lewako, R. Landolfo, V. Ungureanu, L.S. Silva (Eds.)

Sustainability of Constructions

Integr
Appro
Life
Str
En

Contents

Chapter 0. Sustainability and Integrated Life-Cycle Design

Chapter 1. Criteria for sustainable construction

Chapter 2. Eco-efficency

Chapter 3. Life-time structural engineering

Environmental characterization of gypsum-PCM plasters

N. Silva, R. Mateus & L. Bragança
University of Minho, Department of Civil Engineering, Guimarães, Portugal

1 ABSTRACT:

Improvement in materials and building technologies can contribute to energy efficiency towards more sustainable construction. In this paper it is presented new gypsum based interior plastering system, incorporating phase change materials (PCM). Although for PCM no data is yet available, environmental assessment of gypsum plaster impact from extraction to construction phase is presented. Difference between systems operational energy and related Global Warming Potential was also considered, for a life time horizon of 30 years. Comparison with conventional gypsum plaster is made as reference. Results from experiments carried out in Passy's test cells show the potential for energy savings of these materials.

2 DESCRIPTION OF MATERIAL

2.1 *Field and range of applications*

The building sector accounts for about 40% of the energy and greenhouse gases emissions. About one-third of energy's end-use is consumed directly in buildings, mainly for regulating thermal comfort parameters and general services. In 2000, heating was responsible for nearly 80% of the total energy consumption in an EU average household (Ardente et al., 2007). The most effective ways to improve buildings energy performance are by thermal insulation of the building elements and by energy storage. This way is possible to reduce heat losses, save energy and operational costs with heating and cooling.

Phase change materials (PCM) have been used for improvement of thermal comfort inside buildings by thermal energy storage. PCM have the ability to change its physical state by absorbing or releasing latent heat at constant temperature, with much greater energy than the energy stored by sensible heat. PCM can be either organic, such as paraffin waxes or fatty acids, or inorganic, usually salt hydrates. Organic PCM have lower thermal storage capacities when compared to salt hydrates but have the advantage of lower thermal conductivity, leading to uniform transitions and stability of properties in time, under thermal cycling. Paraffin's are cheap and present a wide range of melting temperatures, allowing the suitable choice to the end-use, result of the widespread refining process facilities and processes. Nevertheless their price tends to increase, with fossil fuels prices rising.

Gypsum wallboard incorporating PCM has been studied as passive solar system in lightweight construction has a mean to reduce overheating problems in summer and to decrease heating needs during winter. In buildings with high thermal mass, this problem is not so effective.

It was shown, that the using of hybrid composite cables instead of steel ones enables to decrease energy for the producing of structural materials consumption up to 4 times. Energy for structural materials transportation decrease up to 2.6 times.

REFERENCES

Beers, D.E. & Ramirez, J.E. 1990. Vectran Fibers for Ropes and Cables. *MTS Conference.* Washington: 662-670.

Bengtson, A. 1994. Fatigue Tests with Carbon-Fiber-Reinforced Composite Cable as Nonmetallic Reinforcement in Concrete. Göteborg: 1–14.

Berger, H. 2002. Light Structures-Structures of Light: *the Art and Engineering of Tensile Architecture.* Basel: Birkhauser.

Blum, R. 2000. Material Properties of Coated Fabrics for Textile Architecture. *Proc. of the symposium "The design of Membrane and Light Weight Structures".* Brussels: 63-88.

Costello, G.A. 1997. *Theory of wire rope, second edition.* New York: Springer.

Houtman, R. 2003. There is No Material Like Membrane Material. *Proceedings of the Tensinet Symposium Designing Tensile Architecture.* Brussels: 178-194.

Kumar, K., Cochran, Ir.I.E. 1997. Closed form analysis for elastic deformations of multilayered strands. *Journal of Applied Mechanics*, ASME Vol.54, 898 – 903.

Pinheiro, M.D. 2007. Environmental Methods and Tools to Identify and Classify Sustainability of Buildings. *Home page of COST Action C25* „Sustainability of constructions: Integrated Approach to Lifetime Structural Engineering". Oslo.

Rocens, K., Verdinsh, G., Serdjuks, D., Pakrastinsh, L. 1999. Composite Covering Structure. *Latvian Republic patent Nr.12191.* Riga.

Serdjuks, D., Rocens, K. and Pakrastinsh L. 2000. Utilization of Composite Materials in Saddle-Shaped Cable Roof. *Mechanics of Composite Materials*, Vol.36, No. 5: 385–388, ISSN 0191–5665.

