy consumption of building and their environmental impact.

Nomenclature

CRI Copenhagen Resource Institute

CO_2 Carbon dioxide

DoE Design of experiments

EPBD Energy performance of buildings Directive

EU European Union

EU27 European Union member states (includes: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom)

GDP Gross domestic product

GHG Greenhouse gases

H&C Heating and cooling

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

LCA Life cycle assessment

PCM Phase change materials

TES Thermal energy storage

UN United Nations

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1 Introduction

1.1 Energy consumption of the building sector in the world

Pollution and climate change is a “tragedy of the commons” (Hardin, 1968) because when a country pollutes or emits Greenhouse Gases (GHG) to the atmosphere, it causes harm around the world [1]. When analysing real data of carbon dioxide (CO_2) emissions (from 1961 to 2009) in the building sector in some influential regions such as United States, Europe and China (see Figure 1), results show that they have been constantly but slowly decreasing the last 40 years in Europe and United States. These regions are major players in the fields of global climate change and climate policy. However, Chinese building CO_2 emissions have been dramatically increasing [2] since 2002 due to its rapid economic growth. The reduction of global emissions will certainly benefit every country but this is going to be a challenging process from global and local levels.

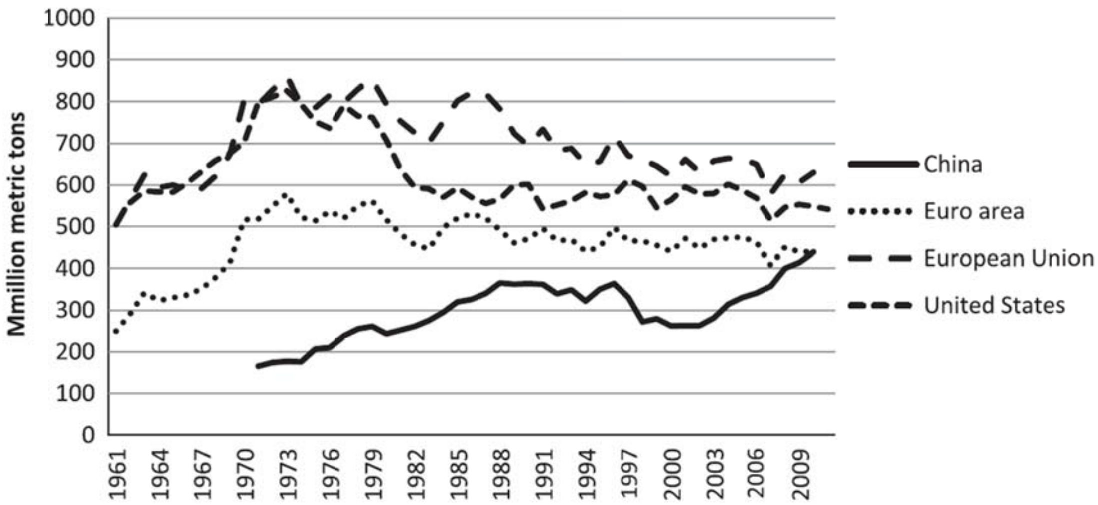

Figure 1. CO_2 emissions from buildings in some influential regions from 1961-2009 [2]

From a global point of view, GHG emissions in buildings were constantly increasing since 1970 till more than doubled in 2010 (Figure 2), representing 25% of total emissions in 2010 (including electricity-related emissions) [1]. Indirect CO_2 emissions from electricity use in buildings are the main cause of the constant growth of GHG emissions (direct emissions have stagnated in the same period). In residential buildings, indirect emissions have quintupled and in commercial buildings, quadrupled. Therefore, Figure 2 demonstrates the necessity of encompassing pollution and climate change together, from a global and local point of view, in order to achieve a real reduction of GHG emissions and climate change mitigation.

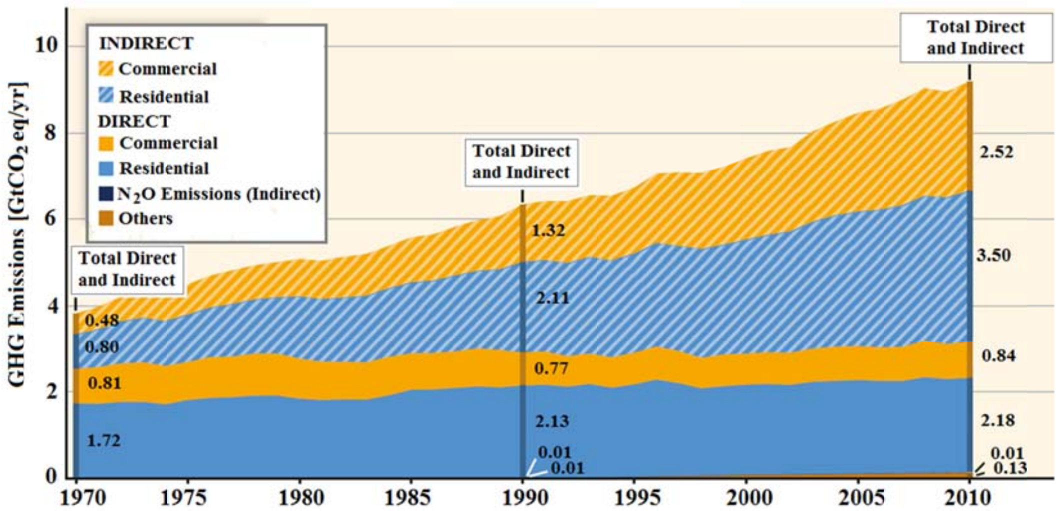

Figure 2. Direct and indirect emissions in the building sector from 1970 to 2010 [1]

International institutions focused on the reduction of building emissions, as the International Energy Agency (IEA), foresee an increasing trend of related emissions. These emissions are expected to double or even triple by 2050 because billions of citizens will gradually have an adequate housing, electricity and cooking facilities in developing countries. Furthermore, other important indicators as population growth, migration to cities, household size changes, increasing levels of wealth and lifestyle, among others, will also contribute to increase building emissions due to the higher energy consumption. Construction of new buildings in developing countries should be an opportunity to mitigate climate change but also it could have high risks.

According to the IEA, in 2010 buildings accounted for 32% of total global final energy consumption, being 24% for residential and 8% for commercial buildings. Taking into account the end-use, space heating and cooling (H&C) represented 34% and 40% of the total global final energy consumption in residential and commercial buildings, respectively, in 2010 (Figure 3) [1].

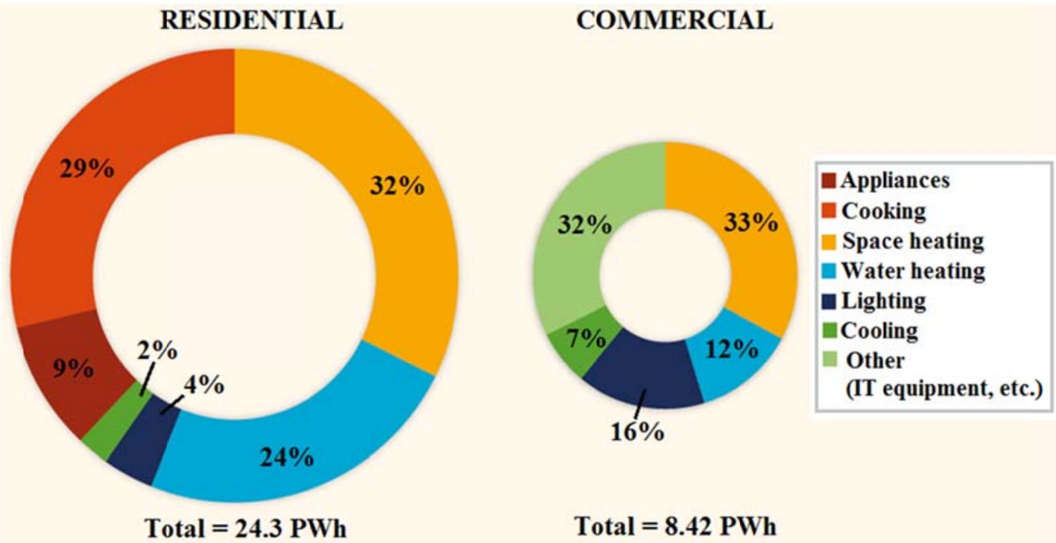

Figure 3. Total final energy consumption in buildings in the world, 2010 [1]

Although GHG emissions have grown dynamically, per capita final energy consumption did not grow in the last 20 years (since 1990 to 2010) in most world regions (see Figure 4). There are some exceptions where the per capita final energy consumption grew in residential buildings as the Former Soviet Union (FSU), North Africa (MNA) and Pacific Organization for Economic Cooperation and Development (POECD), and Western Europe (WEU), Eastern Europe (EEU) and Pacific OECD (POECD) in commercial buildings [1].

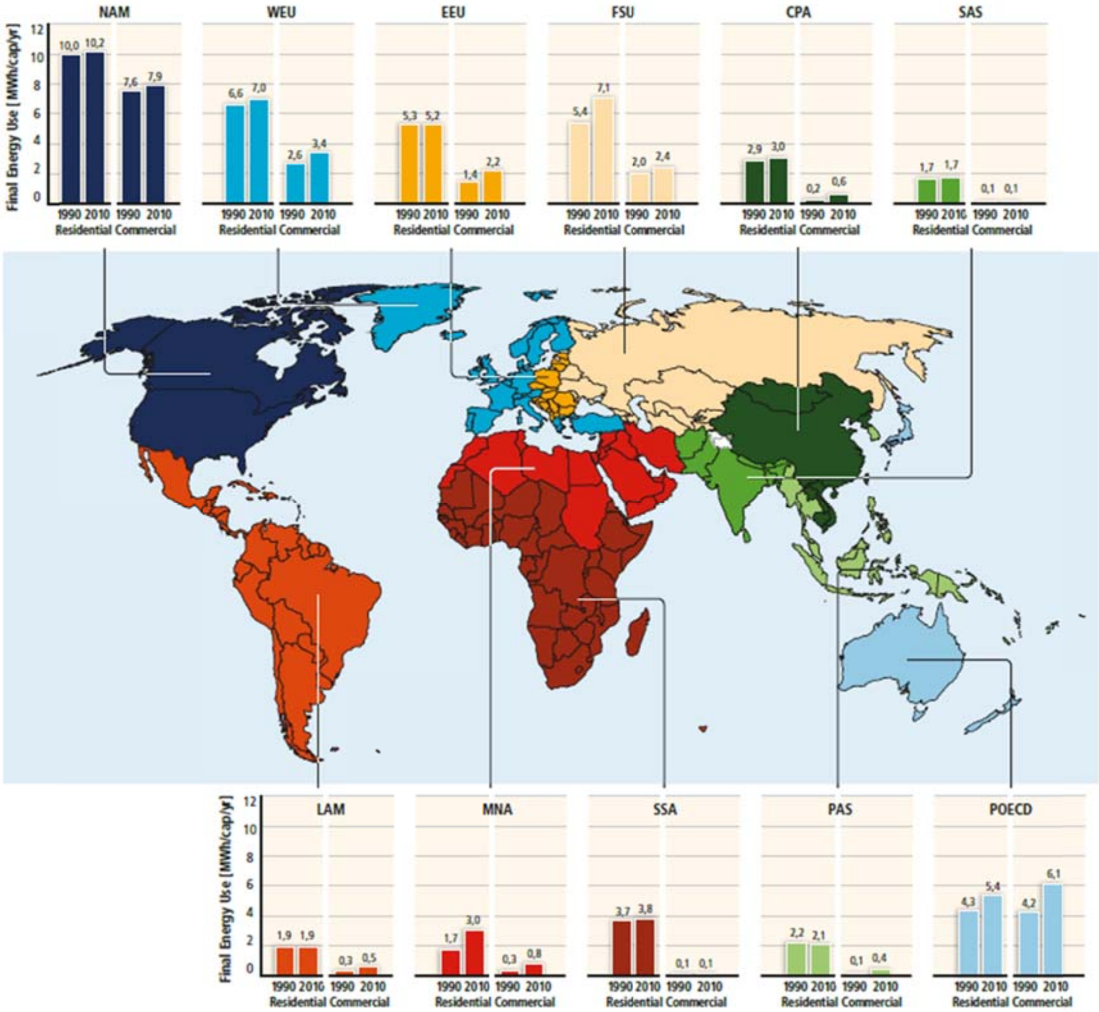

Figure 4. Annual per capita final energy use in residential and commercial buildings [1]

The candidate collaborated in a recent publication [3] that presented the trends in H&C energy use for historic, present and future and its main drivers on a global and regional basis. The data presented in the mentioned paper was consistent with data published in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1], previously shown in Figure 3 and Figure 4. In this paper [3], residential and commercial buildings H&C energy consumption where decomposed in different key drivers following the Kaya identity methodology. Number of households, persons per household, floor space per capita, and specific energy consumption for residential buildings were defined as key drivers; and gross domestic product (GDP), floor space per GDP, and specific energy consumption drivers were defined for commercial buildings. Data for the past and present was obtained from different official sources as the IEA and United Nations (UN) and, the future data was obtained from mathematical models to calculate future projections based on frozen efficiency scenario with the model 3CSEP-HEB (Centre for Climate Change and Sustainable Energy Policy - High Efficiency Buildings) developed by two of the co-authors in the Central European University in Hungary.

Results were presented, both globally for the world and for different world regions, following the IPCC aggregation [4] as Figure 4 shows. Global trends of energy consumption in residential and commercial buildings as well as its main drivers obtained are presented in Figure 5.

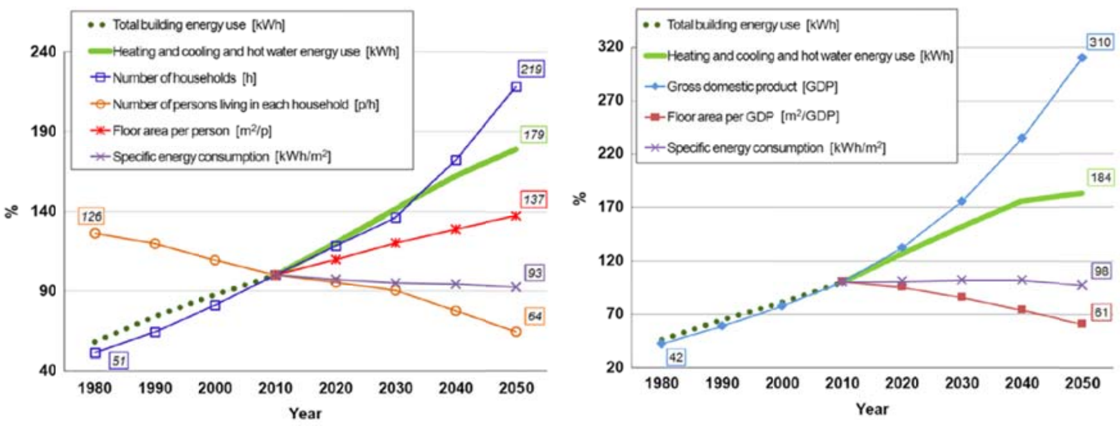

Figure 5. Trends in the drivers of residential (left) and commercial buildings (right) in the world from 1980 to 2050 [3]

In the frozen scenario used, H&C energy consumption is expected to increase until 2050, by 80% in both, residential and commercial buildings. The strongest increase was seen in the number of households' driver in residential buildings (Figure 5 left), but the number of persons living in each household was constantly decreasing and will decrease maybe due to different factors as the rapid urbanization, divorce rates, mobility of young people, and population decline, among others, that will increase the energy consumption of buildings. Total building energy use was included because of the lack of data regarding H&C energy consumption for the past. Notice that the trend in the past of total energy consumption in buildings is very close to future projections of H&C energy consumption. In commercial buildings (Figure 5 right), H&C energy consumption is more related to the economic activity (GDP) than to population. For this reason, a more dynamic increase is expected in commercial buildings than in residential. This paper [3] focused on providing a consistent and comprehensive source of information on the energy consumption in buildings. Although there was certain uncertainty in the results due to the lack of data that, at the same time, demonstrated and corroborated the need for a more consistent and comprehensive data collection related to building energy consumption worldwide, results obtained became a useful tool to experts regarding energy consumption in buildings.

1.2 Energy consumption of the building sector in Europe

Buildings represented the largest energy consumption in Europe in 2010, nearly 40% of the final energy use, increasing around 1% per year from 1990 to 2010 [5]. The European Union (EU) is a diverse region; it presents a combined population (500 million people) with significant variations in per-capita GDP. The climate, which strongly conditions the energy needs of buildings, is also very different around Europe where Northern and North-eastern countries tend to have high number of heating degree days, while demand for space cooling is increasing in Southern countries. Furthermore, the age of buildings also strongly conditions the energy consumption in buildings and in the EU the building stock mainly has more than 20 years old (Figure 6). Because of the direct relation between the building age and the energy consumption, an important potential of CO_2 savings was detected in restoration and renovation by upgrading building envelopes and H&C systems [6].

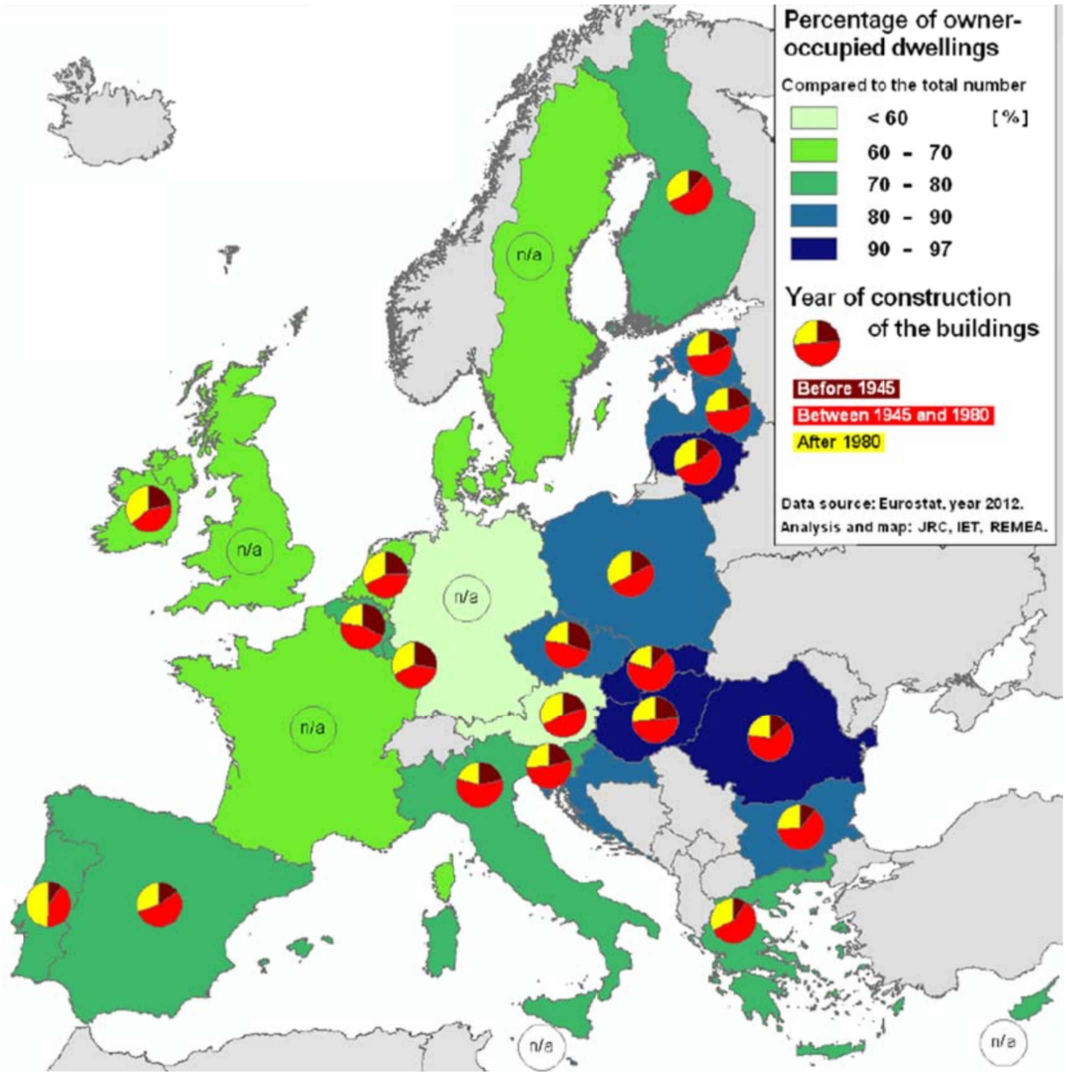

Figure 6. Year of construction of European buildings [6]

Three main construction periods can be considered in European buildings depending on buildings and construction systems used:

- Built before 1945 (before the post-World War II): Use of materials and techniques reflecting local conditions with energy-sufficiency measures incorporated, as bioclimatic design, in many cases.
- Built between 1945 and 1980: Classified as the least efficient buildings built with the first industrial techniques. Requirements established in codes not very stringent. In most Member States, requirements of energy-efficiency were not included in building regulations.
- Built after 1980: Building energy codes more focused on the reduction of the energy consumption of new buildings in all Member States.

