Adaptation of energy storage systems to Cultural Heritage: the application of Phase Change Materials technology to historical buildings and objects

A. Bernardi[1], F. Becherini[1], M.D. Romero-Sanchez[2], Á. M. López-Buendía[2], A. Vivarelli[1], P. Moretti[1], G. Baldisseri[3], C. Ghiretti[3], L. Pockelé[4]

ABSTRACT

The application of Phase Change Materials (PCMs) technology to Cultural Heritage has been investigated within the European MESSIB (Multi-source Energy Storage System Integrated in Buildings) project, aimed at developing, evaluating and demonstrating an affordable multi-source energy storage system integrated in buildings, based on new materials, technologies and control systems, for significant reduction of energy consumption, improvement of energy management in terms of quality, security and indoor environment.

Firstly, the identification of the strong and weak points, the technical and non-technical barriers and the possible solutions to apply PCMs in cultural heritage buildings have been analyzed in general and also through simulations in real case studies: the energy behavior of selected buildings has been studied to evaluate the percentage of energy savings related to the use of the new technology.

Secondly, microencapsulated PCMs in the form of powder and emulsion incorporated in different materials (gypsum, silicone, foam) have been studied in the laboratory and then tested in two experimental sites, the Santa Croce Museum in Florence (Italy) and the Archaeological Museum in Novelda-Alicante (Spain). Numerous thermal cycle tests have been performed to evaluate the effect of using these materials on the microclimatic conditions of cultural heritage objects. At the same time, extensive tests were carried out to assess emission risks of these materials, in particular of VOCs.

The research performed both in the laboratory and on the field confirmed the effectiveness of the PCMs as thermal storage solutions, in particular in the stabilization of the microclimate near works of art, reducing the amplitude of thermal fluctuations.

Keywords

Thermal energy storage, phase change materials, cultural heritage conservation, painting, gypsum panel, silicon coating, wooden panel

1. Introduction

The worldwide economic and technological development requires higher energy demands and higher comfort expectations (heating and cooling systems). However, energy sources are limited and related to harmful gases, which are responsible for climate changes, global warming and environmental problems. In this framework, Phase Change Materials (PCMs) have been recognized as one of the advanced technologies in enhancing energy efficiency and sustainability of buildings [1-3].

In general, the use of PCMs in buildings has two main advantages: enhancing indoor thermal comfort for occupants due to the reduced temperature fluctuations and lowering global energy consumption due to the load reduction/shifting.

The thermal energy storage property of PCMs is based on their capability of latent heat storage, because large amounts of energy can be stored in a small volume of PCM. Therefore, the material containing PCMs can absorb and release heat more effectively than conventional building materials [4]. Several authors have published scientific reviews including main types of PCMs and classification, major applications in buildings and related problems [1, 2, 5-7]. The possibility of using PCMs with their different melting temperatures, chemical nature and properties make them versatile materials for diverse applications adaptable to the requirements and characteristics of the location.

Several references in literature have been found regarding the use of PCMs incorporated in construction materials, such as gypsum and concrete. In these systems, the effectiveness as thermal energy storage systems has been demonstrated both experimentally and theoretically by software simulations [2, 3, 8-10].

All these aspects have been more or less deeply analyzed to varying degrees in literature for building applications. The adaptation of PCMs technology to Cultural Heritage has been studied within the European MESSIB (Multi-source Energy Storage System Integrated in Buildings) project [11], aimed at developing, evaluating and demonstrating an affordable multi-source energy storage system for significant reduction of energy consumption and improvement of energy management in terms of quality, security and indoor

1 CNR-ISAC, Italy, a.bernardi@isac.cnr.it
2 AIDICO, Spain, md.romero@aidico.es
3 GESTA, Italy, c.ghiretti@gesta.re.it
4 RED srl, Italy, luc.pockele@red-srl.com

environment. The new energy (thermal and electric) storage system is based on new materials, technologies and control systems, and it is integrated with conventional installations, renewable energy sources and building architecture.

