

PCMs IN BUILDINGS: COMPATIBILITY WITH CONTAINER MATERIALS AND ANALYSIS OF ENVIRONMENTAL IMPACTS

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ABSTRACT

Contemporary architecture emphasizes energy efficiency and utilization of renewable energy sources. Main issues connected with these sources are instability of the energy supply and temporal mismatch between energy demand and supply. The solution for both these issues is suitable energy storage technology. This creates opportunity for utilization of latent heat storage (LHS) in phase change materials (PCMs). LHS technologies are already in use for example in solar thermal collectors. However their wider application is limited by lack of credible information on the properties of PCMs and their interactions with other materials. The aim of this paper is to reduce the lack of knowledge in this field. It presents results of long-term experiment evaluating the compatibility of selected organic and inorganic PCMs and metals (possible container materials). This experiment tried to find suitable material pairs that would ensure flawless functionality of the LHS system without corrosion, leakage or other defects. The experiment was followed by evaluation of the environmental impacts of hypothetical application of the tested materials. The results of this environmental assessment were also compared with a reference case representing traditional heat storage options to provide further insight regarding suitability of real-life applications of the tested materials. The results indicate that stainless steel is the most stable of the tested metals, which makes it most suitable PCM containers. However the environmental assessment suggests otherwise. Environmental impacts of the evaluated steel-PCM combinations are the highest. In fact all evaluated metal-PCM combinations have higher environmental impacts than the reference case. This discourages their application in sustainable construction industry.

INTRODUCTION

One of the main issues limiting widespread utilization of renewable energy sources in contemporary architecture is mismatch between energy demand and supply. This issue can be solved with suitable energy storage technology, [Alva, 2018]. One of the progressive technologies in this field works on principles of latent heat storage (LHS). It combines the ability of any material to store heat depending on its density (sensible heat storage, SHS) with the heat storage capacity related with melting and solidification of a material. Materials utilized in this role are therefore known as phase change materials (PCMs).

The ability of PCMs to melt or solidify at relatively low temperatures limits their application in construction industry due to the need for a suitable container. Many solutions are available on the market: metals, plastics,

composites, etc. However there is a lack of credible information regarding their performance: durability, thermal parameters or environmental impacts related with their production, use and disposal. The aim of this paper is therefore reduction of the lack of knowledge. The paper presents a multi-criteria evaluation of selected PCMs in combination with metals that could be used in the containers. This evaluation includes comparison of corrosion of the metals caused by the exposure to PCMs and evaluation of the environmental impacts of a hypothetical application of these PCMs and metals.

THE EXPERIMENT: TESTING COMPATIBILITY OF METALS AND PCMS

Long-term experimental testing was applied to evaluate compatibility of selected PCMs and metals (potential container material). Three PCMs were selected for the testing: two organic (paraffin-based Linpar 17 and Linpar 1820) and one inorganic (salt-hydrate-based Rubitherm SP25). They were selected due to their availability and existing applications in the building industry. These PCMs were combined with metals commonly used as their container material: aluminium (AW 1050 H111), copper (CW024A) and stainless steel (EQ308L). This selection aimed at increasing knowledge regarding long-term durability and functionality of LHS systems.

Testing procedure followed work of [Ferrer et al., 2015] or [Oró et al., 2013]. It comprised following steps:

- Preparation of the samples, where the samples were marked, sealed and cleaned. Afterwards they were inserted in the test beakers with PCMs (in a way that ensured maximum exposition of the samples to the PCMs), which were placed in a small environmental chamber (see Figure 1, left).
- Cyclic testing. The testing comprised of four four-hour stages: First stage was increasing temperature in the climate chamber to 40 °C. This temperature was maintained during the second stage. Then it was lowered to 15 °C during the third stage and maintained at this level during the fourth stage. This process was repeated for 16 weeks. At the end of each week a set of samples was removed from the beakers, cleaned, visually checked and weighted (see Figure 1, right).
- The evaluation of the data from cyclic testing. Corrosion rate (CR) [Moreno et al., 2014] evaluating weight differences of the metal samples before and after exposure to PCMs effects was utilized as the criterion for evaluating compatibility between particular PCMs and metals. It was calculated according to the following equation:

$$CR = \frac{m(t_0) - m(t)}{A \cdot (t_0 - t)}, \quad (1)$$

where CR was corrosion rate in $\text{mg} \cdot \text{cm}^{-2} \cdot \text{year}^{-1}$, $m(t_0)$ was the initial mass in mg, $m(t)$ was the final mass in mg, A was the area of the sample in cm^2 and $(t_0 - t)$ was the experimental time in years. CR expressed the extent of metal corrosion relative to the area of the sample and recalculated for a one-year period.