In 2002, the energy Performance of Buildings Directive (EPBD) [7] was implemented in the EU. This code emphasised the importance of energy efficiency improvements in buildings. The EPBD establish minimum energy performance requirements and calculation method, energy certification and inspection for H&C and domestic hot water systems. In 2010, the EPBD was revised [8] and requirements to ensure nearly zero-energy in public buildings by the end of 2018 and by the end of 2020 in private buildings were established.

Residential buildings energy consumption was double than commercial buildings in the EU in 2010, being space H&C the largest end-use (69% in residential buildings and 45% in commercial buildings) as Figure 7 shows. Although space H&C energy consumption strongly depends on the country (Figure 8), the percentage in the EU was much higher than in global energy consumption (Figure 3), especially in residential buildings.

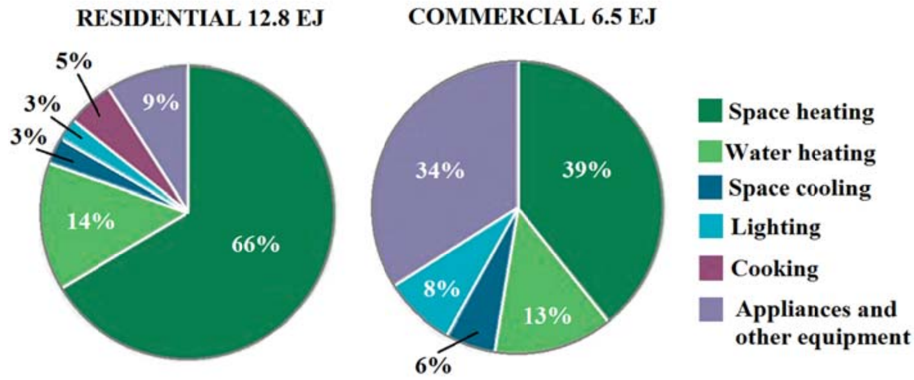

Figure 7. Residential and commercial buildings energy consumption by end-use, 2010 [5]

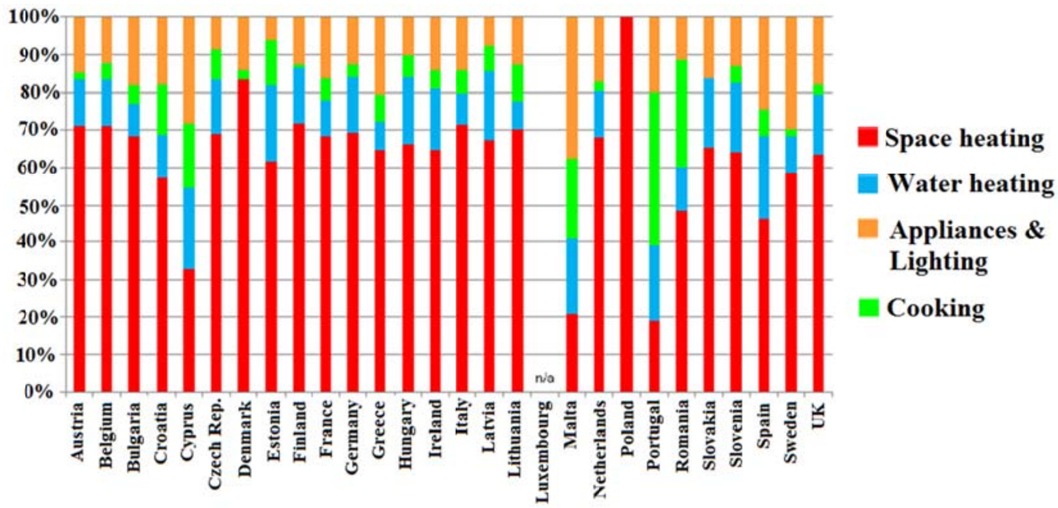

Figure 8. Final energy consumption by end-use in residential buildings, 2012 [6]

According to Figure 6, there is a high number of old and inefficient buildings in the EU with high needs of space heating. For this reason, there is a large potential to improve building envelopes and heating equipment and, therefore, to reduce the energy consumption of buildings. Particularly, by improving building envelopes with appropriate materials and construction systems the energy consumption of buildings could be reduced significantly (Figure 9).

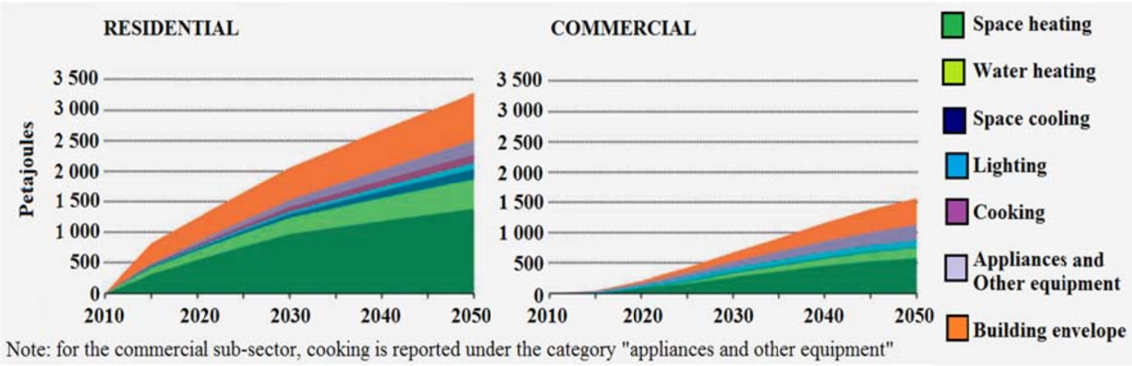

Figure 9. Projections of energy savings in the EU buildings [5]

There is an urgent need to decrease the overall energy consumption of buildings in the EU if objectives regarding climate change mitigation and CO_2 emissions reduction want to be achieved in a foreseeable future [8].

1.3 Possibilities to reduce the energy consumption in the building sector

The IEA recommends two main actions to reduce the energy consumption in buildings [9]. The first recommended action is to improve building envelopes of old and inefficient buildings through deep renovations. However, policies should be extended to all existing buildings (not only the old and big ones) because, nowadays, policies only address renovations larger than 250 m^2. To achieve this goal, energy renovations should be based on energy efficiency and sufficiency measures together with renewable energy sources in H&C systems. The second action recommended is to modify policy actions in every country in order to introduce energy efficiency measures in all buildings. Moreover, the energy efficiency improvement of appliances and equipment is also mandatory and standardization should be updated.

This thesis is focused on the reduction of the energy consumption of buildings by acting in the building envelope, aiming with the first recommended action of the IEA. To reach this goal, materials with thermal properties improved using latent thermal energy storage (TES) in passive systems and/or sustainable materials were deeply studied.

1.4 Latent thermal energy storage (TES) in passive systems in the building envelope

TES is implemented in construction systems to reduce the energy consumption of buildings. There are three main technologies of TES: sensible, latent, and thermo-chemical energy storage [10] (Figure 10).

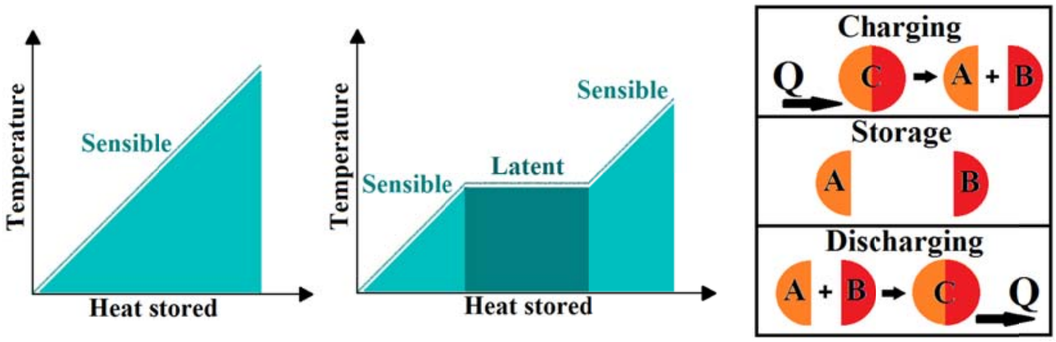

Figure 10. TES technologies: sensible, latent and thermo-chemical (from left to right) adapted from [10]

Historically, buildings used sensible heat storage by the use of high thermal mass materials (stone, earth and concrete, among others). However, latent heat storage materials have been implemented in building envelopes the last decades to store energy because they require less space than sensible materials to store heat if an appropriate construction system is designed [11].

Heat stored as sensible is the most common and simplest method to store energy, which consists on accumulating or releasing heat when a temperature gradient is applied. The effectiveness of this method depends in several factors as the heat capacity of the storage material, the mass of the storage material used and the thermal gradient to which the material is exposed [12].

The second technology to store heat is as latent. This technology provides higher energy storage density with small temperature differences; therefore, the volume of the storage material can be reduced. Latent heat storage occurs when a change in the phase state of a material occurs. The most common phase change used in buildings is solid-liquid because conditions are easy to control [11]. In this method, melting and solidification processes are used to store and release heat when the phase change occurs.

The third technology uses thermo-chemical materials and it should be the most efficient method to store heat but, at this moment, there are no real thermo-chemical building applications because it is under developing phase [13]. By using this technology, a reversible endothermic (charge) and exothermic (discharge) reaction process is used. The endothermic reaction (charge) occurs when a heat is applied to material C and, as a result, it separates in two different materials A and B (Figure 10). These materials can be separated and stored until discharge process is needed. In the exothermic process (discharge), materials A and B are mixed under specific conditions of pressure and temperature, and the heat released due to the reaction process is obtained. Thermo-chemical heat storage has important limitations to be solved before implementing this method in buildings as corrosion, find appropriate materials with reversible reactions, low heat storage, among others [12].

1.5 The use of PCM in passive systems

Phase change materials (PCM) has been broadly investigated by researchers to be incorporated in passive systems of buildings [11,12,14,15]. As shown in Figure 11 [14], there is a wide range of PCM that can be used in buildings and they can be classified according to their nature and their melting temperature range. However, melting temperature of PCM used in buildings envelopes passive systems should be around the comfort temperature range (see Figure 11), therefore, PCM should be selected depending on the requirements of the application [10].

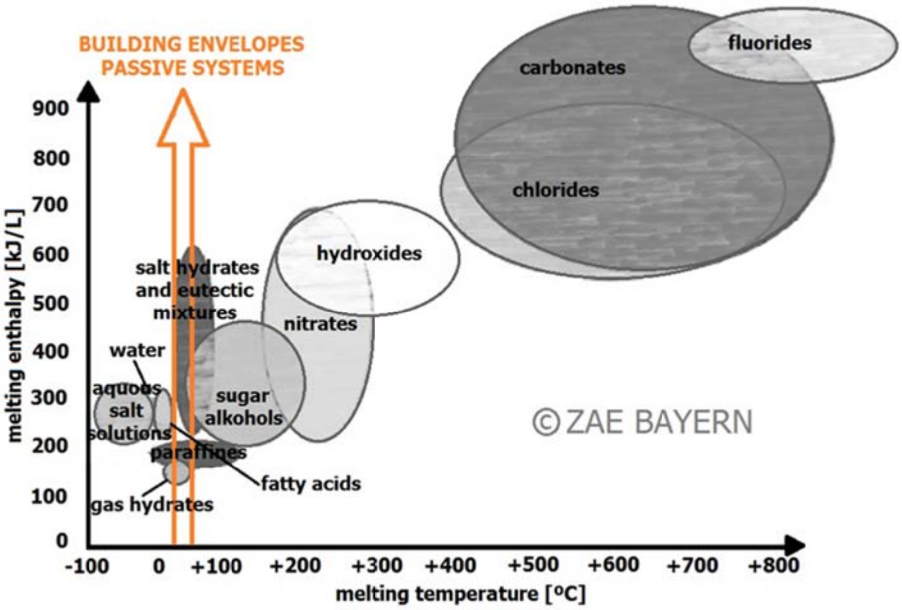

Figure 11. PCM classification with regard to their typical range of melting temperature and melting enthalpy (adapted from ZAE Bayern)

Three main types of PCM meet the requirements to be used in building envelopes passive systems: paraffin, fatty acids and salt hydrates. Paraffin and fatty acids, which have organic nature, present some advantages such as no sub-cooling, low or no corrosion and they are thermally and chemically stable. In contrast, they present disadvantages as low phase change enthalpy and possible flammability [14]. On the other hand, salt hydrates (inorganic nature) present higher phase change enthalpy; however, they have important disadvantages such as sub-cooling, corrosion, phase separation and segregation, and lack of thermal stability which increases the drawbacks to be implemented in building envelopes as storage material.

1.6 Sustainability and sustainable building materials

The first definition of sustainable development was done by the World Commission on Environment and Development (WCED) in 1987 as follows: *"Sustainable development is the development which meets the needs of the present without compromising the ability of future generations to meet their own needs"*. This definition has not been fulfilled in buildings because, for long time, research has been focused on developing high-tech materials and construction systems to implement in buildings in any type of situation so as to increase basically economic incomes. These actions have caused negative effects such as high pollution and enlargement of prime matter, because building materials industry has been based on the massive production of goods instead of saving or optimizing the use of resources.

Although energy performance is the most used indicator to assess the sustainability of a building, there are other parameters that should be accomplished to build under sustainable criteria [16]. Not only high energy efficiency should be achieved in buildings, an efficient use of water and materials are also mandatory in sustainable buildings. Furthermore, the impact on human health and the environment should be reduced throughout the whole life of the building.

Until a few years ago, sustainability of buildings only looked at the operational life of buildings. But materials used in buildings have to be considered in a long term perspective because around 65% of total aggregates (sand, gravel and crushed rock) and approximately 20% of total metals are used by the construction sector [17]. The massive use of these materials generates a considerable impact on the environment.

The EU27 consumed between 1.2 and 1.8 billion tonnes of construction materials per year for new buildings, refurbishment and maintenance between 2003 and 2011 [17]. Figure 12 and Figure 13 show the material composition of this total demonstrating that concrete, aggregate materials and bricks represents the 90% (by weight) of the materials used in buildings.

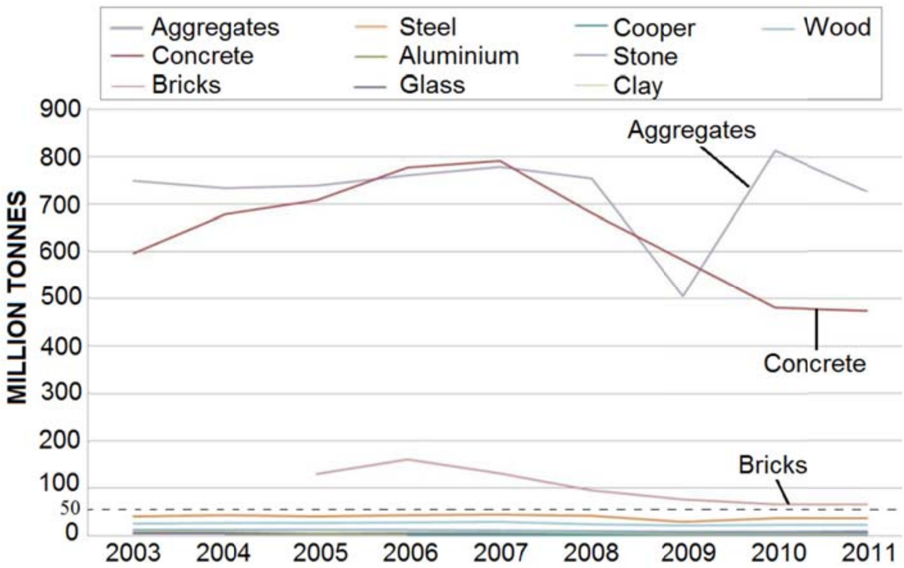

Figure 12. Use of construction material for new buildings, maintenance and refurbishment in the EU27 (million tonnes). Source: CRI calculations. Adapted from [17]

In order to show how the use of these materials affect to the environment, the global warming potential (GWP) from production of materials used in buildings calculated from a cradle-to-gate is shown in Figure 14, where concrete is responsible for one third of all total global warming potential impacts from building construction materials, followed by steel, aluminium and bricks that also have significant impact.

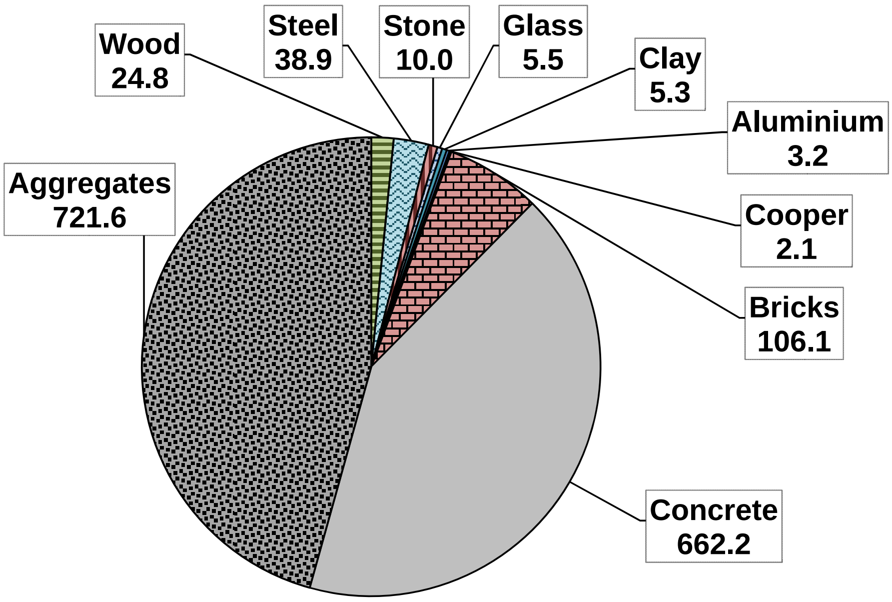

Figure 13. Average use of construction materials in the EU 27 buildings from 2006 to 2010 (million tonnes). Source: CRI calculations. Adapted from [17]

In the last three decades, materials demand has strongly increased worldwide due to the increasing access to affordable housing in developing countries and the continuing high demand of materials in developed countries [18]. Even though in Europe this materials consumption seems to have decreased or stagnated the last decade in the building sector (Figure 12), a higher use of sustainable and low environmental impact building materials should be promoted. To achieve this goal, more ambitious policies to promote the use of resources efficiently through innovation and research are needed, and they have to be focused on improve natural resources management and building materials production by using the 3Rs principle: Reduce, Reuse and Recycle.