Serdjuks, D., Rocens, K. 2003a. Hybrid Composite Cable Based on Steel and Carbon. *Materials Science*, Vol.9, No.1: 27–30, ISSN 1392–1320. Kaunas.

Serdjuks, D., Rocens, K. 2003b. Evaluation of mechanical interaction between components in hybrid composite cable. *Scientific proceedings of Riga Technical University, Vol.2 Architecture and construction science*: 208 – 215, ISSN1407-7329.

Serdjuks, D., Rocens, K. 2004. Decreasing the Displacements of a Composite Saddle-Shaped Cable Roof. *Mechanics of Composite Materials*, Vol.40, No.5: 675–684, ISSN 0191–5665. Riga.

Pakrastinsh, L., Serdjuks, D., Rocens, K. 2001.Some Structural Possibilities to Decrease the Compliance of Saddle Shape Cable Structure. *Proc. of the 7^{th} Int. Conf. Modern Building Materials, Structures and Techniques.* Vilnius: 24 – 25.

The incorporation of PCM seems therefore also a logical way to shift peak demands from network to night period.

Gypsum plasters exhibit good insulating properties due to low conductivity and high thermal inertia, very good hygrometric behaviour acting as a moisture regulator, high composition stability, good tensile and bending strength absorbing background movement, very good fire resistance and acoustic properties.

In order to avoid leakage during melting and freezing cycles and ensure density through materials lifetime, containment of the PCM inside the gypsum plaster matrix must be ensured. One way to do it is by microencapsulation in a thermosetting resin, supporting volume variation of the PCM during transition and increasing surface transfer area. The microencapsulated PCM exhibits good latent heat (thermal storage), low thermal conductivity and good fire properties. In the form of a powder it is easy to incorporate in plasters during production or mixing stage.

By incorporating PCM, the construction elements' thermal mass is significantly increased. When compared to conventional plaster, the system contributes to a more effective interior temperature regulation, reducing maximum and increasing minimum temperatures, by absorbing and releasing latent heat. It is expected that mainly in autumn and spring, energy costs be reduced by shifting energy consumption to night period, when the cost is lower. Besides that, this advantage is archived with just a small increment in the initial cost, when compared to conventional solutions. As little maintenance is required, life-cycle period is not affected when compared to conventional solutions.

2.2 *Components*

The presented product is a finishing plaster that incorporates PCM and gypsum and is based in a conventional plaster, containing over 50% gypsum binder, fillers, water retainers and setting retarders mixed with a dispersion of commercial hexadecane paraffin wax, micro-encapsulated in a melamine-formaldehyde resin (low formaldehyde content), with an average particle size distribution of 20-30 μm, melting temperature around 20 °C and a latent heat of fusion of 140 kJ/kg.

The final mixture, containing 20% weight PCM (70-80% weight paraffin), is mixed with a water/plaster ratio of 65%. Bending, compressive and adhesion strengths were determined according to European Standard EN 13279-2:2004 (CEN 2004) and are presented in Table 1. Insitu specific consumption around 0,75 kg/m^2 is expected, assuming support regular levelling.

Table 1. Mechanical properties of the gypsum-PCM plaster (Silva et al., 2006).

Bending Strength (MPa)	Compressive Strength (MPa)	Adhesion Strength (MPa)
1,77	2,70	0,48

2.3 *Installation Techniques*

It is possible to apply the presented system using conventional tools and techniques. This system is suitable for every conventional wall support material and is built with a plaster layer of 15 mm thick and three thin hands of gypsum-PCM finishing plaster, which can also be applied over cement render.

The first layer is applied directly to the support and covered with a very thin gypsum finishing plaster layer, manually applied. After at least 12 hours it is applied the first hand of the gypsum-PCM plaster layer, assuming dry weather, temperature bounded between 5 to 40 °C and good ventilation conditions. There should be an interval of at least 1 hour between the last two hands of gypsum-PCM plaster.

A remark should be made, referring to the mixture procedure of the plaster with water. In order to guarantee the integrity of the microcapsules and the effectiveness of the system in time (i.e. avoid the leakage of the PCM by degradation of the container), it is important to keep the mixer speed low and under control. Additionally, sharp metal paddle edges should be avoided.