Figure 1. (Left) Beakers with metal samples immersed in PCMs in the climate chamber. (Right) Illustration of the progress of corrosion: copper samples removed from the beakers with inorganic PCM Rubitherm SP25 after one, two, three and four months of cyclic testing (from left to right).

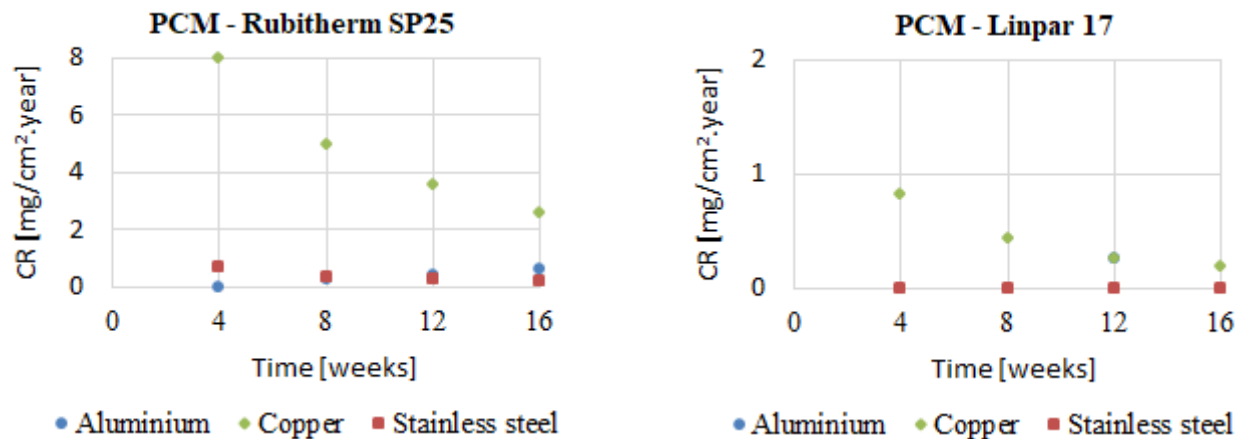


Figure 2. Dependence of Corrosion rate of tested metals on duration of the testing for Rubitherm SP25 (left) and Linpar 17 (right) PCMs.

Figure 2 shows the result of the experiment: CR rates of metals exposed to inorganic Rubitherm SP25 and organic Linpar 17 PCMs. Results of exposure to Linpar 1820 are not presented as they were significantly lower compared to Linpar 17. Initial assumption was that the exposure of metal samples to PCMs would affect their shape, surface flatness, weight and perhaps their colour. This assumption was confirmed in case of aluminium (partially) and copper. Stainless steel samples have shown no visual changes and only negligible weight changes after removal from the beakers with PCMs (see Figure 2). Small CR fluctuation in inorganic PCM Rubitherm SP 25 (Figure 2, left) was probably caused by a measurement error (due to accuracy of measuring equipment).

Corrosion of aluminium samples was most pronounced in Rubitherm SP25 (see Figure 2, left). There its CR reached up to $0.8 \text{ mg}\cdot\text{cm}^{-2}\cdot\text{year}^{-1}$. However the most interesting was the fact that whole surface of the samples was covered by white corrosion after two months of the experiment. This phenomenon was not observed in other PCMs.

Copper samples were the most influenced by immersion in the PCMs. They suffered blue corrosion after more than one month of exposure to the PCMs. The effect of the corrosion is visible in Figure 1 (right), which shows copper samples that were exposed to Rubitherm SP25. The right-most sample was exposed to the PCM for 104 days and the corrosion covered approx. 40 % of its surface. This corresponds to the high CR values that reached up to $8 \text{ mg}\cdot\text{cm}^{-2}\cdot\text{year}^{-1}$ in Rubitherm SP25.

ENVIRONMENTAL ASSESSMENT

The experiment was followed by environmental assessment. Its aim was evaluation of environmental impacts of the tested metal-PCM combinations. This assessment included all three metals, but only one PCM: Rubitherm SP25, which was selected based on availability of environmental data (see below). The environmental impacts of the metal-PCM combinations were not evaluated alone in this paper. The materials were incorporated into a hypothetical interior (heat storage) partition to provide more insight into their actual performance. Four partitions (labeled P1 – P4) were therefore evaluated in this part of the research. P1 (see Figure 3, left) is a common 0.15 m thick non-bearing partition made of solid bricks, cement mortar and plaster. Thanks to its sensible heat storage potential it serves as a good reference case for partitions P2-P4 including Rubitherm SP25 (using LHS principle). Partitions P2-P4 (see Figure 3, right) share the same light-weight structure: metal frame, mineral wool (acoustic insulation) and plasterboard panels. They differ only in the material of the PCM containers: aluminium (P2), copper (P3) and stainless steel (P4). All four partitions were designed so they share the same acoustic and heat storage parameters.