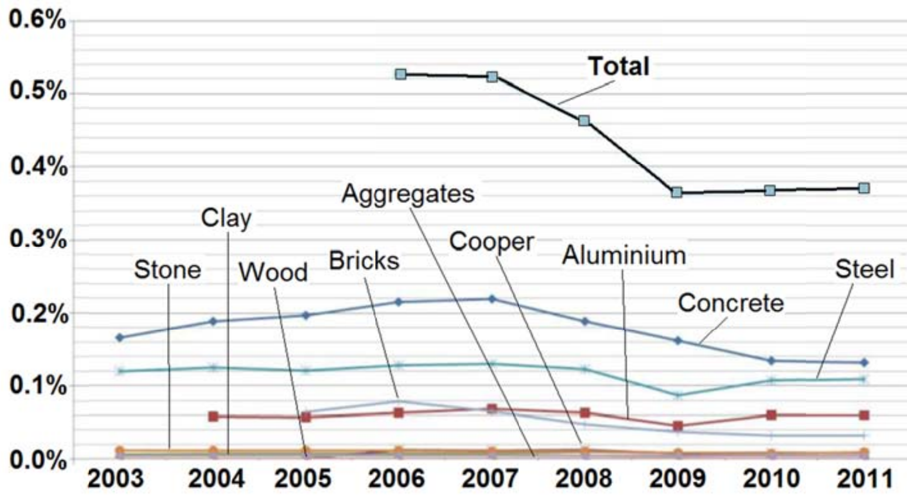

Figure 14. Total cradle-to-gate global warming potential from production of building materials in the EU27. Source: CRI calculations. Adapted from [17]

By a proper selection of materials, important reductions on the embodied energy can be achieved as Gonzalez and Navarro demonstrated [19]. Although environmental impact of building materials must be taken into account in order to reduce GHG emissions in the building sector, there are other key factors that definitely affect building material selection as the cost and social and technical requirements such as thermal properties, mechanical properties, aesthetics and feasibility to build in the shortest time possible. Therefore, a combination of environmental, economic, social and technical factors should determine the selection of building materials [20,21].

The building process (materials manufacture, construction, operation, and end-of life) is a huge factor of human impact on the environment through material and energy consumption and it results in the consequent drastic pollution and waste.

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2 Objectives

The objective of the present thesis is to contribute to the reduction of the energy consumption of buildings by acting in the building envelope, in particular, in building materials and construction systems. To achieve this goal, the candidate focused her investigation in three main research topics. The first one, which consists on evaluating the current situation of the energy consumption of buildings in Europe since international agencies foresee an important increasing trend, is focused on the evaluation of the H&C energy consumption in European residential buildings in order to demonstrate the necessity to improve building envelopes. The second research topic aims with PCM gypsum materials to be used as interior coatings with thermal properties improved. However, the research is not only focused on thermal properties characterization and improvement that has been widely studied and proved previously by many researchers, but also, technical issues that will condition the implementation of these materials and that has not been addressed by scientific community, are considered and studied when different types of PCM and inclusion methods are used. The third one is based on materials and construction systems mainly composed by earth, which is considered a sustainable and low environmental impact material, to be used as enclosure in buildings in order to reduce the CO_2 emissions and the environmental impact of building materials during the manufacturing and disposal phases. In particular, this second research line is divided in two sub-sections where, the first one is focused on the adaptation of rammed earth to the current building requirements reducing the wall thickness while improving the thermal behaviour and, the second one aims with the use of different by-products in adobe bricks.

Therefore, this thesis is mainly focused on materials placed in building envelopes aimed on reducing the energy consumption of buildings (and consequently the GHG emissions), which most of them address the reduction of the environmental impact following sustainable material selection criteria. To fulfil the global objective of the present thesis, the following sub-objectives are defined for each part of the thesis.

In the energy consumption evaluation for European buildings:

- To provide a source of information regarding energy consumption in the building sector and to evaluate the current situation.
- To define the main indicators (drivers) that affected H&C energy consumption in residential buildings in the last decades and analyse their trends at three levels: globally, by region and by country.

In the PCM gypsum materials part:

- To include PCM paraffin wax into gypsum using three different methods that avoids PCM leakage.
- To deeply study how affects the inclusion of paraffin wax PCM into gypsum in its fresh and hardened state properties and, afterwards, to provide some recommendations regarding the way to implement these materials as interior coatings in buildings.
- To present and demonstrate an effective, low-cost, low-tech and environmentally-friendly way to solve fire reaction problems related to the use of paraffin wax in building coatings.
- To evaluate the best way to include shape-stabilised fatty-ester PCM into gypsum taking into account thermal properties.

In the sustainable earth-based materials part:

- To improve mechanical and thermal properties of rammed earth once the wall thickness is reduced by the addition of stabilisers and microencapsulated PCM.

- To improve mechanical properties of adobe bricks by adding different local by-products.
- To demonstrate, under real weather conditions and at pilot plant scale, that sustainable construction systems based on insulated thin rammed earth walls can behave similarly and even better than conventional construction systems under summer conditions regarding thermal behaviour.

3 Methodology and structure of the PhD

The PhD thesis includes seven papers, all of them published in SCI journals.

The thesis is within the frame of the reduction of the energy consumption in buildings by acting in the building envelope materials and it is structured in three main parts. In the first part, that includes Paper 1, the energy consumption of buildings is deeply studied to provide an overall view of the trends in energy consumption in European residential buildings. This paper demonstrates that there is a need on reducing energy consumption of buildings due to the constant increase of the energy demand. For this reason, the second (Paper 2, Paper 3 and Paper 4) and third (Paper 5, Paper 6 and Paper 7) parts are focused on the energy consumption reduction in buildings by acting in the building envelope, specifically, in materials and construction systems.

In the second part, different PCM are added into gypsum to be used as interior coatings in order to reduce the energy consumption of buildings in the use phase. It covers all the possibilities to introduce PCM into gypsum with no presence of leakage and all of them are evaluated in different ways, depending on the goal and scope of each study. However, this part not only aims with physical, mechanical and thermal characterization that has been extensively studied and its effectiveness has been also demonstrated by many researchers (see introduction of Chapter 5), as a novelty, it is also focused in different important construction issues that will condition the implementation of these materials in building envelopes from a technical point of view.

To reach this goal, Paper 2 evaluates how key fresh state properties of gypsum, which are currently standardized and regulated, are affected by the addition of paraffin wax PCM into gypsum and some recommendations regarding installation are provided. On the other hand, in Paper 3 a comprehensive study of physical, thermal and mechanical properties of these three gypsum PCM compositions is done. However, the key of this study is also to develop multi-layered gypsum PCM materials to protect the material against fire while avoiding the addition of fire retardant materials that increase the final embodied energy and cost of the material. Finally, in Paper 4 shape-stabilised fatty-ester PCM is introduced into gypsum in order to assess the most thermally efficient way to introduce this type of PCM into gypsum coatings.

The third part of this thesis is focused in the reduction of the energy consumption of buildings; however, in this part not only the use phase of buildings is taken into account but also materials production, construction and end-of-life phases are considered. Earth as building material was the selected one to perform different studies at both, laboratory and pilot plant scale because of its sustainability, low embodied energy and cost.

Paper 5 is focused on the improvement of thermal properties of rammed earth by doping the material with microencapsulated PCM while optimizing compressive strength. By improving thermal properties of rammed earth, thinner walls can be used in order to maximize the useful floor area of a building and, therefore, be competitive in the building materials market. On the other hand, in Paper 6 several by-products with different nature (agriculture, transport and industry) are added into adobe bricks in order to fulfil the maximum CO_2 emissions reduction. The variability of flexural and compressive strength properties due to the addition of these by-products is assessed. Finally, in Paper 7, two earth based construction systems are thermally tested at pilot plant scale under real weather summer conditions and results obtained are compared with conventional Mediterranean construction systems with high embodied energy.

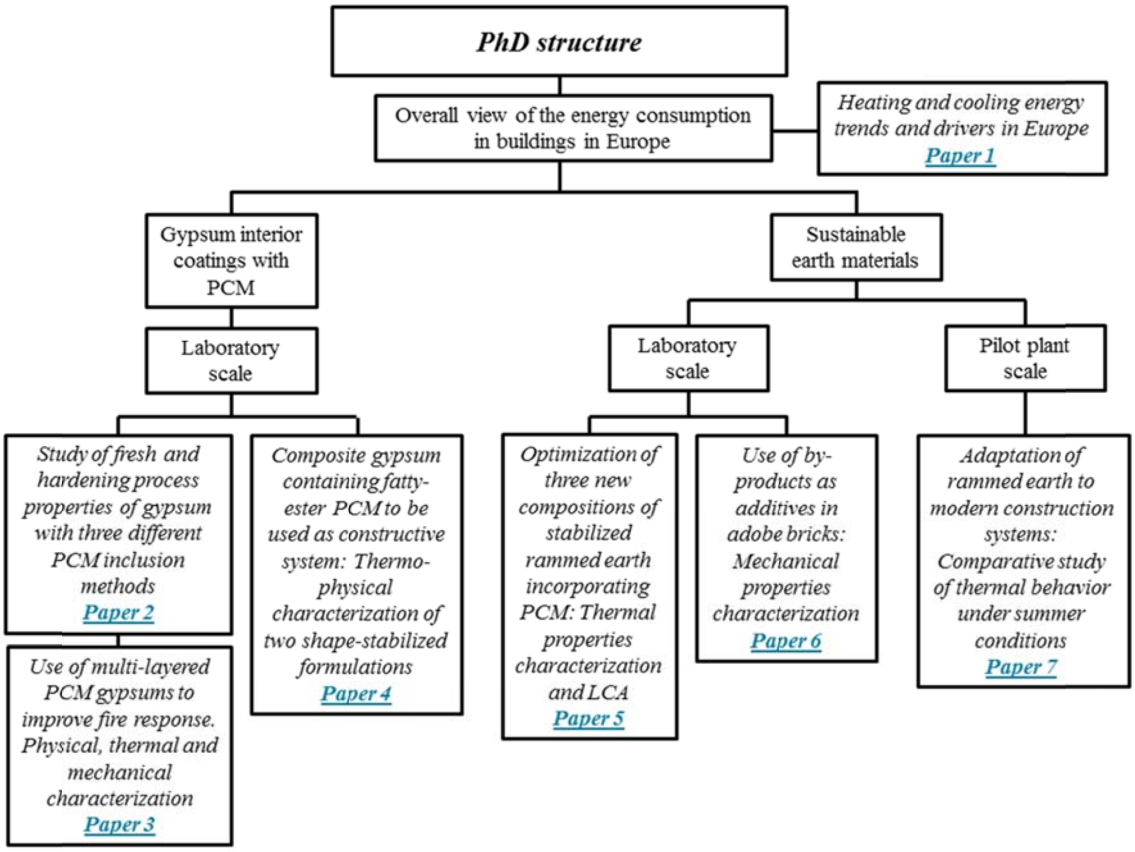


Figure 15. PhD structure scheme

4 Heating and cooling energy trends and drivers in Europe

4.1 Introduction

In Chapter 1 of this thesis a global overview of the energy consumption in buildings and their contribution to the GHG emissions has been done with the aim of raising awareness of the energy consumption situation, particularly, in the building sector.

The candidate collaborated in a previous study [1] where the main drivers that contribute to the H&C energy use in commercial and residential buildings were deeply studied. Some examples of these drivers are the number of households, persons living in each household, energy consumption per square meter, and gross domestic product (GDP), among others. Furthermore, the trends of these drivers as well as the total energy consumption and H&C energy consumption were analysed for the past (with real and available data obtained from the UN, IEA, and other official data bases) and the future (using mathematical models developed by the Central European University researchers in Hungary) in a global and regional basis. Some interesting results of this study were included in Chapter 9 related to Buildings of the 5th assessment report of the IPCC [2] as the ones presented in Chapter 1 (see Figure 5).

According to the 5th Assessment Report of the IPCC, buildings accounted for 32% of total global final energy, 19% of energy-related GHG emissions, around one-third of black carbon emissions [2], and an eighth to a third of fluorinated gases. The most worrying situation is that this energy use and emissions are expected to increase (double or even triple) due to several factors as the access to housing and energy of citizens in developing countries, population growth, migration to cities, increasing levels of wealth, among others. The way to address these changes will strongly determine trends in building energy consumption and related emissions.

Once the global study were carried out noticing the growing trends of the energy use in buildings (and the drivers) in the world, the candidate considered mandatory the same study in depth for European countries.

4.2 Contribution to the state of the art

The aim of this study was to provide a complete set of data for residential energy consumption in European buildings and assess the trends of the main conditioning drivers, the total energy consumption and H&C energy consumption in the past 20 years. This kind of information was not available at the moment of writing the published paper for residential buildings and it is sure to be an interesting tool for experts in modelling and planning H&C energy use with the aim of modelling more accurate future projections [3].

To achieve this goal, the same methodology than in Ürge-Vorsatz et al. 2015 [1] was followed. H&C and domestic hot water energy consumption in residential buildings was decomposed in several drivers (activity, use intensity and energy intensity drivers) following the Kaya identity methodology (see Figure 16).

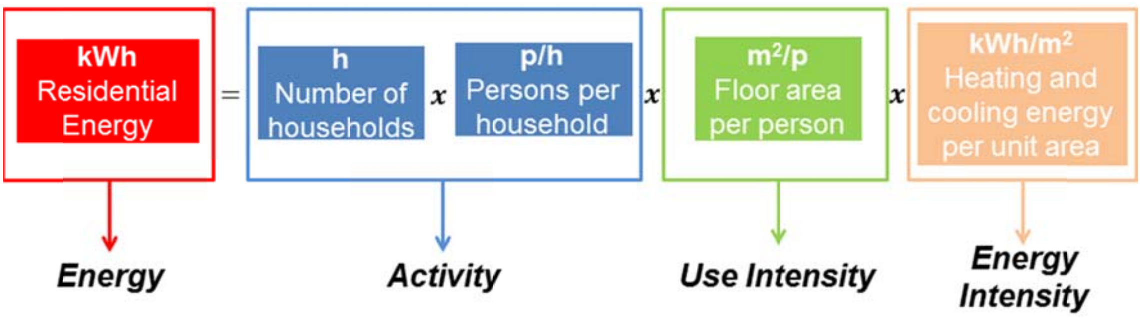


Figure 16. Kaya identity methodology scheme

Furthermore, results were presented globally for Europe, for the different regions grouped by the UN geographical classification (Western Europe, Eastern Europe, Southern Europe, and Northern Europe) and for each country.

The data was obtained from different official sources like the UN [3,5], Odyssee [6], and the IEA [7].

The main results obtained for Europe are presented in Table 1 where households, floor area, per capita floor area and population have been increasing till 2010. Otherwise, persons per household and specific energy consumption have been decreasing. By analysing the trends of some of these drivers, it can be shown that, in general, lifestyle levels have increased, however, they also made to increase the H&C and total energy consumption in residential buildings the last three decades. On the other hand, the growing population and floor area built also affects the energy consumption of buildings by increasing it. As a positive trend to mention is the decreasing trend of the specific energy consumption, that shows efficiency has been improved the last decades.

Table 1. Energy consumption data in residential buildings in Europe, 1990-2010

			KAYA drivers				*Other drivers*	
Year	*Total energy (TWh)*	*H&C energy (TWh)*	*Households (h, millions)*	*Persons per household (p/h)*	*Per capita floor area (m^2/p)*	*Specific energy consumption (kWh/m^2)*	*Population (millions)*	*Floor area (m^2, billions*)*
1990	3.83	2.63	189.12	2.93	15.25	311.10	553.63	8.44
2000	3.92	2.92	205.08	2.76	16.94	304.21	565.66	9.58
2010	4.18	2.80	216.86	2.70	18.63	256.41	585.52	10.91

*Billions are considered 10^9.

When data was analysed by regions (Figure 17), the trends were different in each one. Changes in trends of H&C and total energy consumption were less than 15% in Western, Northern and Eastern Europe, while in Southern Europe increased up to 37% in the period studied. The same behaviour can be noticed in the specific energy consumption, where it decreased in all regions except in Southern Europe.

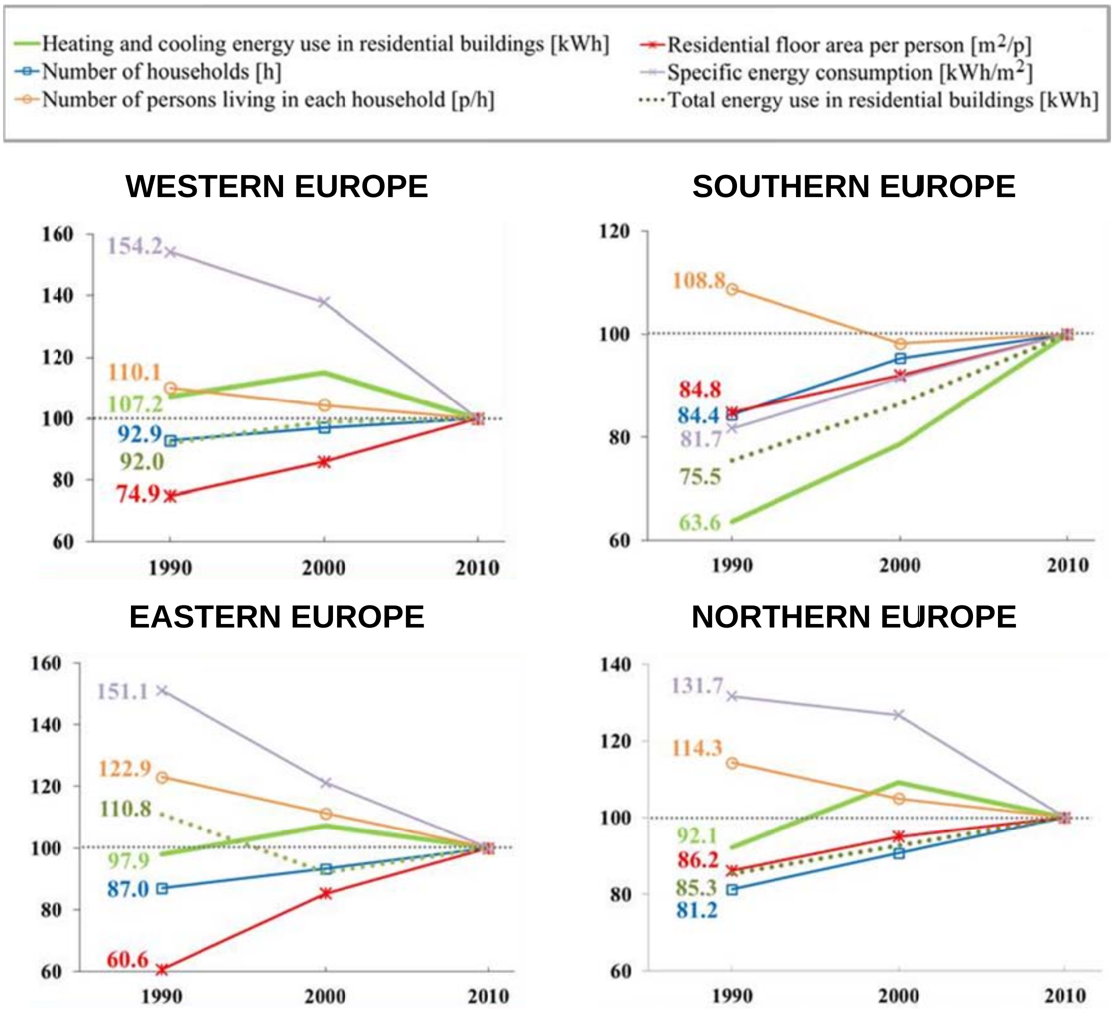


Figure 17. Trends in the drivers of energy consumption in residential buildings by key European regions, 1990-2010

On the other hand, the persons living in each household decreased in all regions and the floor area per person increased. It is important to highlight that Figure 17 analysed the trends of each drivers, taking the value in 2010 as the reference in each region, however, absolute values of drivers change between regions.

In Figure 18 absolute values of H&C energy consumption per capita and per capita floor area are shown. H&C energy consumption per capita and the floor area per capita were compared in order to see differences between absolute values in each region. In Southern Europe, the energy consumption per capita increased more than the floor area per capita while in Northern Europe the energy consumption per capita stagnated while the floor area per capita notably increased. But, in general, the floor area per capita increased more than the energy consumption per capita.