2. PCMs storage barriers and possible solutions to Cultural Heritage

In historical buildings devoted to conservation and/or exhibitions of works of art, the use of PCMs has to be evaluated not only in terms of human comfort and energy saving benefits, but also taking into account conservation issues. For the analysis of the viability of using passive PCMs embedded in buildings components as thermal energy storage materials in Cultural Heritage applications different aspects have been analyzed, including the main barriers and possible solutions to overcome them. This analysis considers that the main objective for using PCMs for Cultural Heritage is the reduction of the thermal fluctuations to which heritage objects are subjected in order to increase their durability.

For construction applications, commercially available PCMs can be found with melting temperatures between 20-30°C, hence they are versatile materials that can be adapted to the requirements and characteristics of the place where they are located. Since the PCMs need to change phase in order to store and release heat, the first action to optimize their performance is to select the melting temperature in the range of the average temperature of the environment. Moreover, the PCMs under examination are a passive system, therefore any interference with other systems is possible.

Besides this general consideration, the main barriers related to the use of PCMs in the Cultural Heritage field have been analyzed in depth within the project and divided into three groups [11]:

- Architectural integration;
- Environmental emissions and safety;
- Economic aspects.

2.1.1 Architectural integration

The main barrier for the use of PCMs in the Cultural Heritage field is the method of incorporation. In fact, the direct incorporation of PCMs into construction materials for heritage buildings is not possible in general, because this operation would require an invasive intervention on the building, modifying its cultural value. In particular, the incorporation of PCMs into existing architectonical elements may alter the aesthetics, due to leakage of the PCMs with temperature changes or modification of brightness. Also changes in other features, such as porosity or permeability, are very dangerous. Since these properties are extremely important in determining the equilibrium balance of moisture content of the material and also its hygrometric behaviour with respect to the environmental conditions, altering these properties may increase the risk of damage.

Hence, the most feasible application of PCMs technology in Cultural Heritage would be similar to the application in the building industry e.g. to place boards of different materials incorporating PCMs in contact with the roof/walls of historic buildings, only if they are not painted, nor decorated with sculptures or heritage elements.

2.1.2 Pollution and safety

Normally PCMs are ecologically harmless and non-toxic. The most important danger could be the emission of VOCs but measurements performed in the laboratory and in the field demonstrated that at normal conditions the emissions are in the same order of magnitude as the typical values of indoor environments and several orders of magnitude below the guideline values both for human health and conservation of CH materials [12].

PCMs work at melting temperature close to the environment and human comfort temperatures, therefore there are no problems relayed to pressure. Moreover, paraffin waxes are chemically inert and stable below 500°C. However, one of the main drawbacks in the use of paraffins is their flammability. Where fire risk is of particular importance, such as in buildings where works of art are preserved and/or exhibited, flame retardant compounds can be added.

2.1.3 Economic aspect

PCMs are a lot more expensive than other construction materials. However, it is difficult to establish a cost, because often the market or large-scale production do not offer the specific requirements needed. Most of the time, the costs are greatly influenced by the particular application and the benefits obtained. However, against the initial investments, PCMs used as passive systems do not require any operation or maintenance. Moreover, the consequent reduction in the use of heating and cooling systems will imply a direct reduction in the electricity bill. For these reasons the payback period is expected to be very short.

2.1.4 Possible applications

Even though there is a great amount of scientific literature concerning the use of PCMs in building applications, no specific reference to Cultural Heritage has been found. After an in-depth analysis of the advantages and disadvantages related to the application of PCMs technology in Cultural Heritage buildings, the project outcome is that the solution of incorporating the PCMs in construction materials is possible only for new or refurbished buildings, not always for historical ones, as this operation requires an invasive intervention on the building.