2.4 *Maintenance*

Gypsum plasters require little or no maintenance. Most of the degradation problems are related to moisture and support surface conditions. Maintenance is usually limited to surface treatment consisting in painting within undefined periods. Procedures, equipment and tools are the same as for conventional gypsum plasters.

As mentioned above, gypsum presents very good thermal and hygrometric properties, making it more suitable for interior plastering, due to moisture and comfort regulation effect, when compared to cement mortars. The main disadvantage of gypsum-PCM plasters when compared to conventional gypsum plasters and cement mortar is lower mechanical properties.

When in situ, mainly walls, plaster is sometimes exposed to accidental mechanical actions caused by different object shapes. Analysing the bending, compressive and adhesion strengths, a significant fall in the impact strength is expected. Nevertheless, it is not expected to have big differences in the mechanical behaviour in the final system, when compared to the conventional gypsum rendering, since the gypsum-PCM layer is very thin, and the support layer is assumed to be the same as in the conventional system.

2.5 *Demolition*

Gypsum recycling is a simple process, consisting mainly in crushing and dehydrating the material at temperatures around 160 °C. Melamine-formaldehyde resins are thermosetting plastics with good temperature resistance. Thermal gravimetric analysis performed (Su et al, 2005), reported degradation of the microcapsules with mass (mainly water) loss up to 20%, at this temperature, therefore further thermal studies should be carried in order to accurate define the recycling procedures for this type of product. Nevertheless selective demolition, dehydration of the product at the mentioned temperature and the incorporation of recycled mixture in new product would be a solution for the life-cycle' end of the presented solution.

3 ENVIRONMENTAL ASSESSEMENT

3.1 *System boundaries*

For this scope, system boundaries are defined from raw materials extraction to final application of the system, in construction site. Difference between systems operational energy and related Global Warming Potential was also considered, for a life time horizon of 30 years. The selected functional unit for this assessment is the quantity of material and related environmental impacts necessary to cover 1 m^2 of wall.

3.2 *Data of considered example*

This assessment is based on experimental work that is being carried out in Passy's type test cell in the University of Minho. The cell, oriented North to South in length, is 4,10 m length x 2,60 m width x 2,50 m high (internal dimensions). Interior floor, ceiling and walls are thermal insulated with a double layer of expanded polystyrene 5 cm thick plates, except for the south façade, consisting in a hollow polycarbonate sheet mounted in a wood frame.

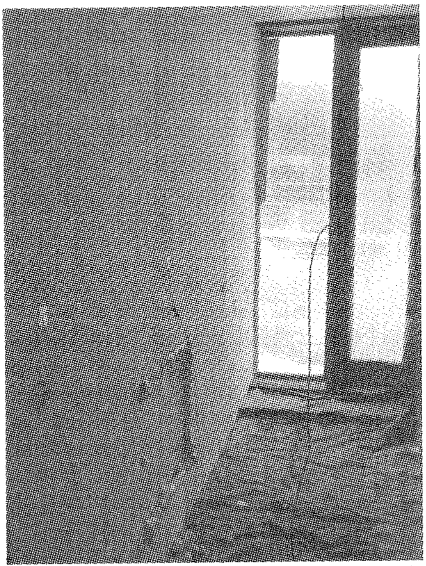

Figure 1. Experimental wall (gypsum-PCM).

An 11 cm hollow brick wall with 4,05 m x 2,50 m was built, dividing the cell in two rooms each with 4,10 m x 1,20 m and leaving an aperture of 65 cm x 60 cm, to allow plastering, instrumentation and maintenance of the East room (this opening was then closed with a double layer of expanded polystyrene 5 cm thick plates and polyurethane foam).

Each surface of the wall was covered with a 1,5 cm thick and 14 kg/m^2 density levelling layer of conventional gypsum plaster. After 24 hours, three very thin layers of finishing plaster were manually applied in both surfaces. In the West surface, gypsum-PCM mixture was used as finishing (Figure 1), while in the East surface was used only conventional gypsum plaster (conventional solution) . Table 2 presents the characteristics of the finishing used on both wall surfaces.

Table 2. Material unit data for both solutions in study.