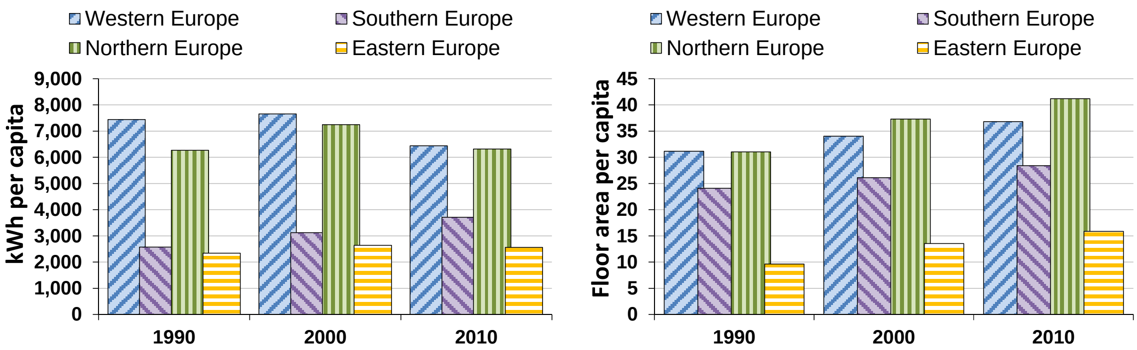


Figure 18. H&C energy consumption per capita and per capita floor area in each EU member region

The main conclusions of this study were the following:

All drivers followed a consistent trend at global, regional and country level during the studied period of time:

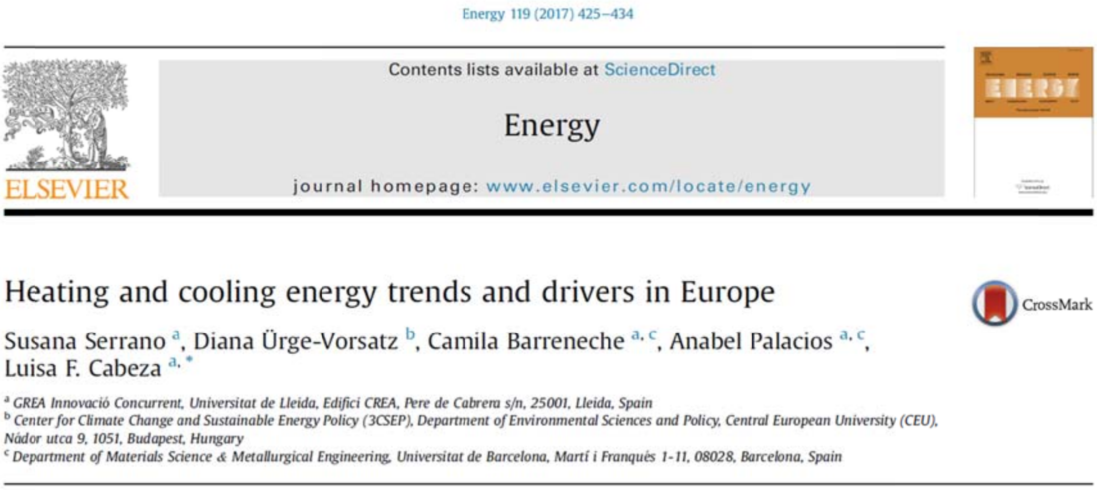
- The number of households increased at all levels while the persons per household decreased (activity drivers)
- The floor area per person increased (use intensity driver)
- The specific energy consumption decreased (energy intensity driver)
- However, the H&C energy consumption did not follow the same trend if it was considered at global, regional or country level showing that it was very influenced by all the drivers and did not follow the same trend as the specific energy consumption

Trends of the indicators studied showed that European citizens live in bigger houses than 20 years ago but they spend less in energy per person.

4.3 Contribution of the candidate

The candidate searched for all the data, processed it and generated all the graphical information of the article. She decided in collaboration with all co-authors the best way to represent the European regions and all the available data. She collaborated in the writing of the paper, mostly in the introduction, methodology, data sources and results. Furthermore, she collaborated in the submission preparation.

4.4 Journal paper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Heating and cooling energy trends and drivers in Europe

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5 Study of fresh and hardening process properties of gypsum with three different PCM inclusion methods

5.1 Introduction

The benefits of using PCM in the building envelope as thermal storage passive system to reduce the energy consumption in buildings during the usage phase has been shown in Chapter 1. There are a wide number of publications [1-5] where authors give chemical, physical, mechanical and thermal characterization of gypsum with PCM using different types of gypsum as binder, adding different types of PCM and using different inclusion methods. But this characterization is always done once the material is hardened just in order to evaluate the variability of their properties and, especially, to deeply evaluate the enhancement of thermal properties. However, there are other important properties to be characterized that should be taken into account because they will determine how the material should be manufactured (if they are presented as prefabricated boards) or implemented in the building site (if they are placed using *in situ* techniques).

The current Spanish legislation referred to gypsums [6,7] states several properties in fresh state as key parameters to be controlled in the manufacturing process of gypsum. Fresh state of gypsum is important to be controlled because it will determine how the material can be implemented in the building (as *in situ* or prefabricated material, manual or mechanical application, etc.), but also, it will determine the time that workers will have to implement the material in walls when the hydration of gypsum starts, if dilation joints are needed and the distance between them, or the time needed to be completely dry. Moreover, properties of gypsum will be modified by the addition of PCM, and they will change in different ways depending on the inclusion method used by making it more fluid or drier, increasing or decreasing the setting time of the material, retractions or expansions, and even the adherence of gypsum into walls.

These parameters are considered as key elements to be controlled for future implementation of the material. For this reason, the candidate considers mandatory the evaluation of gypsum properties in fresh state once PCM is added into the formulation.

5.2 Contribution to the state of the art

The aim of this study was to assess the variability of gypsum properties in fresh state and during the hardening process after the inclusion of 10% of PCM using three different methods (microencapsulated, suspended and impregnated). Properties in fresh state define the workability of gypsum with PCM that are key properties to be controlled once the material have to be implemented in buildings using *in situ* techniques or manufactured as prefabricated boards.

To perform this experimentation, hemihydrate gypsum with high purity E-35 was used as the matrix and two types of PCM, microencapsulated Micronal® DS 5001 X and paraffin wax Rubitherm RT-21 with a melting temperature of 26ºC and 21ºC, respectively, were added into the formulation. PCM materials were added using three different methods as follows (see Figure 19):

- Method 1: mixing microencapsulated PCM powder and gypsum E-35 firstly and afterwards adding the mixing water.
- Method 2: making a suspension of water and paraffin wax RT-21 and then adding gypsum powder.
- Method 3: mixing gypsum E-35 and water and, once the material is completely cured paraffin wax RT-21 is vacuum impregnated.

Figure 19. Method 1, method 2 and method 3 (from the left to the right)

Special attention had to be paid in the formulation process to calculate the required amount of water in each gypsum type in order to ensure a proper hydration of gypsum whilst obtaining optima workability of the material.

Therefore, four different gypsum compositions were studied: one of them without PCM that was used as the reference (*REF*) to quantify the variability of properties of gypsum with PCM materials, the second one with 10% of microencapsulated PCM (*M*), the third one with 10% of RT-21 PCM by suspension method (*S*) and, finally, the fourth one with 10% of RT-21 PCM by vacuum impregnation method (*I*).

Properties during fresh and hardening process under study were workability, setting times, adherence and dimensional stability. Workability is directly related with the water/gypsum content and, workability can be guaranteed by defining fluid consistency that was achieved when the flow value (calculated as the average of perpendicular diameters as Figure 20a shows) was between 150–210 mm.

Setting times were measured by Vicat needle and it determined the initial time of hardening process and finalised when the needle sunk 22±2 mm of depth. The adherence test, on the other hand, consisted on the application of a perpendicular traction force between gypsum samples and the wall material.

Finally, dimensional stability was calculated by measuring changes in length and volume of 40 x 40 x 160 mm samples.

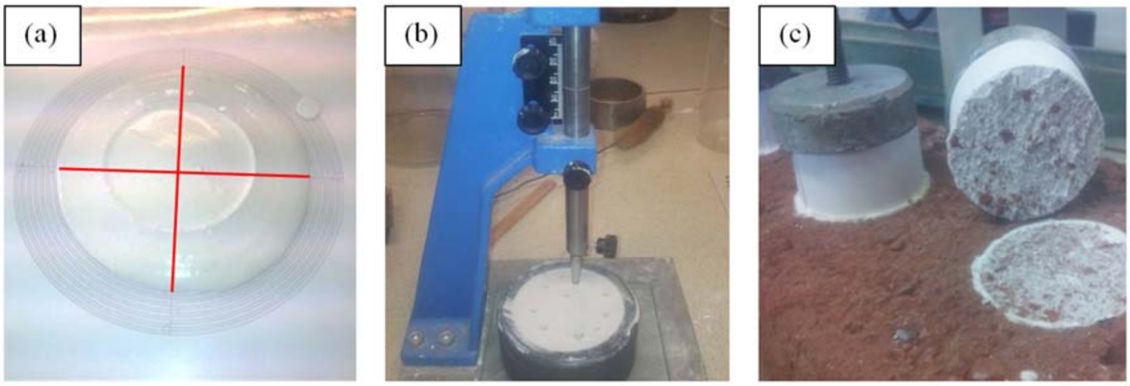

Figure 20. (a) Workability test, (b) setting time test and (c) adherence test.

These properties were evaluated following the current Spanish and European standardization of gypsum UNE-EN 13279 serial [6,7] and, as expected, the addition of PCM strongly modified properties of gypsum in fresh state and condition the implementation of the material in buildings. It is important to clarify that, *M* and *S* type can be implemented using *in situ* techniques and as prefabricated boards, while *I* type can be only used as prefabricated board because the sample must be hardened in the same way than *REF* and then be impregnated filling the PCM inside its porous. Therefore, workability, setting time and dimensional stability results of *I* type were the same than *REF* type and adherence properties was not possible to be measured in *I* type.

The most relevant conclusions reached in this study were the followings:

- The addition of PCM into gypsum accelerated setting times, especially RT-21 (*S*), which reduced by 80% the setting time.
- The required water to hydrate the gypsum was higher by adding microencapsulated PCM (*M*) because microcapsules acted as an aggregate with high specific surface.

- Adherence was also strongly penalized reducing up to 45% in ceramic surface using both, microencapsulation (*M*) and suspension methods (*S*) because the PCM was acting as a lubricant in the interface and it affected the differences on surface tension.
- Volumetric variations were reduced by adding PCM probably thanks to their high stability, especially in microencapsulated type (M), where microcapsules acted as strain scattering.
- Vacuum impregnation method could allow higher PCM loadings to enhance thermal properties because it only depended on the porosity of the material that was directly related with the capacity of impregnating PCM without modifying properties in fresh state.

5.3 Contribution of the candidate

The candidate conceived and designed all the experimentation in collaboration with all the co-authors. Furthermore, she performed all the experimentation as well as she analysed the data obtained and generated the graphical information of the article. The candidate also leaded the writing and submission preparation as well as the revision process. Co-authors mainly collaborated in the discussion of results and conclusions of the article.

5.4 Journal paper

materials
MDPI

Article

Study of Fresh and Hardening Process Properties of Gypsum with Three Different PCM Inclusion Methods

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6 Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization

6.1 Introduction

Different types of PCMs have been investigated with different nature as paraffin wax, salt hydrates, fatty acids, and ester compounds [1]. However, because of their cost, availability, appropriate thermal storage capacities (up to 200 kJ/kg), and chemical and thermal stability, paraffin wax have been the most commonly used in buildings [2]. Regarding building materials, the use of PCM into gypsum to improve its thermal behaviour has been widely studied by many authors and results obtained of thermal response have been successful [3]. However, as previously demonstrated, paraffin waxes have poor behaviour against fire [4], therefore, the investigation of fire retardants or different methods to improve their fire response is mandatory [5]. The addition of other materials and/or process as fire retardants to the base material increases two key parameters that will constrain the market: cost to the costumer and environmental impact of the material.

In this study, authors developed three types of PCM gypsum materials with fire protection but, unlike other studies, no fire retardants or materials were added. To reach this goal, multi-layered PCM gypsum materials were developed, adding an external thin layer of common gypsum without PCM as fire barrier. This fact takes advantage of specific chemical properties of gypsum which has not fire contribution. Furthermore, relevant physical properties as porosity, bulk density, PCM distribution, vapour absorption, among others, were studied. Moreover, mechanical and thermal properties were also studied as compressive and flexural strength, modulus of elasticity, thermal conductivity, heat capacity, etc.

This paper is the continuation of paper 2 (Chapter 5.) of this thesis. Therefore, the same materials and methodology to perform materials and samples were used.

6.2 Contribution to the state of the art

This study aimed with the development of PCM gypsum interior coatings with behaviour against fire improved but, as a novelty, no additional materials as fire retardants were added. The objective of this paper was to solve behaviour of paraffin wax PCM included in gypsums against fire with a low tech and cheap solution and without increasing the environmental impact of the material. As is explained in the introduction of Chapter 5, the same materials and methodology to add PCM paraffin wax into gypsum were used (suspension, impregnation, and microencapsulation). Moreover, key properties were analysed regarding physical, mechanical and thermal properties in order to asses a proper characterization of the materials.

Some physical and mechanical requirements of gypsum coatings, as minimum density, compressive and flexural strength, are standardised by the Spanish and European standard UNE-EN 13279-2 [6]. These properties were verified to be fulfilled by the new compositions of gypsum with PCM. Other important properties of gypsum coatings considered in this study like porosity, water vapour absorption and velocity of water absorption in low pressure (that became important parameters to be controlled when gypsum coatings are placed in wet rooms), dynamic modulus of elasticity, thermal transmittance, thermal conductivity and, heat capacity were tested by adapting other building materials standards or methodologies [7-15]. Furthermore, the PCM distribution among the samples (Figure 21) was also studied in order to check the homogeneity of the materials.

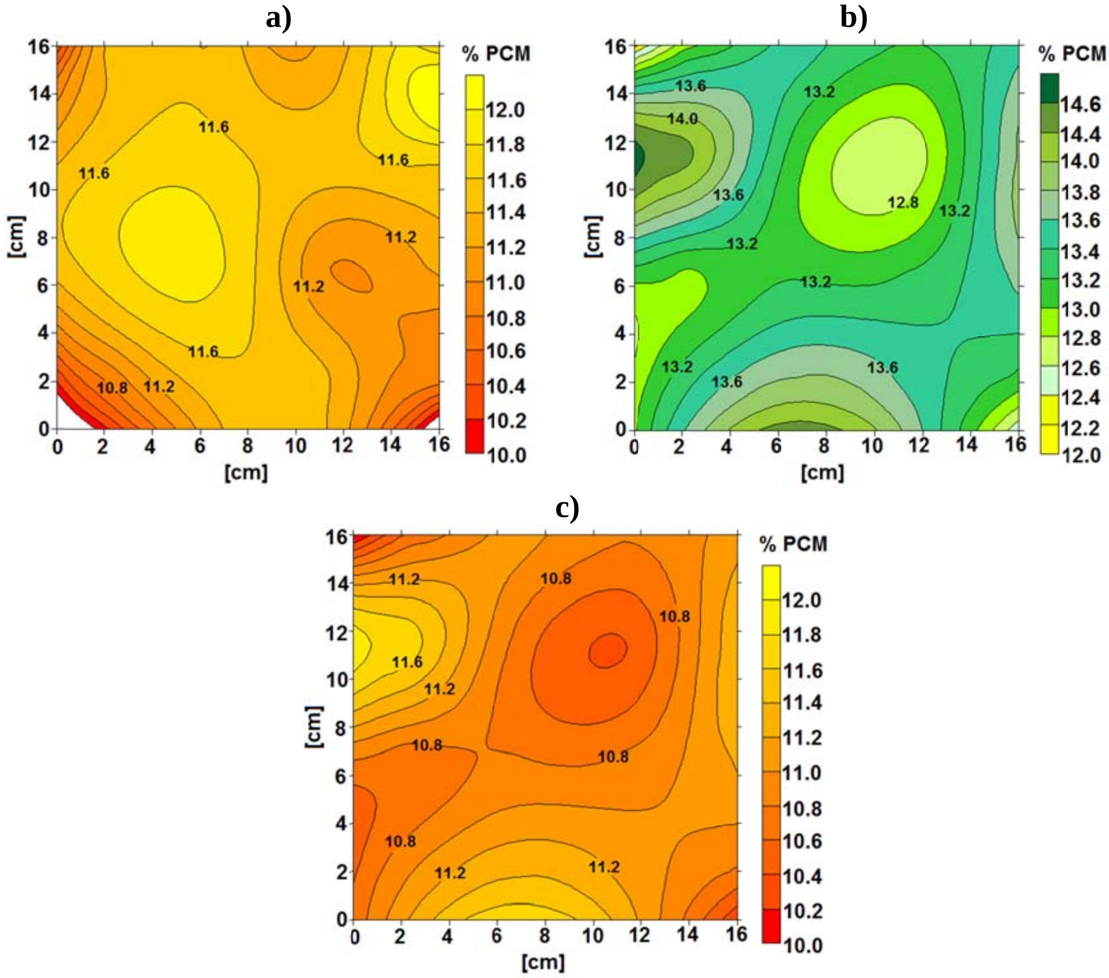

Figure 21. Mapping PCM distribution a) Microencapsulated, b) Suspension, and c) Impregnation

Finally, fire reaction tests to evaluate the self-extinguish capability of these materials called dripping tests were performed to calculate the number of ignitions/extinctions in a certain period of time and the duration of flame when a heating source is applied (Figure 22). The aim of the test was to find the minimum thickness of external gypsum coating without PCM of the tested ones (0.5, 2.5 or 5 mm) that could behave as a real fire barrier.

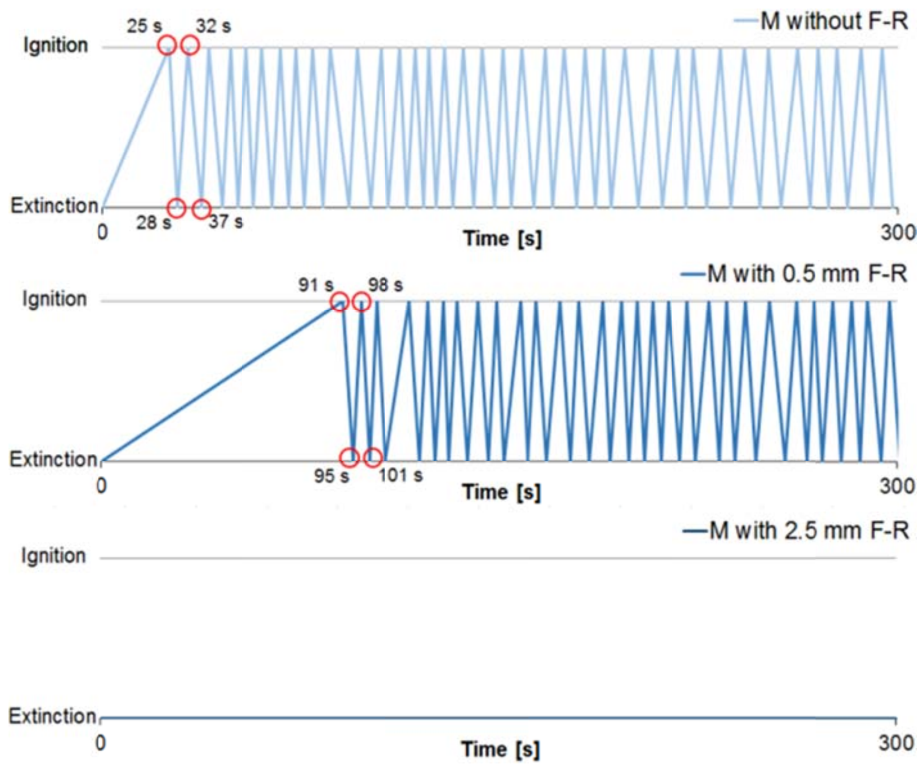

Figure 22. Fire response of gypsum with microencapsulated PCM with and without fire retardant

The most relevant conclusions of this paper were:

- Apparent porosity decreased by the addition of paraffin wax without encapsulation but, contrary, worsened water vapour permeability. Paraffin wax also reduced water absorption in low pressure because it filled gypsum pores (reducing apparent porosity) and also acted as water repellent. On the other hand, microencapsulated PCM acted as an aggregate increasing apparent porosity of the material and obtaining the opposite results than in non-encapsulated PCM.
- Compressive strength was adversely affected by the addition of PCM but, on the other hand, flexural strength was improved when paraffin wax is added using impregnation method.