A more feasible application for heritage buildings is to incorporate PCMs in boards or panels of different materials to be installed in contact with the roof/walls of the building (only if not painted, nor decorated). In the MESSIB project this application has been evaluated through simulation in three case studies (Section 3). These boards or panels incorporating PCMs could also be used for temporary exhibitions inside museums: they can be sized according to the dimensions of the room and they can be easily installed and removed according to specific needs. This potentially new application of PCMs technology to stabilize the thermal behaviour of heritage objects has also been studied in the project: model samples and real objects in contact with materials containing PCMs have been monitored both in the laboratory and in the field (Section 4). The impact of this application is currently being investigated with further research.

Materials incorporating PCMs can be also used as a passive solution for thermal stabilization of the atmosphere inside showcases. The PCMs can contribute to reducing thermal fluctuations and thus stabilize the temperature within the ranges of safety for heritage materials, complying with the main goal to enhance their durability.

3. Analysis of energy behaviour and savings

Within the MESSIB project, the energy behaviour of selected buildings was studied as a first step to evaluate the application of the new technologies and in particular of PCMs. The buildings selected were office buildings, as the potential of application of the new technologies was considered higher with respect to other buildings. Moreover, the buildings were representative of different climatic areas.

The energy analysis was performed with the dynamic simulation software Design Builder version 3.0.0.097, which utilized the calculation engine Energy Plus version 7. This numerical analysis tool can simulate a large number of different kinds of parameters (energy consumption, comfort, thermal performances of the envelope, etc.) that together give an accurate description of the energy related topics of the analyzed building. The results from the simulation are of relative importance and are used to see how energy storage technologies could be applied given the yearly, monthly, daily and hourly cycles of the energy demand. The absolute energy performance of the building is not the priority in this study.

The analysis carried out for The Bell, located in Amsterdam, showed that the building, already efficiently re-qualified, is characterized by a very good level of energy performance. The building is classified A+ so the energy demand for heating fulfills the criteria set for this classification level. The envelope is able to filter the external climate, nevertheless there is some margin of intervention for the application of thermal energy stocking devices, such as panels with PCMs, which can further reduce temperature oscillations and higher peaks.

The electricity consumption for office activities (i.e. electrical devices and lightning) is by far the major source of energy consumption, as much as four times the heating consumption. Moreover, of the different energy consumption sources (electricity, lighting, heating, cooling), only that connected to cooling generation has significantly irregular performance profiles. However, what changes is the maximum energy requirement and not its distribution throughout the day. Hence, the use of PCMs was evaluated as a solution for reducing the maximum energy requirement for cooling.

For the simulation, it was decided to insulate the roof using typical PCMs 2,5 mm thick panels. PCMs with melting temperature of 21°C were selected as more suitable for a continental climate. Figure 1 shows the PCMs monthly energy storage, possible only from May to August, as the only period when external climatic conditions would allow the activation of PCMs. In fact, the daily cycles of storage and de-storage are taken into account when crossing the activation temperature of 21°C. The night ventilation was not taken into account because it is irrelevant for the PCM performance in this case. Indeed, without internal gains overnight from lighting, computers and people the temperature decreases below 21°C and energy is stored in the PCM's for the next day.

The whole building was considered as one zone in the simulation and the ceiling was simulated with a commercially available PCM panel (5.2 mm thick, 4.5 kg/m^2 ; latent heat storage capacity 200 kJ/kg). As a result of the simulation, the energy saving related to the application of PCMs technology to The Bell building was estimated of about 10000 kWh (1.9%), thus giving an indication of the economic advantage related to the use of PCMs in this specific case.