Property	Reference Solution	Studied Solution
Plastered area (m^2)	9,74	9,74
Gypsum plaster used (kg)	10	7,5
PCM used (kg)	---	1,9
Gypsum specific consumption (kg/m^2)	1,03	0,77
PCM specific consumption (kg/m^2)	---	0,20
Storage capacity (Wh/m^2)	---	7,6

3.3 *Environmental impact categories*

Table 3 presents data for the environmental impact of the three different systems: reference and studied solutions and a third, considering different transportation impacts for the studied solution. ,The probable solution represents the possibility of premixing the components of the gypsum-PCM plaster in the gypsum plant.. This possibility was assessed because is the most plausible from the commercialization point of view. Impacts shown are based on inventory results presented below, in paragraph 3, considering all materials of both systems, life-cycle from extraction of raw materials to the end of construction.

Table 3. Environmental impacts of the considered solutions.

Impact categories	Unit	Reference Solution	Studied Solution*	Probable Solution*
Water use	l/m^2	247,3	232,4	232,4
Energy use	MJ/m^2	33,6	33,1	33,2
Global Warming Potential (GWP)	g_{CO2}/m^2	1075	1046	1055
Eutrophication Potential (EP)	g_{NOx}/m^2	0,04$^{(1)}$	0,03$^{(1)}$	0,03$^{(1)}$
Acidification Potential (AP)	g_{SO2}/m^2	38,6	30,4	36,3
Photochemical Oxidant Creation Potential (POCP)	g_{NOx}/m^2	2,9$^{(2)}$	2,6$^{(2)}$	2,8$^{(2)}$

*PCM impacts were not considered, since life-cycle inventory data is not yet available

[1] Considering only the transportation impact

[2] Not considering the materials transportation impact

Considering 30 years of operational energy for both solutions, according to the experimental and inventory results, the Global Warming Potential of the studied solution is lower than the reference solution in about 92x10^{6}g of CO$_2$ per net square meter of the test cell.

4 INVENTORY RESULTS

4.1 *Components*

The results for inventory of the environmental impacts of system components were collected by Berge (2000) for Central Europe. Gypsum data is based in plasterboard while for PCM no data was found. Table 4 presents data collected.

Table 4. Materials environmental impacts inventory.

Impact categories	Unit	Gypsum
Water use	l/kg	240
Energy use	MJ/kg	5
Global Warming Potential (GWP)	g_{CO2}/kg	265
Acidification Potential (AP)	g_{SO2}/kg	3
Photochemical Oxidant Creation Potential (POCP)	g_{NOx}/kg	2

4.2 *Package & Transport*

For this study, it is considered that system components produced in different plants were mixed at construction site. Gypsum plaster was packed in recyclable Kraft paper bags of 30 kg, stacked in wood pallets and wrapped in PE film, while PCM was packed in reusable plastic bags.

Both gypsum plaster and PCM were transported by road in diesel truck, although from different locations. The distance from gypsum plant to construction site is about 240 km and from PCM plant to construction site is about 30 km.

In case the gypsum-PCM is pre-mixed in the gypsum plant , what for commercial reasons is a possibility that must be taken into account, the total transportation distance for this product would be around 480 km for PCM and 240 km for gypsum.

Table 5 presents the energy consumption and air pollutant emissions, considering both solutions studied and the third possibility presented.

Table 6 presents the transportation's environmental impacts of the materials to construction site, for the two analyzed systems, as well in the case of the pre-mixed solution.

Table 5. Air pollutant emissions and primary energy consumption during materials transportation (Energy Research Group 1999).

			Reference Solution	Studied Solution	Probable Solution
		Emissions (g/t.km) Energy (kWh/t.km)	Emissions (g/m^2) Energy (kWh/m^2)		
Emissions	CO_2	207	51,0	39,5	58,0
	CH_4	0,3	0,07	0,06	0,07
	NOx	3,6	0,89	0,69	0,83
	CO	2,4	0,59	0,46	0,56
	VOC's	1,1	0,27	0,21	0,25
	Energy	0,8	0,20	0,15	0,19

Table 6. Environmental impacts related with materials transportation.

Impact categories	Unit	Reference Solution	Studied Solution	Probable Solution
Energy use	MJ/m^2	0,71	0,55	0,67
Global Warming Potential (GWP)	g_{CO2}/m^2	52,7	40,8	49,6
Eutrophication Potential (EP)	g_{NOx}/m^2	0,04	0,03	0,03
Acidification Potential (AP)	g_{SO2}/m^2	35,5	27,5	33,4
Photochemical Oxidant Creation Potential (POCP)	g_{NOx}/m^2	0,89	0,69	0,83

4.3 *Installing*

For installation no difference between reference and studied solution is verified. Except for the mixture of the plaster, all the work is manually done and no additional energy consumption is required. Table 7 presents data for the installation environmental impacts. According to the Portuguese energy mix, 500 g of CO_2 equivalents are produced per each kW of delivered energy. The mixture was performed with a 1500 W plaster mixer, during 1 minute per hand.