- PCM distribution among the samples was homogeneous regardless the method used.
- As expected, heat capacity was increased by the addition of PCM but thermal conductivity was only reduced in microencapsulated PCM due to the effect of polymeric microcapsules
- The addition of a thin layer of common gypsum acted successfully as fire barrier in gypsum coatings with 10% of PCM, 2.5 mm were needed in microencapsulated and suspension methods, and 5 mm in impregnation method.

6.3 Contribution of the candidate

The design of the experimentation, testing, and the analysis of the data obtained, as well as the graphical information was mainly leaded by the candidate. During the experimentation, decisions concerning the results obtained in the experimentation to redirect successfully the study were actively taken by the candidate and co-authors. Moreover, the candidate leaded the writing and submission preparation of the article, and the revision process. Co-authors mainly collaborated in the conclusions of the article and the revision process.

6.4 Journal paper

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Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization

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Serrano S, Barreneche C, Navarro A, Haurie L, Fernández AI, Cabeza LF. Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization. Energy and Buildings 2016;127:1-9.

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7 Composite gypsum containing fatty-ester PCM to be used as constructive system: Thermophysical characterization of two shape-stabilized formulations

7.1 Introduction

As introduced in Chapter 1 of the present thesis, PCM can be classified as organic and inorganic [1] depending on their nature, and they can also be classified depending on their melting temperature (see Figure 11). Paraffin, salt hydrates and fatty acids are the main used types of PCM that can be used in building envelopes as passive system because of their melting temperature that is near to comfort temperature range. Fatty acids also have organic nature; therefore, they present the same advantages and disadvantages than paraffin waxes (see Chapter 1) [1] but, in contrast, they present certain corrosivity, bad odour and sublimation during heating process [2]. To solve these problems, researchers have replaced fatty acids with a derivative compounds obtained by the fatty acid esterification with alcohols called fatty-ester. In addition, fatty-ester PCM (also known as bio-based PCM) present long term advantages compared to paraffin as no changes in mass when the material is heated, thermal stability and not from fossil fuel origin [3].

For this reason, in Chapter 7 shape-stabilized fatty-ester PCM was incorporated into gypsum in order to cover all methods to include PCM into gypsum material that doesn't present PCM leakage [7]. In this technique, shape stabilization support materials and PCM are heated using high temperatures in order to melt both materials. After the mixing process, the material is cooled till supporting material is in solid phase. Melting temperature of supporting material is notably higher than PCM and, ideally, a proper shape-stabilized fatty-ester PCM does not present leakage when the PCM is melted.

7.2 Contribution to the state of the art

The main objective of this paper was to assess which was the most efficient way to introduce the shape-stabilized fatty-ester PCM into gypsum, as pellets or sheets (see Figure 23), taking into account thermal properties. The use of shape-stabilized fatty-ester PCM gypsum wallboards were focused on reducing temperature fluctuation in buildings and improving indoor comfort conditions.

Figure 23. Shape-stabilized fatty-ester PCM: pellets and sheet

The fatty-ester PCM used along the experimentation was obtained from vegetable oil methyl ester at an esterification plant and it had a melting point of 27.6 ºC and 187 kJ/kg melting enthalpy. On the other hand, common gypsum (YG/L) was used as the matrix material.

The three compositions under study were gypsum blank (without shape-stabilized fatty-ester PCM), gypsum with 3.9% wt. of shape-stabilized fatty-ester PCM in weight in sheets form and, gypsum with 3.9% wt. of shape-stabilized fatty-ester PCM in weight in pellets form. The thermal characterization was performed using the Thermal Behaviour Analyser developed at the University of Lleida [8] which enables to test different materials as homogeneous, non-homogeneous, composites, multi-layered materials, among others, using samples of 19 x 19 cm. The Thermal Behaviour Analyser (Figure 24) is able to simulate real environmental conditions under steady and unsteady states by performing different experiments to test and calculate several thermal properties as thermal transmittance, thermal conductivity, total heat accumulated by the sample and average heat capacity with a relative error of 8% due to the propagation of errors in the measurement devices.

Figure 24. Thermal Behaviour Analyser and examples of data processing

Final results of thermal properties characterization are listed in Table 2.

Table 2. Thermal properties of shape-stabilised fatty-ester PCM gypsums

		Gypsum blank	*Gypsum + sheets shape-stabilized fatty-ester PCM*	*Gypsum + pellets shape-stabilized fatty-ester PCM*
U_{value}	[W/m2·ºC]	11.57	8.59	8.20
k	[W/m·ºC]	0.50	0.31	0.29
q_{acc}	[kJ/kg]	21.74	42.03	36.04
Cp	[kJ/kg·ºC]	0.92	12.91	12.17

The main findings of this study were the following:

- In general, thermal conductivity and thermal transmittance were decreased due to the addition of a PCM with organic nature and, total heat accumulated and heat capacity was increased due to the latent heat exchange during the phase change.
- Thermal conductivity was reduced 25% by the addition of shape-stabilized fatty-ester PCM, regardless of the shape.
- Average heat capacity was notably increased by the addition of shape-stabilized fatty-ester PCM in both cases. However, the effect was higher when shape-stabilized fatty-ester PCM was placed as sheets showing an improvement of 41% and 33% by using sheets and pellets, respectively.
- Shape and distribution of shape-stabilized fatty-ester PCM in wallboards should be further studied in order to optimize the PCM effect.

7.3 Contribution of the candidate

The candidate actively collaborated in the experimentation design with all the co-authors. She performed the experimentation, analysed the data obtained and generated the graphical support for the article. The candidate also leaded the writing and submission preparation as well as the revision process. Co-authors collaborated in the discussion of results and conclusions.

The shape stabilised fatty-ester PCM (bio-based PCM) was previously developed and manufactured by one of the co-authors of this paper, Mohammed M. Farid, at the University of Auckland (New Zealand).

7.4 Journal paper

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Composite gypsum containing fatty-ester PCM to be used as constructive system: Thermophysical characterization of two shape-stabilized formulations

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Serrano S, Barreneche C, Fernández AI, Farid MM, Cabeza LF. Composite gypsum containing fatty-ester PCM to be used as constructive system: Thermophysical characterization of two shape-stabilized formulations. Energy and Buildings 2015;86:190-193.

DOI: 10.1016/j.enbuild.2014.10.015

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8 Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA

8.1 Introduction

The operation phase is the main responsible of the energy consumption in buildings (almost 80% of life cycle energy). For this reason, the reduction of energy consumption and, therefore, GHG and acidifying gasses has become one of the most important goals to be achieved around the world by international institutions [1-4] focusing their efforts in the operational phase of buildings. However, embodied energy of materials represents around 20% in the majority of buildings (or even more in modern energy efficient buildings). So that, special attention should be paid in the other building phases in order to achieve higher emissions reductions [5]. Selection of materials has an important role in the amount of embodied energy and GHG gases because they are involved in several building phases as Figure 25 shows.

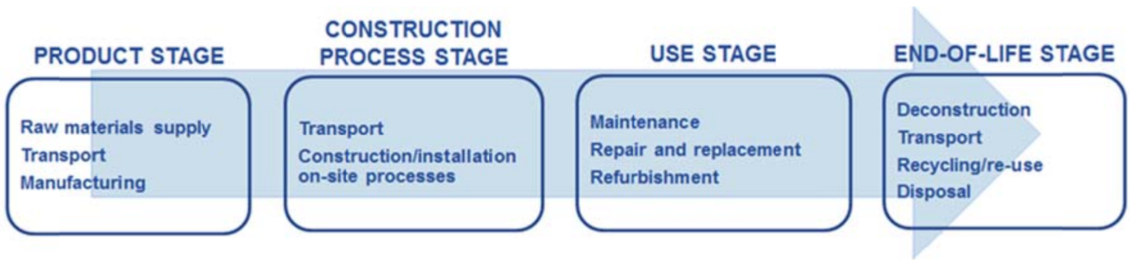

Figure 25. Building phases that involve material selection

Industrial materials as materials based in cement, ceramics, steel, among others, are widely used in buildings being major energy consumers during product and construction process stages. Moreover, their recycling or re-use is not possible in some cases [6]. Therefore, the use of alternative materials with lower embodied energy becomes a key strategy to reduce the emissions of buildings. Rosselló-Batle et al. 2015 [7] estimated a potential reduction (up to 30%) of the embodied energy and CO_2 emissions by just replacing the most energy intensive elements in a large building with budget increases lower than 8%.

The use of rammed earth as building material encompasses some of the problems previously stated: it is a local material that can be used in the construction site if necessary, it does not need high tech processing and it can be re-used or, in some cases, just be returned to nature [8]. However, technical and, especially, cultural issues are strong barriers to the market entry of rammed earth material.

Rammed earth is an ancient material widely used around the world that has been an answer to the housing demand of population. However, in recent history the use of rammed earth declined with the use of other modern construction techniques during the Industrial Revolution. Rammed earth has important structural limitations, especially in multi-storey buildings, and these limitations are aggravated in modern construction systems. In addition, rammed earth is characterized by their good thermal behavior. However, they are achieved by using width thicknesses. In order to face these problems and be competitive in modern buildings market, rammed earth should be adapted to current requirements by using smaller wall thicknesses to optimize the useful floor area and reduce structural limitations. To achieve this goal, thermal properties of rammed earth need to be improved due to the reduction of thickness but also structural limitations can be reduced or even avoided by using rammed earth as enclosure material (prefabricated or in situ) and/or by using stabilization techniques to improve mechanical properties.

8.2 Contribution to the state of the art

The main objective of this paper was to improve the thermal behaviour of rammed earth by doping the material with microencapsulated PCM and to optimize compression strength response after the addition of different types of stabilizers. Furthermore, life cycle assessment (LCA) was used to quantify the environmental impact of adding microencapsulated PCM and stabilizers into rammed earth during the manufacturing phase.

To reach this goal, three different types of rammed earth were formulated with percentages of clay, silt and gravel fixed. Each one has a physical stabilizer (straw or pneumatic fibres by-product), a chemical stabilizer (lime or alabaster) and microencapsulated PCM Micronal® DS5001. Type 1 included straw and lime as stabilizers, type 2 included straw and alabaster and, type 3 included pneumatic fibres and lime. Notice that straw and lime are well known stabilizers in rammed earth and each composition try to use an unknown or not-tested-before stabilizer with a well-known stabilizer.

In order to deduce which components influenced the mechanical properties of each composition and to obtain maximum information with minimum number of experiments, a DoE Box-Behnken was carried out. The three factors analysed were the content of straw or pneumatic fibbers (5–10% in weight), the amount of lime or alabaster (5–10% in weight), and the percentage of microencapsulated PCM (0–10% in weight). Samples tested and the order of manufacture followed a random order to minimize systematic and accumulative errors in results. Table 3 shows the formulations given by the DoE and compression strength results obtained for each composition. The higher compression strength results were obtained by using straw and alabaster as stabilizers.

Table 3. Formulations of the DoE and compression strength results

Run	Matrix mixture (%)	Physical stabilizer (%)	Physicochemical stabilizer (%)	Micronal® (%)	Type 1 (N/ mm^2)	Type 2 (N/ mm^2)	Type 3 (N/ mm^2)
1	80.00	7.50	7.50	5.00	2.60	4.09	1.91
2	80.00	7.50	7.50	5.00	3.06	3.00	1.58
3	80.00	7.50	7.50	5.00	2.53	4.08	1.78
4	80.00	7.50	7.50	5.00	2.33	3.26	1.68
5	75.00	10.00	10.00	5.00	3.05	3.75	1.95
6	77.50	7.50	5.00	10.00	2.84	3.79	1.57
7	72.50	7.50	10.00	10.00	3.38	2.85	1.50
8	72.50	10.00	7.50	10.00	2.73	3.31	1.62
9	82.50	7.50	10.00	0.00	3.19	4.87	1.84
10	80.00	10.00	5.00	5.00	3.13	4.06	1.16
11	77.50	5.00	7.50	10.00	2.57	1.90	1.37
12	87.50	5.00	7.50	0.00	1.91	3.45	1.42
13	80.00	7.50	7.50	5.00	2.59	4.00	1.17
14	82.50	10.00	7.50	0.00	2.47	4.18	1.17
15	87.50	7.50	5.00	0.00	1.81	4.06	1.35
16	80.00	5.00	10.00	5.00	2.40	2.66	1.68
17	85.00	5.00	5.00	5.00	2.43	4.32	1.51

According to the method, models of type 1 and 2 were statistically significant while type 3 were not. DoE is statistically significant if p-value is lower than 5% that means there is a chance less than 5% that a calculation done by this model can occur due to noise in the range studied. For this reason, type 3 was not included in the thermal characterization.

The models gave the equations (1) and (2) defining compressive strength (in N/mm^2) depending on the percentage of stabilizers and microencapsulated PCM used and they were used to define the seven optimal formulations to be thermally tested: the blank (without stabilizers nor microencapsulated PCM) and three compositions for each type with percentage of microencapsulated PCM fixed (0%, 5% and 10%) and compressive strength maximized.

$$\boldsymbol{\sigma_1 = 0.92885 + 0.10341 \cdot (\%Straw) + 0.09017 \cdot (\%Lime) + 0.053543 \cdot (\%PCM)} \quad (1)$$

$$\boldsymbol{\sigma_2 = 3.88896 + 0.14816 \cdot (\%Straw) - 0.10462 \cdot (\%Alabaster) - 0.11798 \cdot (\%PCM)} \quad (2)$$

In Table 4, the main results of the optimization process and thermal characterization are shown.

Table 4. Compressive strength and thermal properties of the seven optimal formulations

Sample		*Matrix mixture (%)*	*Physical stabilizer (%)*	*Physicochemical stabilizer (%)*	*PCM (%)*	*R_c (N/mm^2)*	*k (W/m·°C)*	*Cp (J/kg·°C)*
Matrix		100.00	0.00	0.00	0.00	3.47	0.51	846.5
Type 1	Opt. 1.1	70.17	9.99	9.84	10.00	3.38	0.39	1027.2
	Opt. 1.2	75.00	10.00	10.00	5.00	3.13	0.38	942.6
	Opt. 1.3	80.00	10.00	10.00	0.00	2.86	0.45	836.5
Type 2	Opt. 2.1	75.00	10.00	5.00	10.00	3.66	0.42	1098.9
	Opt. 2.2	80.00	10.00	5.00	5.00	4.26	0.46	934.5
	Opt. 2.3	85.00	10.00	5.00	0.00	4.85	0.50	862.1

Finally, environmental impacts of LCA were calculated for the manufacturing process with Eco-indicator impact point given by Eco-Indicator 99 (EI99) and extracted from the database EcoInvent 2009 (Figure 26).

The main relevant results of this paper were the following:

- The highest compressive strength was obtained by adding alabaster and straw stabilizers into rammed earth (type 2).
- The best thermal properties were achieved in type 1, using straw and lime as stabilizers.
- The addition of stabilizers into rammed earth increased up to 1.5 the impact points of the material in the manufacturing phase.
- The addition of microencapsulated PCM strongly affected LCA results, increasing up to 4.5 the impacts points of rammed earth in the manufacturing phase.
- The use of macroencapsulated PCM (preferably, a more sustainable one) in rammed earth was strongly recommended for further research.

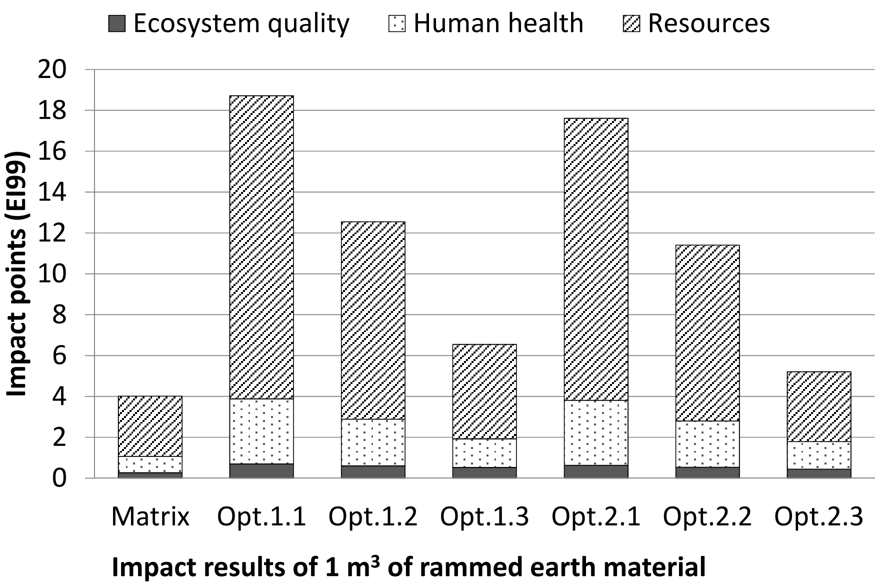

Figure 26. Impact points (EI99) of the manufacturing phase.

8.3 Contribution of the candidate

The candidate actively collaborated in the experimentation design. She performed the experimentation, analysed the data obtained and generated the graphical support for the article. The candidate also leaded the writing and submission preparation as well as the revision process. Co-authors collaborated in the discussion of results and conclusions. This article was published as a result of the successful final degree project of the candidate and motivated by their thesis supervisors.

8.4 Journal paper


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Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA

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9 Use of by-products as additives in adobe bricks: Mechanical properties characterisation

9.1 Introduction

The development of new building materials using by-products as an alternative to raw materials should be encouraged worldwide to face and reduce CO_2 emissions of buildings. There are several studies that demonstrate the potential of a proper material selection in buildings, as in Gonzalez 2006 [1] where authors concluded that savings around 30% of CO_2 emissions could be achieved just by the selection of low-environmental impact construction materials. In addition, by using by-products instead of producing additional new materials to fulfil the same purpose, wastes in landfills can be reduced while preserving raw materials. Not only could environmental issues be improved because, from the economic point of view, costs could be remarkably reduced.

Because of the advantages mentioned before, the interest in using by-products in building materials has notably increased in recent years and, as a result, researchers started investigating their effects in different building materials. There are plenty of by-products that are able to be used in building materials with different nature and shape. For example, different industrial by-products were added in cement based materials, as coal fly ash [2,3], calcareous fly ash [4], steel slag [3,4], foundry sand [3], recycled concrete [3], waste derived from pickling steel [5], among others. By-products from agriculture or other natural by-products as rice stalk fiber [6], seashell [7], bagasse [8], biomass [9], olive stone flour [10], wheat straw residues [10], hemp shiv [11], sunflower bark [11], sunflower pith [11], flax shiv [11], rape straw [11], were also investigated to be used in cement based materials, fired clay bricks, insulations, partition walls, coatings, etc.

Sustainable materials should be used in order to maximize the reduction of CO_2 emissions. Earth used as building material is one of the most abundant materials in the world and it is totally sustainable. Moreover, if earth is used as unfired material, it needs no energy for processing nor generates waste and, in addition, it can be recycled or go back to nature. There are different earthen construction systems but adobe bricks are one of the most interesting due to its similarity to conventional masonry. Moreover, the fabrication process can be easily industrialized and they can be stored.

In Chapter 9, different local and abundant by-products with different nature (industry and agriculture) and shape (pellet and fibre) were added into adobe bricks in order to fulfil the maximum CO_2 emissions reduction. Furthermore, the candidate considers that the marketing of adobe bricks is easier than other earthen construction systems because of, as mentioned before, all their similarities with fired clay bricks extensively used nowadays.

9.2 Contribution to the state of the art

The aim of the investigation was to study the variability of flexural and compressive strength properties of adobe bricks (composed by clay and sand) once six different by-products (Figure 27) were used as additives which are local, abundant and economic. These six by-products can be classified by their nature and shape as Table 5 shows. Mechanical properties were evaluated [12] within a design of experiments (DoE) by using different percentages of fibres (1–3% in weight) or pellets (5–15% in weight). The ranges tested were different because of their substantial different densities.

Figure 27. By-products used as additives in adobe bricks.

Table 5. Classification of by-product according to its nature and shape

		Shape	
		Fibres	*Pellets*
Nature	Agriculture	Straw Corn plant Fescue	Olive stone
	Transport	---	Rubber crumb
	Industry	---	Polyurethane

When using agricultural by-products, adobe bricks could be perfectly reintegrated into the earth once the building has to be demolished. On the other hand, despite adobe bricks cannot be reintegrated once rubber crumbs or polyurethane are added into adobe bricks, their reutilization once the building has to be demolished could be an interesting option because there are no chemical reactions.