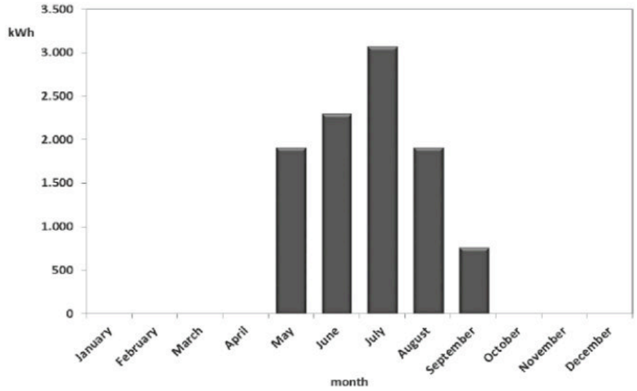

Figure 1 PCMs monthly energy storage.

4. Evaluation of the impact of PCMs technology

After the computer simulation on the use of PCMs, the impact of PCMs technology on Cultural Heritage buildings and materials was studied through experimental tests. The effectiveness of the PCMs as thermal storage materials when incorporated in different materials was evaluated both in the laboratory and in the field. When interpreting the results, it has to be taken into account that no specific standards for evaluating the effectiveness of the PCMs are available.

4.1 Laboratory tests

Commercial paraffin based PCMs (formaldehyde free) micro-encapsulated in polymer spheres were selected for testing. PCMs in the form of powder and emulsion with two different melting points were selected: 21°C and 26°C. PCMs were provided by BASF: Micronal® DS 5001X, 5029X, 5000X. They were included (10% wt) in three different materials: gypsum, silicone, foam.

As there is considerable uncertainty about the property values provided by manufacturers, the objective of laboratory tests was to gain in-depth knowledge about the thermal behaviour of selected PCMs when embedded in a specific building material. Hence, the different materials incorporating PCMs were first analyzed by using Differential Scanning Calorimetry (DSC) in order to determine the melting temperature and the enthalpy of the process. Then, the samples were subjected to thermal cycles in a climatic chamber to evaluate their efficiency as thermal energy storage systems and their capacity to reduce thermal fluctuations. Experimental results showed the reduction of maximum temperatures (more than 1°C) and a time-lag to reach maximum temperature for the materials containing PCMs (Figure 2). Also the cooling process was slower for the samples containing PCMs (Figure 2). Similar results were obtained in the many thermal cycles performed, concluding that the thermal behaviour of the samples is reproducible.

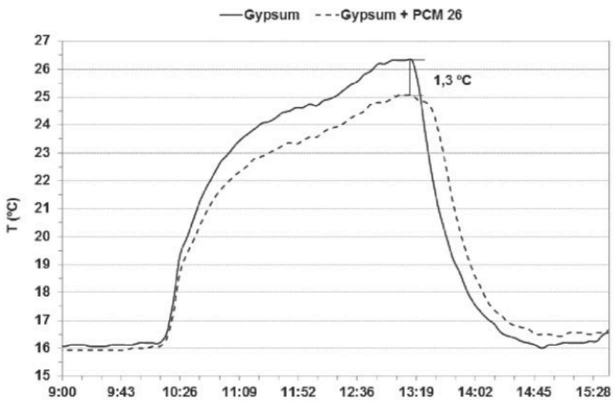

Figure 2 Air temperature and surface temperatures of different gypsum samples.

As already pointed out, as the incorporation of PCMs in building materials is an invasive operation, the most feasible application of PCMs technology in the Cultural Heritage field is to place boards of materials incorporating PCMs in contact with the roof/walls of historic buildings and/or with the works of art to be exhibited, such as paintings hung on boards containing PCMs. Silicon coatings containing PCMs were placed on the back of paintings exposed to environmentally controlled conditions. The maximum temperatures reached by the painting in contact with the silicon containing PCMs were lower than those reached by the painting in contact with a simple silicon panel (0.6°C difference front side, 1.4°C for the rear side) (Figure 3). Moreover, the painting in contact with the silicon containing PCMs was subjected to high temperatures values for shorter times when compared to the painting in contact with a simple silicon panel (Figure 3).