Table 7. Environmental impacts of installation procedures.

Impact categories	Unit	Reference Solution	Studied Solution	Probable Solution
Water use	l/m^2	0,72	0,63	0,63
Energy use	MJ/m^2	27,7	27,7	27,7
Global Warming Potential (GWP)	g_{CO2}/m^2	750	750	750

4.4 *Operation –Thermal monitoring*

In order to evaluate systems performance and assess environmental impacts during operation, temperatures and relative humidity of both rooms and wall surface temperatures were monitored. Figure 3 presents temperature data collected during the first 3 monitored days of approximately 26 days of experiment (640 hours).

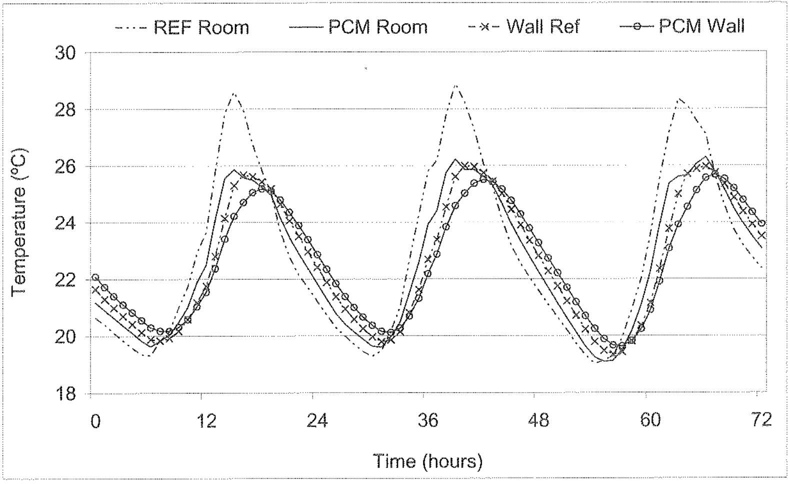

Figure 3. Measured air and wall temperature profiles for the two test rooms.

From the results obtained was possible to verify that PCM has a benefit effect in room environment, decreasing maximum and increasing minimum temperatures up to 3°C and 1°C respectively. Higher minimum temperatures in PCM room were expected, however, the high outside temperatures during the period in which this experiment ran, inhibited in large extent the material from freezing, releasing the stored fusion heat (hexadecane paraffin has a melting temperature around 20°C but the freezing temperature is around 18°C).

The amplitude between wall and room temperatures is higher for the reference side as expected. For the reference room, 3°C in maximum and 1°C in minimum temperatures were observed, while in the PCM room, these values were both about 1°C. Additionally, the delay between maximum wall temperatures shows the heat absorbing during melting and heat transfer from the room to the wall.

In rooms with low thermal mass such as test cells used, the incorporation of PCM effectively contributes to the increase of this characteristic. This can be seen in Fig. 3 with the delay in maximum temperature of the PCM wall, in particular occurring for temperatures over 22°C, after PCM fusion.

From temperatures measured, the different heat fluxes between the wall and the air were calculated for both solutions, in order to isolate the PCM effect. Table 8 presents the results achieved. Here are represented the thermal resistance between wall surface and air (R), wall and room areas (A_{wall} and A_{room}), the difference of heat fluxes between wall surface and air for both solutions during the total period analysed and hourly (ΔQT_{640} and ΔQ_H) and these heat fluxes per functional unit considered (ΔQ_W, ΔQ_{annual}, ΔQF and ΔQ_{WF}).

Table 8. Difference between heat fluxes for the considered solutions.

R ($m^2.°C/W$)	A_{wall} (m^2)	A_{room} (m^2)	ΔQT_{640} (W)	ΔQ_H (W)	ΔQ_W (W/m^2_{wall})	ΔQ_{annual} (MW/m^2)	ΔQ_F (W/m^2_{floor})	ΔQ_{WF} ($W/m^2_{wall}.m^2_{floor}$)
0,13	9,74	4,92	12164	19,0	2,0	61,6	3,9	0,4

4.5 *Maintenance*

Assuming regular use of the habitation and its elements, maintenance is almost irrelevant, as stated in paragraph 1.3. Should there is any accidental impact by a sharp object, it could be necessary to repair the affected area. In this case, procedures which are similar to reference solution, involve the application of new plaster in the affected area. Repairing procedures, equipment and tools of these plasters are the same as for conventional plasters, with the remark of paragraph 1.3.