The methodology followed was as follows, parameters as the sample mass (500 g of sand, clay and additive), and the amount of water (120 g) were fixed. Moreover, adobe bricks with straw fibres were used as the reference material along the experimentation because it is a well-known additive used in adobe bricks. Results obtained by the other five additives, that had never been tested before, were compared with the reference ones.

Variability of flexural and compressive strength was evaluated by a DoE, which allows maximum information with minimum number of experiments. Specifically, a 3k factorial design was used that means that *k* factors were considered, each at 3 levels (low, intermediate and high). Furthermore, additional centre point runs were added to provide a measure of process stability. As Table 6 shows, each design of experiments had 13 runs with flexural and compression strength tested for each composition. Results of fibres types showed that fescue samples had the best flexural strength behaviour while straw samples had the lowest. In contrast, compressive strength results were very similar in all of them. On the other hand, flexural and compressive strength of pellets types were, in general, strongly reduced.

The model was statistically significant for flexural strength only when the agricultural by-products were used, straw (*S*), corn plant (*CP*), fescue (*F*) and olive stones (*O*). In the case of rubber crumbs (*R*) and polyurethane (*PU*), the model was not statistically significant in the range studied. The DoE was statistically significant if p-value is lower than 5% that means that, there was a chance less than 5% that a calculation done by this model can occur due to noise. On the other hand, compressive strength was statistically significant in the case of *CP*, *F* and *O*; but, *S*, *R* and *PU* were not statistically significant in the range studied due to the same reason explained before. Figure 28 shows flexural and compressive strength behaviour of each type.

Table 6. DoE flexural and compressive strength results of adobe bricks

FIBRES

Run	*Sand (%)*	*Clay (%)*	*Fibres (%)*	*Corn plant (CP)*		*Fescue (F)*		*Straw (S)*	
				Rf (N/mm^2)	*Rc (N/mm^2)*	*Rf (N/mm^2)*	*Rc (N/mm^2)*	*Rf (N/mm^2)*	*Rc (N/mm^2)*
1	27.5	70.5	2.0	0.314	2.149	0.578	2.585	0.279	2.569
2	40.0	58.0	2.0	0.306	2.365	0.486	2.405	0.196	2.071
3	27.5	70.5	2.0	0.395	2.157	0.562	2.365	0.275	2.696
4	40.0	57.0	3.0	0.347	3.253	0.487	2.338	0.271	2.908
5	27.5	70.5	2.0	0.346	2.612	0.549	2.425	0.287	2.090
6	27.5	70.5	2.0	0.361	2.309	0.555	2.367	0.287	2.047
7	40.0	59.0	1.0	0.251	2.610	0.605	2.884	0.157	2.141
8	15.0	83.0	2.0	0.396	3.226	0.373	2.248	0.251	2.281
9	27.5	70.5	2.0	0.322	2.209	0.519	2.310	0.271	2.265
10	15.0	84.0	1.0	0.295	1.980	0.330	2.483	0.196	2.483
11	27.5	71.5	1.0	0.302	1.998	0.468	2.187	0.177	2.560
12	15.0	82.0	3.0	0.381	2.982	0.436	1.937	0.299	2.438
13	27.5	76.5	3.0	0.314	2.584	0.420	1.972	0.285	2.059

PELLETS

Run	*Sand (%)*	*Clay (%)*	*Pellets (%)*	*Olive stones (O)*		*Rubber crumbs (R)*		*Polyurethane (PU)*	
				Rf (N/mm^2)	*Rc (N/mm^2)*	*Rf (N/mm^2)*	*Rc (N/mm^2)*	*Rf (N/mm^2)*	*Rc (N/mm^2)*
1	15.0	70.0	15.0	0.089	1.282	0.107	1.524	0.090	1.776
2	27.5	67.5	5.0	0.164	1.551	0.142	1.605	0.163	1.839
3	27.5	62.5	10.0	0.141	1.455	0.095	1.254	0.103	1.709
4	27.5	62.5	10.0	0.132	1.512	0.103	1.261	0.101	2.031
5	40.0	45.0	15.0	0.074	1.082	0.108	2.013	0.078	1.233
6	27.5	62.5	10.0	0.141	1.447	0.118	1.239	0.110	1.748
7	15.0	80.0	5.0	0.160	1.619	0.105	2.521	0.104	2.627
8	40.0	55.0	5.0	0.109	1.358	0.117	1.704	0.110	1.333
9	27.5	62.5	10.0	0.125	1.227	0.136	1.882	0.142	2.144
10	27.5	62.5	10.0	0.137	1.294	0.158	1.805	0.173	1.550
11	27.5	57.5	15.0	0.102	0.986	0.164	1.206	0.131	1.611
12	40.0	50.0	10.0	0.110	1.105	0.102	1.400	0.137	1.573
13	15.0	75.0	10.0	0.120	1.035	0.138	1.621	0.137	1.455

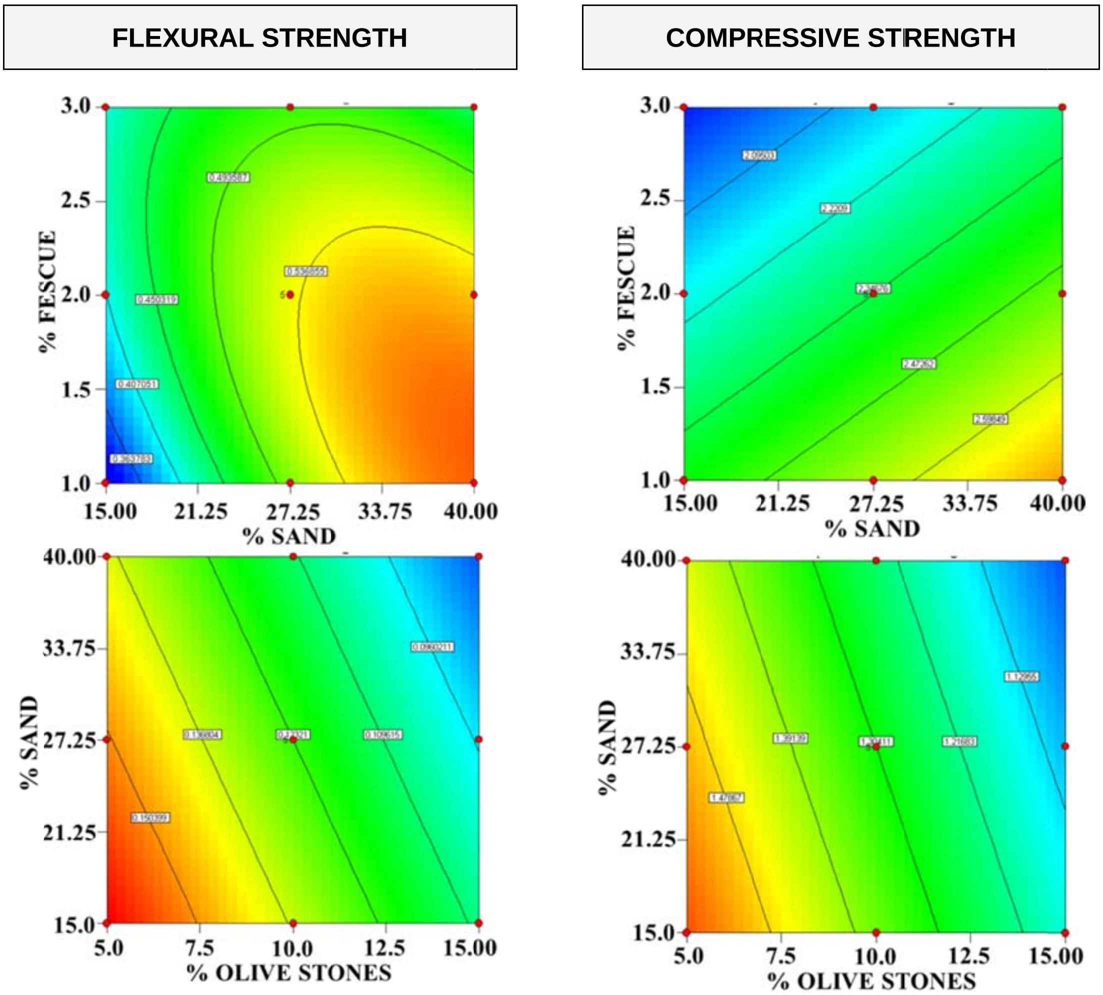

Figure 28. Behaviour of flexural and compression strength of some adobe brick compositions

The optimisation process was done in order to evaluate the variability of both mechanical properties after the incorporation of additives and thus, to select the optima formulations as follows:

1) with flexural strength maximised, without controlling the amount of additives
2) with flexural strength and the amount of additives maximized

Table 7 shows the optima formulations chosen. According to results of optima formulations and maximizing only flexural strength, *F* type achieved the highest flexural strength followed by *CP* and *S* type, and the lowest results were obtained with by *O* type. Compressive strength followed the same trend. In the second optimization process where flexural strength and the amount of additive was maximised, *F* type showed the higher results and *O* type the lowest also, however, in *CP* compressive strength achieved the highest value.

Table 7. Optima formulations selected

	1) Flexural strength maximized						
	Rf (N/mm^2)	*Desirability*	*Sand (%)*	*Clay (%)*	*Additive (%)*	*Rc (N/mm^2)*	*Desirability*
S Type	0.3067	1.00	23.95	73.05	3.00	-	-
F Type	0.5801	0.91	40.00	58.84	1.16	2.6818	0.98
CP Type	0.3869	0.94	15.00	82.00	3.00	2.4950	0.74
O Type	0.1640	0.99	15.00	80.00	5.00	1.5660	0.97
	2) Flexural strength and additive maximized						
	Rf (N/mm^2)	*Desirability*	*Sand (%)*	*Clay (%)*	*Additive (%)*	*Rc (N/mm^2)*	*Desirability*
S Type	0.3067	1.00	23.12	73.88	3.00	-	-
F Type	0.4984	0.75	30.44	66.70	2.86	2.0730	1.00
CP Type	0.3869	0.97	15.00	82.00	3.00	2.4950	0.74
O Type	0.1189	0.63	15.00	71.94	13.06	1.2491	0.64

The main findings of this study were the following:

- The statistical model used during the present work was appropriate to define the equations of flexural and compressive strength of fescue, corn plant and olive stones types and, for flexural strength in the case of straw, with a maximum error of 5% in the ranges studied.

- Flexural strength could be improved by the addition of straw and corn plant but, contrary, fescue and olive stones were not recommended to increase flexural strength of adobe bricks.
- In general, the addition of additives was not recommended to increase compressive strength, except in corn plant, where compressive strength remained constant in the range studied.

9.3 Contribution of the candidate

The candidate designed and performed the experimentation. She analysed the data obtained and generated the graphical support for the article. Furthermore, the candidate also leaded the writing and submission preparation as well as the revision process. Co-authors collaborated in the discussion of results and conclusions.

9.4 Journal paper

Construction and Building Materials 108 (2016) 105–111

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Use of by-products as additives in adobe bricks: Mechanical properties characterisation

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HIGHLIGHTS

- Six by-products from agricultural, transport and appliances are added into adobe.
- A three-level design of experiments is done to evaluate the effect of the additives.
- Flexural and compressive strength of optimised formulas are tested and evaluated.

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10 Adaptation of rammed earth to modern construction systems: Comparative study of thermal behaviour under summer conditions

10.1 Introduction

Rammed earth provides suitable thermal resistance properties into walls using width thicknesses that have been theoretically [1] and experimentally [2] demonstrated. The problem is that construction systems used today tend to reduce thickness and mass of walls in order to reduce the cost of the building but, unfortunately, rammed earth is not able to provide a proper thermal behaviour by itself when thin walls are used [3]. For this reason, the addition of insulation into thin rammed earth walls is considered as an interesting option by researchers. There are some recent studies regarding insulated rammed earth, as Dong 2015 [4] where authors optimized different design parameters of insulated rammed earth as shades, windows and insulation thickness; and Windstorm 2013 [5] that was focused on the design of contemporary stabilized rammed earth incorporating reinforcing steel and rigid insulation to satisfy current American building codes. However, stabilized rammed earth and high embodied energy insulation materials (extruded polystyrene, mineral wool or polyisocyanurate) were used in these studies. Therefore, benefits of rammed earth as sustainable material is being negatively affected if the system is not considered and designed as a whole, following the same sustainable criteria.

For the first time, a real sustainable and low-tech construction system based on insulated thin rammed earth walls was thermally tested at real scale. The construction system under study was based on non-stabilized rammed earth (only straw fibres were used in order to reduce shrinkage in the curing process), wooden insulation fibres panels and an external coating based on clay and straw. Furthermore, sustainable criteria were also used when designing the roof construction system that is based on a wooden green roof.

In this study, it was also demonstrated that sustainable, "low-tech" and low embodied energy materials and construction systems can be adapted to different site conditions in order to provide environmental and economic savings by using local resources and, furthermore, similar thermal behaviour than conventional construction systems with higher embodied energy can be achieved.

10.2 Design and construction phase of rammed earth building prototypes

Two identical rammed earth building prototypes were built in the experimental set-up of Puigverd de Lleida (Spain). This location has Csa climate according to Geiger climate classification [6] that corresponds to Mediterranean climate (C: Warm temperate, s: Summer dry, a: hot summer).

The full construction was divided in two phases. First of all, the two rammed earth building prototypes were built at the same time and, once they were finished and completely monitored, different experimentation was carried out during some summer and winter campaigns. Once the experimentation was finished, the second construction phase was performed that consisted on the insulation of one cubicle. The description of both cubicles once they were completely finished is detailed hereafter.

Both prototypes have 2.4 x 2.4 x 2.4 m as inner dimensions and orientation N–S, 0º, with an insulated metal door in the north wall and no windows. Foundations consist of a 3.60 x 3.60 m reinforced concrete base with gravel drainage layer. Construction systems of both rammed earth building prototypes walls consist on:

- Non-insulated rammed earth (Figure 29, RE) composed by load-bearing rammed earth walls of 29 cm (Figure 30 B and C) with ground humidity protection of 19 cm (one row of alveolar brick and a polypropylene waterproof sheet, see Figure 30 A).
- Insulated rammed earth (Figure 29, IRE): The same construction system than RE but walls are insulated with natural wood fibres panels of 6 cm (SYLVACTIS 140 SD ITE) (Figure 31 A, B and C) and **1** cm of natural coating based on clay and straw (thickness <2 cm) (Figure 31 C, D and E).

Following the same sustainable guidelines, a wooden green roof was selected as roofing system (Figure 32) that was insulated with 5 cm of insulation.

The candidate wants to notice that there is an errata in the figure that contains the construction details of rammed earth cubicles (Figure 2 of the published paper). The correct construction details are the ones illustrated in Figure 29 of this thesis. The correction has been requested to Applied Energy Journal.

The candidate would like to thank by mentioning all the collaborators involved in the second phase of the construction. The wooden insulation panels were donated by Actis and the full installation was achieved with the active support and collaboration of EPSEB (UPC) researchers. Materials of clay and straw based coating were also donated by two local companies, Fet de Terra donated the clayey material and Farratges la Noguera SL donated the straw fibers. The coating process was installed with the active support and collaboration of GICITED (UPC) researchers and Terram Association.

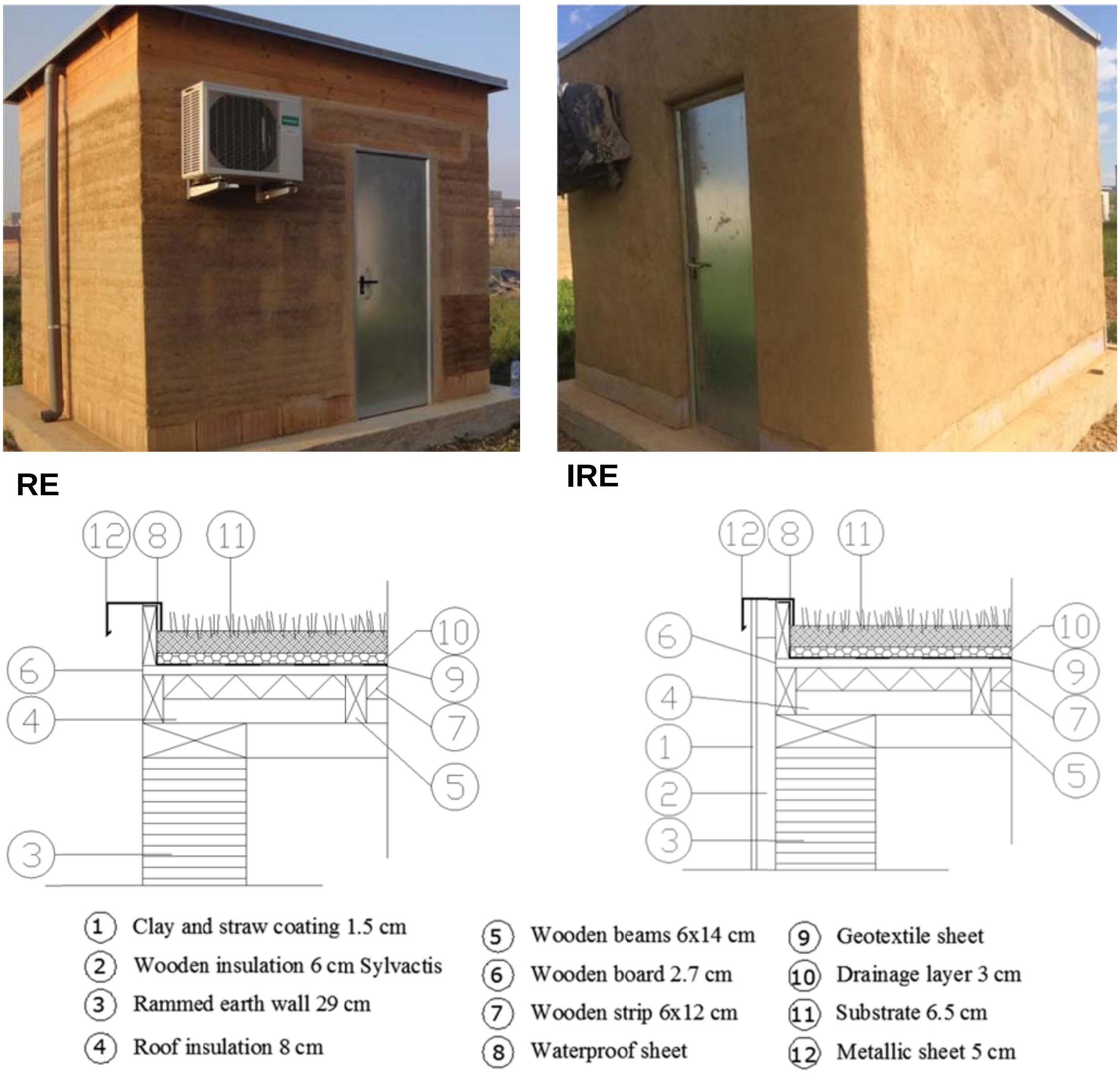

Figure 29. Construction details of rammed earth building prototypes

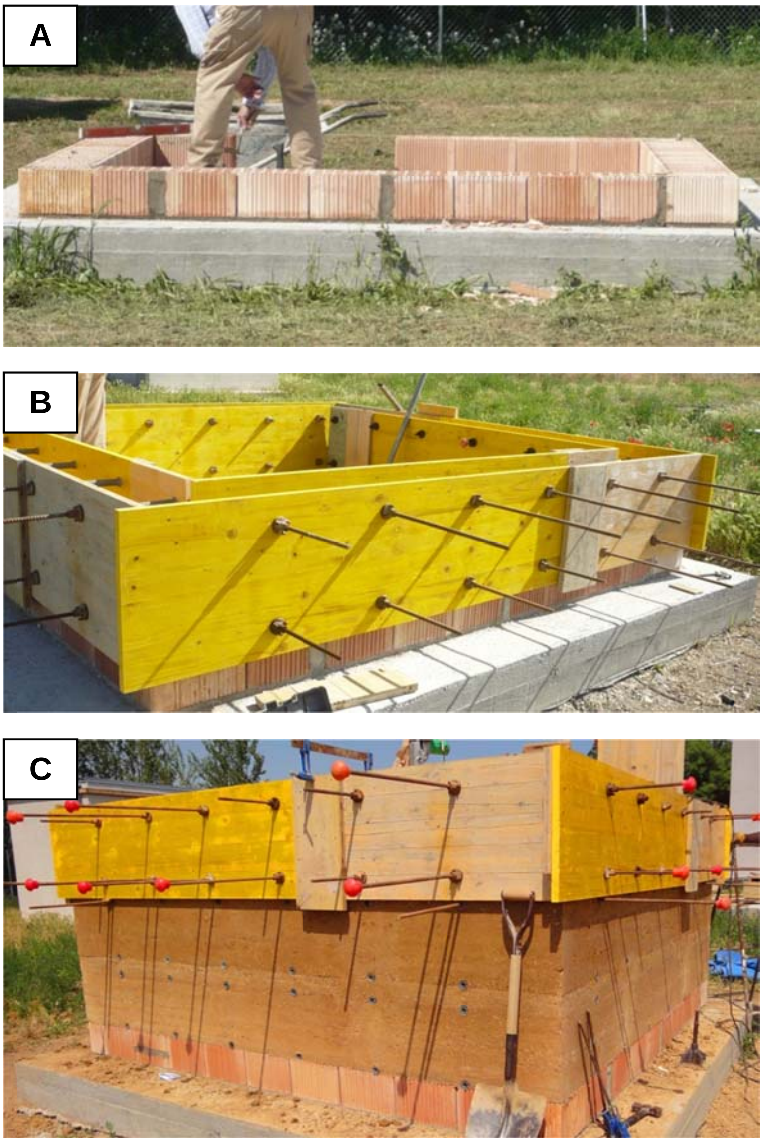

Figure 30. Ground humidity protection (A) and construction of rammed earth wall (B, C)