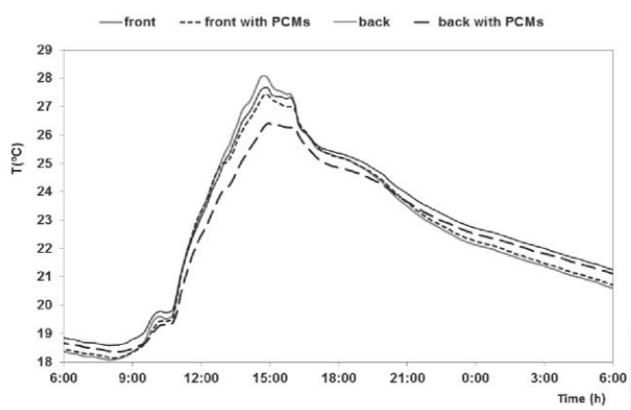

Figure 3 Surface temperatures of paintings in contact with silicon panels with or without PCMs.

Another possible non-invasive application of PCMs for the conservation of heritage objects is inside showcases. Hence, the silicon, gypsum and foam panels containing PCMs were also used to build a small box where a wood sample simulating a painting was placed (not in contact with the panels but at 20 cm distance from them). The air temperature inside the box at 10 cm from the panels and the contact temperature of the wood sample were monitored under thermal cycles. Results obtained showed PCMs potential to buffer air thermal fluctuations (Figure 4). The effect on the wood sample was less evident than on the air, but visible (Figure 4).

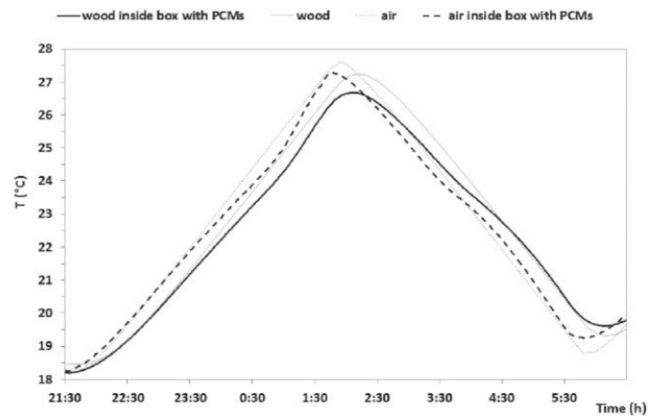

Figure 4 Air and surface temperatures inside a showcase with PCMs.

4.2 Field tests

PCMs were also evaluated in the field in two real heritage buildings included as case studies in the European MESSIB project: the Santa Croce Museum in Florence (Italy) and the Archaeological Museum in Novelda-Alicante (Spain).

4.2.1 Santa Croce Museum, Florence

The monitoring of the microclimatic conditions of the museum allowed researchers to select the most suitable rooms for the PCMs testing, taking into account the melting temperatures of PCMs available (21 and 26 °C). Subsequently, PCMs were incorporated in gypsum panels placed in contact with wooden panels simulating paintings. The panels (with and without PCMs) were placed at 1m above the floor, close to each other, in a corner of room I (Figure 5) and close to a wall of room VI. Air temperature and relative humidity in proximity of each panel, and the surface temperature of the wood and of the gypsum panels were measured.

The monitoring on site confirmed the results of the laboratory tests, even though in real environmental conditions the effect of PCMs was less evident than in the laboratory. However, data still showed the reduction of maximum temperatures of the gypsum panels incorporating PCMs and of the wood panels in contact with them, with respect to the configuration without PCMs, and also time-lag to reach the maximum and minimum temperatures.

4.2.2 Archaeological Museum, Novelda-Alicante

A foam core board panel impregnated with PCMs was placed inside a showcase in the Archaeological Museum in Alicante and results were compared with a similar panel without PCMs (Figure 6). Again, temperature of the panel without PCMs was slightly higher (0.5 °C) than that of the panel with PCMs. Moreover, the time required to reach maximum temperatures was longer for the panel with PCMs, indicating thermal storage by the PCMs. Another difference was the time during which the panels were subjected to high temperature values; for example the panel without PCMs was at temperatures higher than 32 ºC for 4 h a day, whilst the panel with PCMs for half that time (2.2 h).