4.6 *Demolition*

The presented system shows no difference to reference system when selective demolition is carried. Both solutions require the transport of construction waste to gypsum plant for recycling.

5 COMPARISON BETWEEN SOLUTIONS

Comparison between presented solutions should be done in terms of physical, mechanical and thermal properties. An interesting extra comparison can be made with other possible solutions, namely cement renders.

In terms of mechanical properties, as referred in paragraph 1.2, the gypsum-PCM system presents lower performance due lower binder content of the final plaster with the PCM not presenting binding nor filling characteristics. Obviously when compared to cement mortars, both reference and studied system have lower performance however, considering appropriate use, durability of the studied system is very good.

Hygrometric behaviour is at some extent improved with the incorporation of PCM. From the experiment that was carried out it was observed that relative humidity (HR) in the PCM room is lower (average around 55% versus 62%) and with narrow amplitude (around 20% versus 40%). Both systems present better moisture regulation effect when compared to cement render.

Thermally the studied system presents the advantage of latent heat storage, which occurs at approximately constant temperature and can contribute both to delay in time and reduce maximum temperature and increase minimum temperature. In the study presented, the effect on minimum temperature was not verified due to outdoor high temperatures, disabling the PCM to discharge, however an increase in thermal mass was observed. In terms of thermal conductivity, both systems should present similar values, since PCM is approximately the same as gypsum (0,25 W/m.°C). Both solutions present better thermal performance when compared to cement mortar, which has higher thermal conductivity (0,70 W/m.°C).

The lack of LCI data available for PCM and the outdoor weather conditions (high temperatures) for the period during which the experiment ran are difficulties to overcome for the accurate assessment. It is expected that mainly during autumn and spring when during daytime temperatures can rise up to 20-25°C but in the night fall to 5-10°C, PCM used can more efficient, loading and discharging energy, instead of mainly acting as inertia thermal mass, as in the case of this experiment.

In spite of not considering the environmental impacts of the PCM, it is expected that the studied solution presents higher impacts until the end of the construction phase, since PCM is petroleum derived.

Although, in a life-cycle assessment that involves operation phase, the lower operational impacts dilute the materials' embodied impacts. Considering a time horizon of 30 years, data collected and the Portuguese energy mix, reference system would need to be provided with 61,6 MW/m^2, for the same energetic performance of the studied system, corresponding to more 92×10^6 g_{CO2}/m^2 GWP.

6 CONCLUSION

From the performed assessment it is possible to see that the benefits of the incorporation of PCM in gypsum plasters. This system presents environmental advantages that produce both indoor comfort and economic benefits. The calculated environmental assessment shows that the PCM system presents similar impacts in all categories but a much smaller impact in terms of GWP due to energy conservation during operation phase.

Comparison between the studied solution and the probable solution presented shows no significant difference in all considered impacts, which from the commercial point of view is very positive, revealing that is possible to develop a new sustainable product, based in some materials whose sustainability has been very discussed, like PCM petroleum derived.

REFERENCES

Ardente, F., Beccali, M., Cellura, M. and Mistretta, M., *Building energy performance:A LCA case study of kenaf-fibres insulation board.* Energy & Buildings (2007), doi:10.1016/j.enbuild.2006.12.009.

Berge, B., *Ecology of building materials.* Oxford: Architectural Press (2000).

CEN. 2004. EN 13279-2, Gypsum binders and gypsum plasters – Part 2: Test methods, *European Committee for Standardiation* , Brussels, Belgium.

Silva, N., Aguiar, J.B., Bragança, L.M., Freire, T. & Cardoso, I., *Properties of gypsum-pcm based mortars for interior plastering of construction systems.* Materiais 2007 – 13th Conference of Sociedade Portuguesa de Materiais / IV International Materials Symposium, Proceedings – Part II, p.702, 1-4 April, 2007, Porto, Portugal.

Su. J., Wang, L. & Ren, L., *Fabrication and Thermal Properties of MicroPCMs:Used Melamine-Formaldehyde Resin as Shell Material.* Journal of Applied Polymer Science 101:3 (2006) 1522-1528.