Figure 31. Installation of wooden insulation panels (A, B, C) and outer coating (D, E, F)

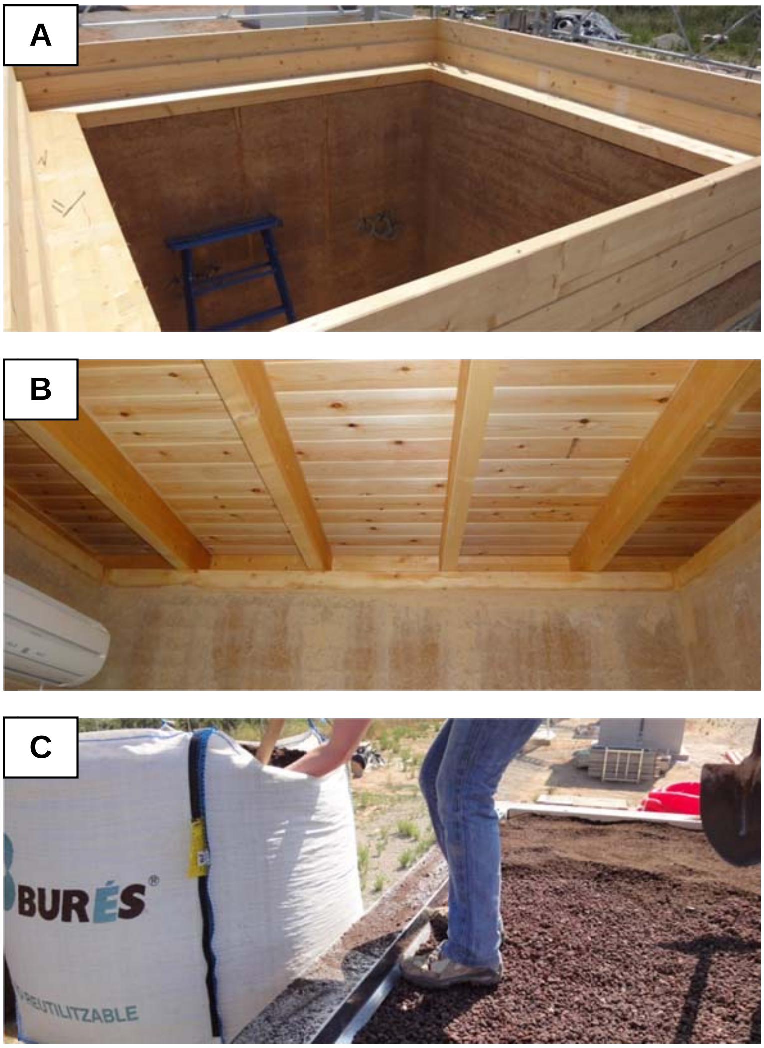

Figure 32. Wooden structure (A), wooden roof (B) and green roof (C) construction

Both cubicles were monitored so as to register all the data needed to evaluate and compare the thermal behavior of RE and IRE prototypes. Inner ambient temperature and humidity of cubicles was registered using ELECTRONIK EE21 placed at a height of 1.5 m with ± 2% accuracy. Furthermore, inner surface wall temperatures (north, south, east and west), temperature inside walls (north, south, east and west) and temperature between layers (coating - insulation - rammed earth wall in IRE prototype) were measured using Pt-100 DIN B sensors with ± 0.3ºC error. Location of sensors of each prototype mentioned above is shown in Figure 33.

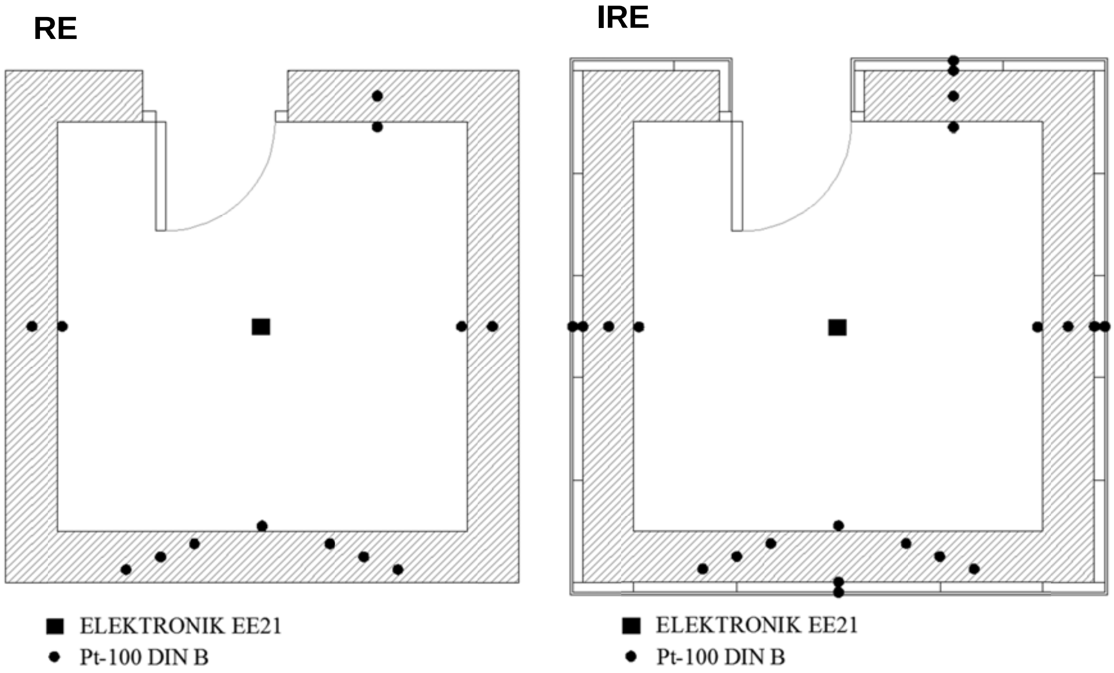

Figure 33. Sensors location in RE and IRE prototypes

Furthermore, each cubicle has a Fujistsu Inverter ASHA07LCC as domestic heat pump to cover H&C demand and its electrical energy consumption is measured by an electricity meter.

10.3 Contribution to the state of the art

The aim of this research was to experimentally demonstrate that similar thermal behaviour can be achieved by only using sustainable and low embodied energy construction systems and materials when comparing with conventional ones with high embodied energy. This comparison was done in the experimental set-up of Puigverd de Lleida (Spain) by five building prototypes built with different construction systems. All of them had the same inner dimensions (2.4 x 2.4 x

2.4 m), orientation (N–S, 0º), and an insulated metal door in the north façade. All of them were built under a foundation based on a 3.60 x 3.60 m reinforced concrete base with gravel drainage layer and all roofs were insulated using 5 cm of insulation. Buildings prototypes dimensions and shape were designed to maximize the effect of the envelope in the thermal performance of the building. Moreover, building prototypes had to be capable to test different construction systems and materials but, at the same time, costs related to the construction and dismantling had to be minimized.

Two building prototypes were built using rammed earth and wooden roof as the main construction systems as detailed in Chapter 10.2 (from Figure 29 to Figure 32) and, the other three, were built using the following conventional Mediterranean construction systems detailed in Figure 34:

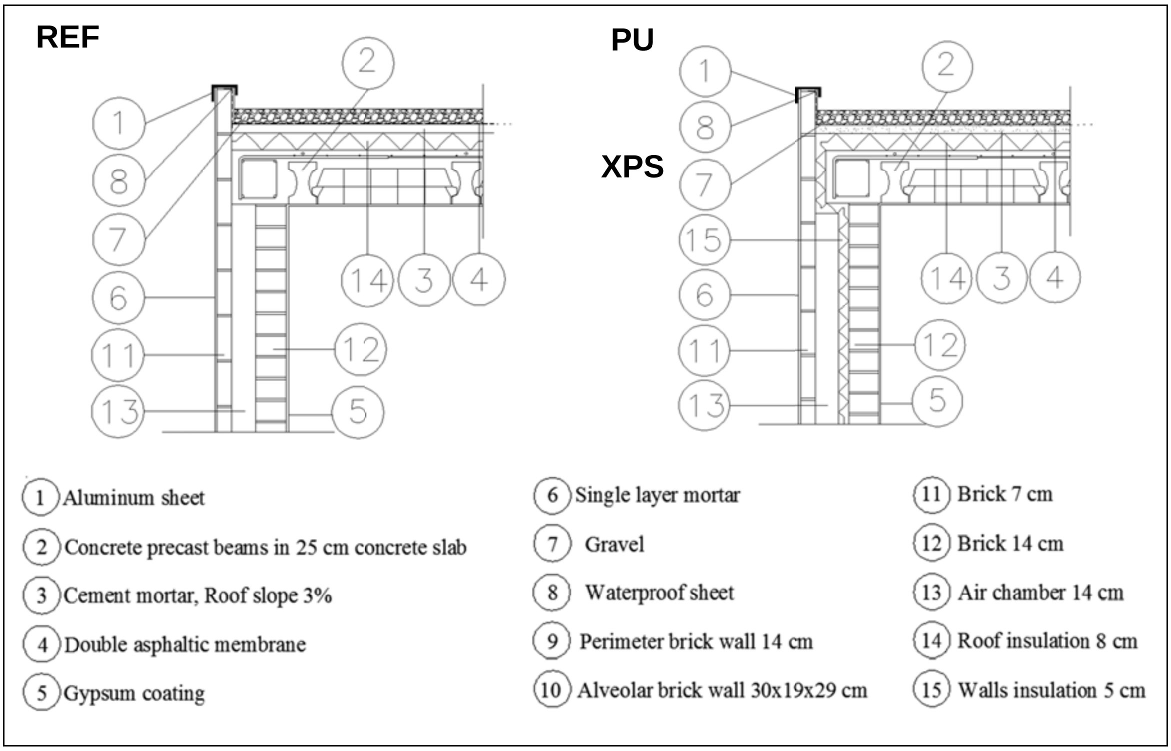

Figure 34. Conventional Mediterranean construction systems details

Building prototypes described in Figure 34 were also equally monitored with inner temperature and humidity sensors (ELECTRONIK EE21 placed at a height of 1.5 m with ± 2% accuracy) and surface wall temperatures in north, south, east and west walls (Pt-100 DIN B sensors with ± 0.3ºC error). Moreover, H&C demand was covered by the same domestic heating pump (Fujistsu Inverter ASHA07LCC facing north) and electrical energy consumption was measured.

The experimental set-up of Puigverd de Lleida also registered weather data (using two MIDDLETON SOLAR meters SK08 to measure horizontal and vertical radiation), ambient temperature and humidity sensors (ELEKTRONIK EE21) protected against solar radiation by a metallic shield, and wind speed and direction (DNA 024 anemometer).

This experimentation was carried out during summer 2015 season. In order to test and compare thermal behaviour of the five cubicles, two different tests were performed:

- Free floating: No use of heat pump to compare the evolution of inner temperatures.
- Controlled temperature: Heat pumps were set under three different demand situations: two within common comfort range (21ºC and 24ºC) and one with high cooling requirements (18ºC). In controlled temperature tests, energy consumptions were also measured.

Successful outcomes were achieved in this experimentation when rammed earth building prototype was insulated (*IRE*). In free floating experimentation, inner temperatures in each cubicle were evaluated in sunny and cloudy days, and moreover, thermal stability coefficient (TSC) and thermal lag were also theoretically and experimentally calculated. Results showed that both cubicles without insulation (*RE* and *REF*) had the largest indoor temperature oscillations while insulated cubicles (*IRE*, *PU* and *XPS*) behaved similarly regardless the construction system tested and the outer climatic conditions as Figure 35 shows.

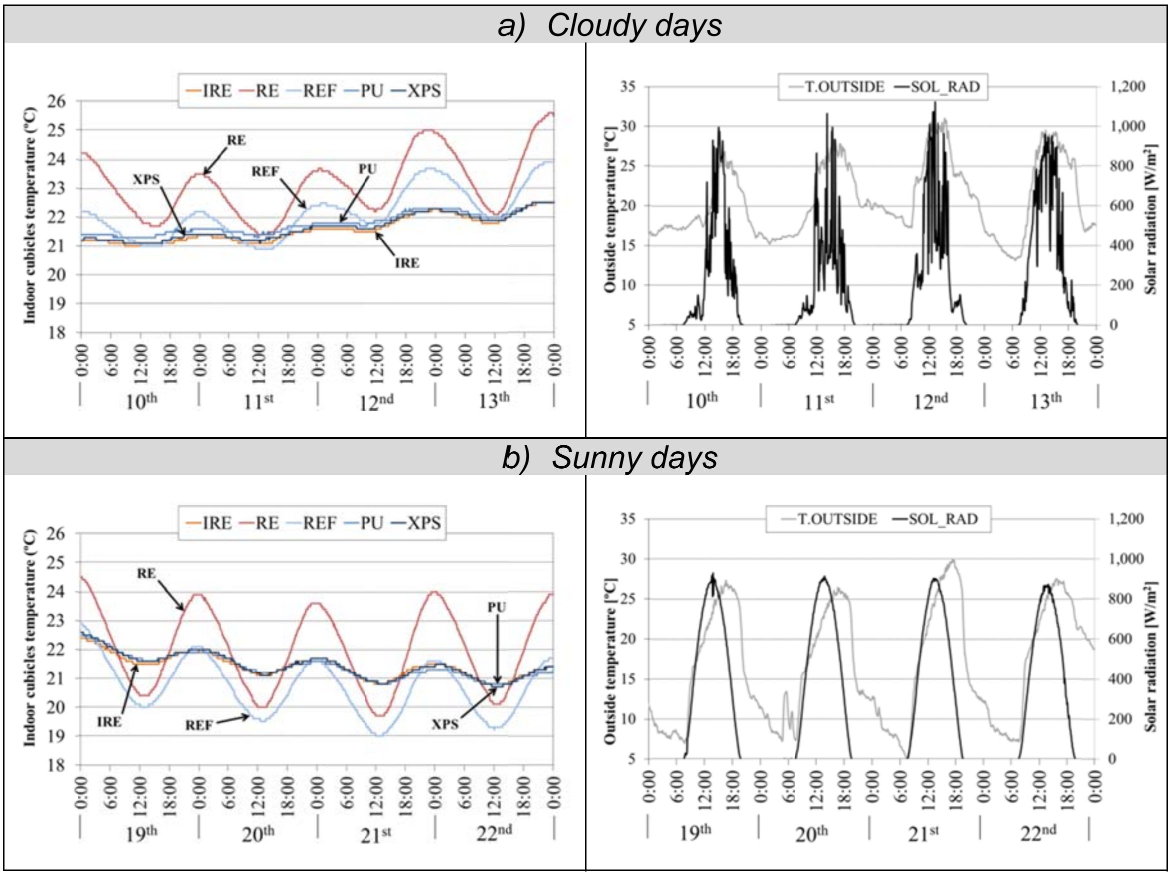

Figure 35. Interior temperature profiles of cubicles and ambient temperature of cloudy and sunny days.

Thermal lag (between outside ambient temperature and inner surface south wall) and TSC are dynamic parameters evaluated in each south wall in order to compare the dynamic response of each construction system. Both dynamic parameters were evaluated following the methodology in [7] that adjusts both temperature profiles to a sinusoidal curve using equation (3) as Figure 36 (left) shows.

$$\boldsymbol{Temp} = \boldsymbol{a_0} + \boldsymbol{a_1} \cdot \boldsymbol{t} + \boldsymbol{a_2} \cdot \mathbf{sin}(\boldsymbol{\omega_1} \cdot \boldsymbol{t} + \boldsymbol{a_3}) + \boldsymbol{a_4} \cdot \mathbf{sin}(\boldsymbol{\omega_2} \cdot \boldsymbol{t} + \boldsymbol{a_5}) + \boldsymbol{a_6} \cdot \mathbf{sin}(\boldsymbol{\omega_3} \cdot \boldsymbol{t} + \boldsymbol{a_7}) \quad (3)$$

where,

ω_1, ω_2, ω_3 frequencies corresponding to periods of 24, 12, and 6 h, respectively

a_i coefficients used to adjust the function.

This methodology was used to calculate thermal lag of each construction system under cloudy and sunny day conditions. The evaluation was done in several days (each one showed in Figure 35) although results presented in Figure 36 (right) were the average and the standard deviation in each climatic condition.

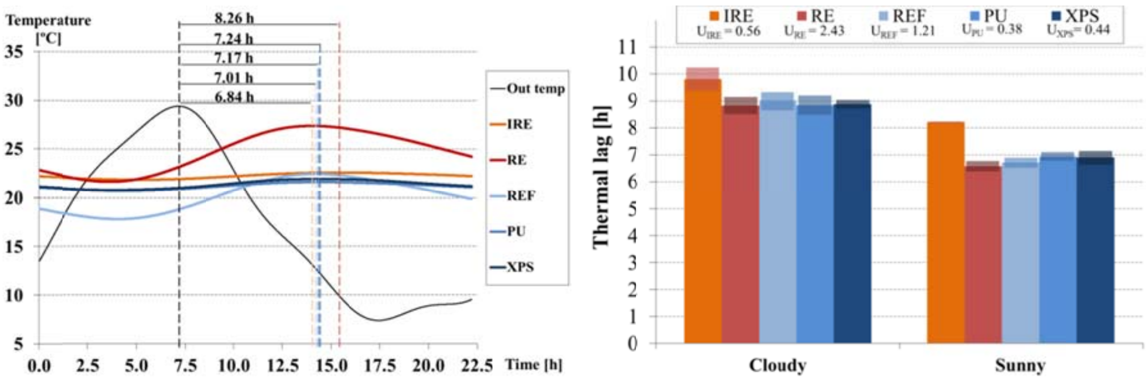

Figure 36. Thermal lag evaluation in one specific day (left) and average thermal lag and standard deviation of results in cloudy and sunny days (right)

Thermal stability coefficient results obtained also showed that *IRE* had the best thermal stability when comparing results against *PU* and *XPS* (26% and 34% higher than *IRE*, respectively, in cloudy days; and 30% and 66%, in sunny days).

Table 8 shows the results of the energy consumed and energy savings of each cubicle under controlled temperatures (18ºC, 21ºC and 24ºC) in one week period. Although set points used were different, *IRE* and *XPS* cubicles experienced 30% of energy savings if results were compared with the reference

(*REF*). Otherwise, *PU* cubicle increased its energy savings from 30% in set point 18 ºC to 40% and 50% using 21 ºC and 24 ºC, respectively.