Figure 5 PCMs testing in room I of St. Croce Museum

Figure 6 PCMs testing inside a showcase at the Archaeological Museum in Novelda-Alicante.

5. Conclusions

The research performed within the MESSIB project confirmed the PCMs potential of storing thermal energy when incorporated in building materials and thus buffering thermal fluctuations. This effect may increase the durability of heritage objects and at the same time enhance human comfort. In addition, the energy performance of historical buildings can be optimized thanks to a reduction in energy demand.

PCMs are versatile materials that can be modified and adapted depending on the requirements and characteristics of the place where they are located. They have good potential for application in the Cultural Heritage field, even where there are a number of barriers of different nature to overcome. Nevertheless, the advantages and disadvantages related to their use have to be carefully evaluated for each specific case, taking into account not only the important objective of economic return and human comfort, but also aesthetic and conservation requirements.

The study carried out highlighted the general lack of experimental results in the use of PCMs in Cultural Heritage. As further research on their impact on heritage buildings and objects is needed, a more in-depth analysis concerning the effect of PCMs on the thermal behaviour of different materials and objects is now in progress.

6. Acknowledgements

The authors would like to acknowledge the financial support of the EC within the framework of the MESSIB project: Multi-source Energy Storage System Integrated in Buildings (FP7-NMP2-LA-2008-211624). Opera di Santa Croce and Geom. Marco Pancani, and also the Archeological Museum in Novelda-Alicante are gratefully acknowledged for their kind collaboration.

7. References

[1] Tyagi V.V., Kaushik S.C., Tyagi S.K., Akiyama T. 2011. Development of phase change material based microencapsulated technology for buildings: A review. Renawable and Sustainable Energy Reviews, 15, 1373-1391.

[2] Khudhair A.M., Farid M.M. 2004. A review on energy conservation in buildings applications with thermal energy storage latent heat using phase change materials. Energy Conversion and Management, 45, 263-275 Hawes D. W., Feldman D. 1993. Latent heat storage in building materials. Energy and Buildings, 20, 77-86.

[3] Zhan D., Li Z., Zho J., Wu K. 2004. Development of thermal energy storage concrete. Cement and Concrete Research, 34, 927-934.

[4] Hawes D.W., Feldman D. 1993. Latent heat storage in building materials. Energy and Buildings, 20, 77-86.

[5] Tyagi V.V., D. Buddhi D. 2007. PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews, 11, 1146-1166.

[6] Cabeza L. F., Castell A., Barreneche C., De Gracia A., Fernandez A.I. 2011. Materials used as PCM in thermal energy storage in buildings: A review. Renawable and Sustainable Energy Reviews, 15, 1675-1695.

[7] Zalba B., Marin J. M., Cabeza L. F., Mehling H. 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering, 23, 251-283.

[8] Hawes D., Paris J., Feldman D., Banu D. 1995. Heat storage and energy conservation in buildings. In: Proceedings of the 2nd Int. Energy Congress, Morocco, Agadir, June 1995.

[9] Hawes D.W., Feldman D. 1992. Absorption of phase changing materials in concrete. Solar energy Mater Solar Cells, 27, 91-101.

[10] Ibáñez M., Lázaro A., Zalba B., Cabeza L.F. 2005. An approach to the simulation of PCMs in building applications using TRNSYS. Applied Thermal Engineering, 25, 1796-1807.

[11] http://www.messib.eu.

[12] Becherini F., Bernardi A., Romero Sánchez M.D., Vivarelli A., Pockelè L., De Grandi S. 2012. Study of PCMs technology for application to Cultural Heritage objects. In: Proceedings of IAQ2012, London, June 2012.