Table 8. Total energy consumption [kWh] and energy savings [%] in one week

Set Point [ºC]	*Energy [kWh] and savings [%]*	*IRE*	*RE*	*REF*	*PU*	*XPS*
18	[kWh]	20.06	32.52	27.52	19.38	20.45
	[%]	-27.1	+18.2	0.0	-29.6	-25.7
21	[kWh]	15.00	28.56	21.81	13.01	14.46
	[%]	-31.2	+30.9	0.0	-40.3	-33.7
24	[kWh]	8.34	15.77	11.54	5.91	7.70
	[%]	-27.7	+36.6	0.0	-48.8	-33.3

Furthermore, the wooden insulation effect in *IRE* cubicle was also evaluated in free floating and controlled temperatures. The insulation effectiveness was demonstrated by plotting the thermal profile of *RE* and *IRE* south walls (Figure 37) in one day with the longest thermal gradient between coating-insulation and inner surface wall temperatures.

Temperature profiles of both south walls in free floating conditions (Figure 37 A) showed large temperature fluctuations in *RE* cubicle while in *IRE* cubicle remained almost constant. In controlled temperature, wooden insulation was able to reduce up to 90% the temperature of the south wall at set point 18ºC whereas rammed earth only reduced 10%. Similar behaviors were observed at set point 21ºC and 24ºC. It is important to highlight that temperature of set points were not reached in *RE*, being always higher and not constant, while in *IRE* were perfectly reached.

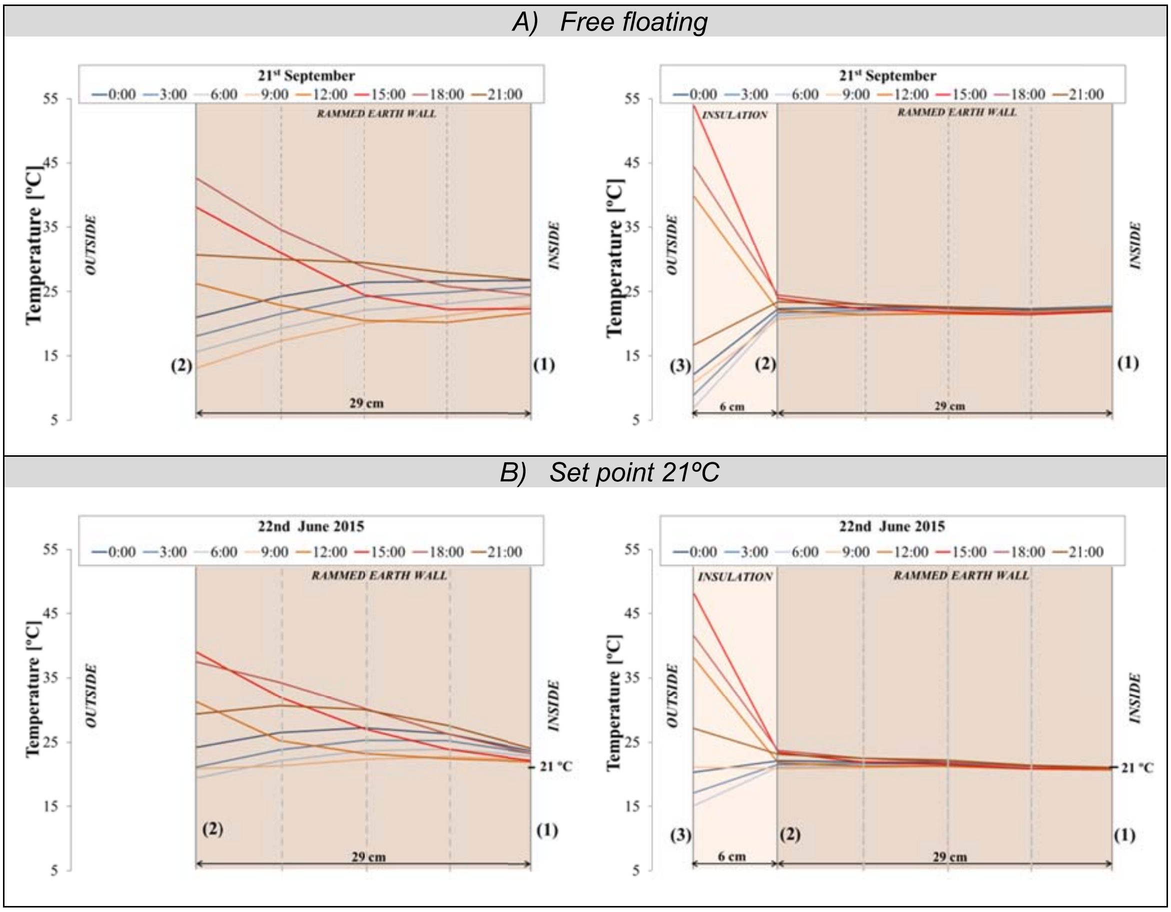

Figure 37. Thermal profile of IRE (right) and RE (left) south wall [A) free floating, B) set point 21ºC]

The main findings of this research were the following:

- The reduction of rammed earth wall thickness heavily penalized the thermal behavior.
- Thermal response of thin rammed earth wall could be notably improved by using 6 cm of sustainable wooden insulation and achieve similar inner temperature profiles in free floating conditions than conventional Mediterranean construction systems with high embodied energy.

- The best dynamic parameters with the longest thermal lag and the best thermal stability coefficient were achieved in insulated rammed earth building prototype.
- The addition of an insulating wood panel of 6 cm in thin rammed earth walls had a significant effect in the thermal performance of the whole building, showing a reduction of the electrical energy consumption of heat pumps around 45% when operating at different set points.
- Wooden insulation panels reduced the temperature between outer and inner surface south wall around 90% meanwhile rammed earth reduced around 10%
- The effect of rammed earth was more visible when insulation material was not added because temperature differences between inner and outer surfaces were bigger.
- It was experimentally demonstrated that insulated rammed earth cubicle (IRE) behaved similarly than conventional construction systems in summer season under free floating and controlled temperature conditions.

Structural limitations of rammed earth walls are aggravated when using thin walls; however, these limitations could be avoided if rammed earth is used as enclosure.

10.4 Contribution of the candidate

The candidate led all the experimentation and she analysed the data obtained to generate the graphical support for the article. Thermal calculations were done in collaboration with co-authors so as to show as much information as possible related to thermal behaviour and properties. Furthermore, the candidate also led the writing and submission preparation as well as the revision process. Co-authors collaborated in the writing and, specially, in the discussion of results and conclusions.

10.5 Journal paper

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Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions

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Serrano S, de Gracia A, Cabeza LF. Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions. Applied Energy 2016;175:180-188.

DOI: 10.1016/j.apenergy.2016.05.010

10.6 References

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11 Conclusions and recommendations for future work

11.1 Conclusions of the thesis

The present thesis has contributed to the reduction of the energy consumption of buildings by acting in envelope materials and construction systems. An overview of the total energy consumption in European buildings and H&C energy consumption was deeply evaluated. This study demonstrated that, although buildings are more efficient than 20 years ago (represented by the energy intensity driver that has notably decreased), the total energy and the H&C energy use in residential buildings in Europe has increased. This increasing trend was mainly affected by activity and use intensity drivers behaviour which demonstrate that quality life of European citizens is better than 20 years ago (the number of households increased, persons living in each household decreased and, floor area per person also increased). Therefore, in order to successfully ensure GHG emissions reduction and climate change mitigation in a near future, energy efficiency of buildings should be improved in a more ambitious way.

This PhD thesis was focused on materials and construction systems used in buildings envelopes because they were identified as one of the key elements that are directly related to the energy consumed in buildings. To achieve this goal, PCM gypsum interior coatings and earth-based sustainable materials are deeply studied at laboratory and pilot plant scale.

PCM gypsum interior coatings aimed towards the reduction of the energy consumption in the use phase of buildings. To achieve this goal, PCM was added in a common gypsum matrix by using four methods that did not present leakage. An extensive characterization was performed in order to evaluate how properties were affected by the addition of paraffin wax PCM using three different inclusion methods and, therefore, how the addition of this PCM could condition the implementation of these three materials in buildings. Furthermore, a simple solution is proposed to avoid problems regarding fire safety of paraffin wax PCM. The most important conclusions of this part are:

- The addition of PCM into a gypsum matrix strongly affects fresh state properties varying setting times, formulation to achieve a proper consistency, adherence, and volumetric variations in a different way depending on the inclusion method used.
- Especially direct incorporation, but also microencapsulation, needs the addition of setting retardant into the formulation if *in situ* implementation is used, increasing the final cost of the material.
- The three methods of PCM incorporation can be used in prefabricated boards.
- Impregnation process was the method that can accept higher percentage of PCM if needed without affecting the hydration process, being the porosity a key parameter that will condition the impregnation capacity of gypsum.
- Physical and mechanical properties are also notably affected by the inclusion method used and they should be taken into account once placed in building envelopes.
- Regarding thermal properties, heat capacity is increased by the addition of paraffin wax PCM taking advantage of sensible storage of PCM and thermal conductivity was only reduced in microencapsulation method.
- Multi-layered PCM gypsum solution proposed behaved successfully against fire. However, the thickness of common gypsum added as fire barrier should be optimized in order to use the thicker PCM gypsum possible.

To cover all PCM inclusion methods with no presence of leakage, thermal properties of shape stabilized fatty-ester PCM (bio-based PCM) are assessed regarding the way to introduce the shape stabilised fatty-ester PCM into common gypsum, decreasing the thermal conductivity due to the organic nature of the PCM. This study demonstrates that the heat storage capacity of the material is higher using sheets than pellets.

Earth is an appropriate material to be used as building material and to reduce the energy consumption of buildings due to its sustainability, availability, low environmental impact and low cost. However, earth-based materials need to be updated to current building requirements by reducing their thickness, but at the same time, thermal properties should be improved to mitigate the penalties of reducing the wall thickness. The present thesis demonstrates that the reduction of rammed earth wall thickness can be compensated in different ways:

- Mechanical properties can be improved by the addition of low environmental impact stabilisers as straw, alabaster and lime and thermal properties can be improved by the addition of PCM in order to increase the heat storage capacity of the material.
- Insulated thin rammed earth walls behave similarly or even better than conventional construction systems regarding thermal behaviour in summer conditions with similar wall thicknesses.
- Mechanical limitations of thin rammed earth walls can be avoided if the construction system is used as enclosure instead of bending walls.

Following the same guideline of reducing the energy consumed by buildings and their effect in the environment, the addition of different types of by-products into adobe bricks becomes an interesting solution to reduce wastes while improving mechanical, thermal and/or acoustic properties. The effect on mechanical properties of adding different agricultural by-products with different shapes (fibres or pellets) into adobe bricks is assessed in this thesis and the main conclusions are the following:

- The design of experiments becomes a useful tool to evaluate the effect of adding different by-products into adobe bricks regarding mechanical properties.
- However, the method has some limitations because results cannot be extrapolated out of the range of study.
- In general, flexural strength is improved when agricultural fibres are added into adobe bricks but, in contrast, compressive strength is negatively affected by the addition of any type of by-product.

11.2 Recommendations for future work

This thesis demonstrates that paraffin wax PCM is a proper material that can be added into common gypsum with the aim of increase the TES in building envelope passive systems and, therefore, the energy consumed in buildings during the operation phase can be reduced. Furthermore, different problems related to the use of paraffin wax PCM in interior coatings as the behaviour against fire can be easily avoided. However, the use of paraffin wax PCM has a high environmental impact because it comes from oil, a non-renewable source. Furthermore, it also has a high cost (especially when it is used as microencapsulated PCM) that can hinder the marketing and the possibility of adding higher percentages of PCM. Therefore, in order to maximize the reduction of the energy consumption and the environmental impact of buildings, more environmentally friendly PCM materials should be used in PCM gypsum materials and, in general, in building materials as well as in earth based ones. Fatty acids, bio-based PCM and natural oils with an appropriate melting temperature and thermal properties could be good candidates to be used in gypsum PCM materials. In addition, the effect of the addition of PCM in interior coating materials into acoustic properties should be also deeply analysed.

Regarding sustainable earth based materials, two main recommendations for future work were found in the use of by-products: on one hand, increase the percentage of by-products added into adobe bricks and evaluate the penalties of increasing the amount of by-products in mechanical properties while comparing the benefits on thermal and acoustic properties. On the other hand, extend the research by using other types of by-products, preferably, the natural ones so as to obtain completely returnable, reusable or recyclable building materials. In the use of thin rammed earth walls, the candidate proposes one future research line focused on the use of rammed earth just as enclosure in order to avoid or reduce structural limitations. Furthermore, if it is used as prefabricated walls, the material could be more homogeneous because the manufacture and process can be controlled.

12 Other research activities

12.1 Other publications

Other scientific research about energy consumption in buildings, building materials and TES was carried out during the execution of this thesis. The resulting publications are listed below:

- Barreneche C, de Gracia A, Serrano S, Navarro ME, Borreguero AM, Fernández AI, Carmona M, Rodríguez JF, Cabeza LF. Comparison of three different devices available in Spain to test thermal properties of building materials including phase change materials. Applied Energy 2013;109:421-427.
- Cabeza LF, Urge-Vorsatz D, McNeil M, Barreneche C, Serrano S. Investigating greenhouse challenge from growing trends of electricity consumption through home appliances in buildings. Renewable & Sustainable Energy Reviews 2014;36:188-193.
- Ürge-Vorsatz D, Cabeza LF, Serrano S, Barreneche C, Petrichenko K. Heating and cooling energy trends and drivers in buildings. Renewable & Sustainable Energy Reviews 2015;41:85-98.
- Barreneche C, Navarro H, Serrano S, Cabeza LF, Fernandez AI. New database on phase change materials for thermal energy storage in buildings to help PCM selection. Energy Procedia 2014;57:2408-2015.
- Haurie L, Serrano S, Bosch M, Fernández AI, Cabeza LF. Single layer mortars with microencapsulated PCM: Study of physical and thermal properties, and fire behavior. Energy and Buildings 2016;111:396-400.
- Serrano S, Rincón L, González B, Navarro A, Bosch M, Cabeza LF. Rammed earth walls in Mediterranean climate: material characterization and

thermal behavior. Accepted in International Journal of Low-Carbon Technologies 2016

- Cabeza LF, Palacios A, Serrano S, Ürge-Vorsatz D, Barreneche C. Evaluation of past projections of total energy consumption. Sent to Renewable & Sustainable Energy Reviews
- Cabeza LF, Ürge-Vorsatz D, Palacios A, Ürge D, Serrano S, Barreneche C. Trends in penetration and ownership of household appliances. Sent to Energy and Buildings

12.2 Contributions to conferences

The PhD candidate also contributed to some national and international conferences:

- Barreneche C, de Gracia A, Serrano S, Navarro ME, Borreguero AM, Fernández AI, Carmona M, Rodríguez JF, Cabeza LF. Comparison of three different equipments available in Spain to test thermal properties of building materials including phase change materials. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- Serrano S, Barreneche C, de Gracia A, Fernández AI, Cabeza LF. Optimization and improvement of rammed earth incorporating PCM. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- Rincón L; Serrano S; Castell A; Pérez G; Cabeza LF. Thermal inertia of rammed earth compared to alveolar brick facade with phase change materials. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- Serrano S, Barreneche C, Rincón L, Fernández AI, Cabeza LF. Mejora de la inercia térmica de un muro de tapia mediante la adición de materiales de

cambio de fase. XII Congreso Nacional de Materiales y XII Congreso Iberoamericano de Materiales 2012, Alicante (Spain).

- Serrano S, Barreneche C, Rincón L, Boer D, Castell A, Cabeza LF. Stabilized rammed earth incorporating PCM: optimization and improvement of thermal properties and life cycle assessment. SHC 2012 - International Conference on Solar Heating and Cooling for Buildings and Industry, San Francisco (USA).
- Rincón L, Serrano S, Navarro L, Castell A, Cabeza LF. Experimental thermal behaviour of an innovative insulation material under real operating conditions. Eurosun 2012, Rijeka (Croatia).
- Solé C, Serrano S, Navarro L, Barreneche C, Rincón L, Cabeza LF. Laboratory and pilot plant experiments with rammed earth walls. COINVEDI 2012 - 2nd International Conference on Construction and Building Research, Valencia (Spain).
- Barreneche C, Navarro H, Serrano S, Cabeza LF, Fernández AI. New database on phase change materials for thermal energy storage in buildings to help PCM selection. ISES SOLAR WORLD CONGRESS 2013, Cancún (México).
- Serrano S, Barreneche C, Navarro A, Haurie L, Fernández AI, Cabeza LF. Characterization of mechanical, thermophysical and fire reaction behaviour of gypsum with suspended PCM. International Sustainable Built Environment Conference – ISBE 2014, Doha (Qatar).
- Serrano S, Barreneche C, Navarro A, Haurie L, Gallardo A, Fernández AI, Cabeza LF. Evaluation of the fresh state properties of gypsum with PCM using three different PCM inclusion methods. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).
- Sol S, Pérez G, Serrano S, Barreneche C, Fernández AI, Cabeza LF. Comparative study of embodied energy using different thermal insulation

materials. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).

- Rincón L, Serrano S, Castell A, Pérez G, Cabeza LF. Thermal behavior of rammed earth in buildings with internal heat loads compared to conventional brick facades: experimental study. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).
- Serrano S, Barreneche C, Navarro A, Haurie L, Gallardo A, Fernández AI, Cabeza LF. Evaluation of the fresh state properties of gypsum with PCM using three different PCM inclusion methods. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).
- Haurie L, Serrano S, Bosch M, Fernández AI, Cabeza LF. Addition of microencapsulated PCM into single layer mortar: Physical and thermal properties and fire resistance. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).
- Rincon L, Serrano S, Cabeza LF, González B, Navarro A, Bosch M. Experimental rammed earth prototypes in Mediterranean climate. VERSUS 2014 - International Conference on Vernacular Heritage, Sustainability and Earthen Architecture, Valencia (Spain).
- Serrano S, Barreneche C, Navarro A, Haurie L, Fernandez AI, Cabeza LF. Improvement of fire reaction behaviour of gypsum with paraffin PCM. GREENSTOCK 2015 - The 13th International Conference on Energy Storage, Beijing (China).
- Serrano S, Gonzalez B, Navarro A, Cabeza LF. Comparative study of sustainable and Mediterranean conventional constructive systems thermal behavior. INNOSTORAGE - Advances in Thermal Energy Storage 2016, Beer-Sheva (Israel).

12.3 Others

12.3.1 Awards

- Best Poster Award of EUROSUN 2012: 'Experimental thermal behaviour of an innovative insulation material under real operation conditions'.

12.3.2 Books

- Rincón L, Serrano S, Cabeza LF, González B, Navarro A, Bosch M. Chapter: Experimental rammed earth prototypes in Mediterranean climate. Earthen Architecture. Past, Present and Future 2014. CRC Press, London. ISBN: 978-1-138-02711.

12.3.3 Projects participation

- EFFIBUILDINGS: Thermal Energy Storage with phase change materials for energy efficiency of European Building stock, PIIF-GA-2009-253914, 2010-2011.
- NeCoE-PCM: Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings, Action TU0802, 2009-2012.
- INNOSTOCK 2012, The 12th International Conference on Energy Storage, 2012
- El almacenamiento de energía térmica como herramienta de mejora de la eficiencia energética en la industria (TES in industry), ENE2011-22722, 2012-2014.
- EUROTHERM Seminar Nº99 - Advances in thermal Energy Storage, 2014

Currently participating in:

- Estudio del potencial de valorización y reutilización del *filler* de las plantas de Villamayor De Gallego (Zaragoza) y Torrelameu (Lleida).
- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica, ENE2015-64117-C5-1-R, 2016-2018.
- Use of innovative thermal energy storage for marked energy savings and significant lowering of CO_2 emissions (INNOSTORAGE), PIRSES-GA-2013-610692, 2013-2017.
- PhD on Innovation Pathways for TES (INPATH-TES), European Union's Horizon 2020 research and innovation programme under grant agreement No 657466, 2015-2018

12.3.4 Organizing committee participation

- Innostock 12th International Conference on Thermal Energy Storage
- Eurotherm Seminar nº 93 - Thermal energy storage and transportation: materials, systems and applications