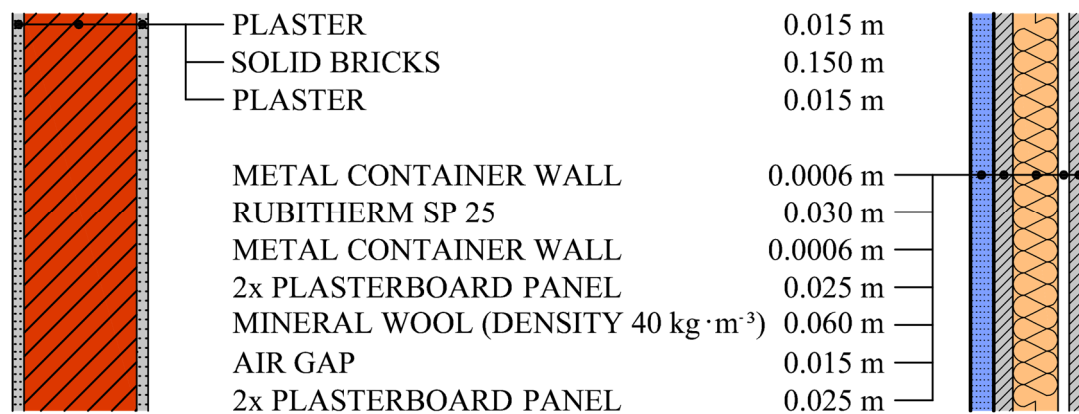


Figure 3. Schemes of the partitions compared during LCA: Traditional brick partition (P1) on the left and partitions with PCM (P2, P3, P4) on the right.

Life-Cycle Assessment (LCA) method specified in EN 15804 [CEN. 2011] was utilized for the environmental assessment in the research. Therefore the assessment follows standardized structure dividing the life cycle of the partitions into four stages (Product stage, Construction process stage, Use stage and End of life stage) and 16 modules: Product stage (modules A1 Raw material supply to A3 Manufacturing) and Construction process stage (modules A4 Transport and A5 Construction-installation process) are included in this assessment completely. Use stage is represented only by module B4 (Replacement). Environmental impacts in other modules of this stage are considered negligible (B1 Use, B2 Maintenance, B3 Repair), inapplicable (B6 Operational energy, B7 Operational water) or overlapping with module B4 (B5 Refurbishment) for the purpose of the assessment. All four modules describing End-of-life stage (C1 Deconstruction-Demolition to C4 Disposal) are also included. However environmental impacts in module C3 (Waste processing) are merged into module C4 due to input data limitations.

The LCA was performed in GaBi software. Almost all data on environmental impacts of materials and processes considered in the assessment were based on datasets available in ecoinvent database in the software. The exception is data on the evaluated Rubitherm SP25 PCM, which were based on a recently published research paper [Horn, 2018]. Utilization of this data also limited the impact categories: [Horn, 2018] shows environmental impacts of the PCM in Global Warming Potential (GWP) and Primary Energy (PE). Therefore the same impact categories are utilized to evaluate environmental impacts in this paper. Other boundary conditions considered in the LCA in this research included:

- Functional unit: 1m² of the evaluated partitions.
- 50 year reference service life of the partitions based on Czech design practice. It was assumed that the bricks and mortar in P1 would be able to function for the whole period. Other materials (plaster in P1, whole P2-P4 compositions) would suffer from wear and tear (e.g. corrosion of PCM containers). Therefore one replacement (LCA module B4) of these materials was considered during the 50-year period based on the producers' information.
- Position of hypothetical building site was set to the centre of Brno. All transport distances considered during LCA (material or waste transport) were calculated from this location.
- Landfilling as only End-of-Life scenario. The reason is that landfilling is commonly considered a worst-case scenario (especially compared to reuse or recycling). Other waste management scenarios should therefore have lower environmental impacts.

LCA results are summed in Figures 4 and 5. Both figures show overall environmental impacts related with the life cycle of evaluated partitions in GWP (left) and PE (right). Figure 4 divides them according to standardized LCA modules. Furthermore the environmental impacts in module B4 are divided into several "sub-modules" corresponding with other LCA modules to increase clarity. In contrast, Figure 5 shows environmental impacts aggregated per individual materials.

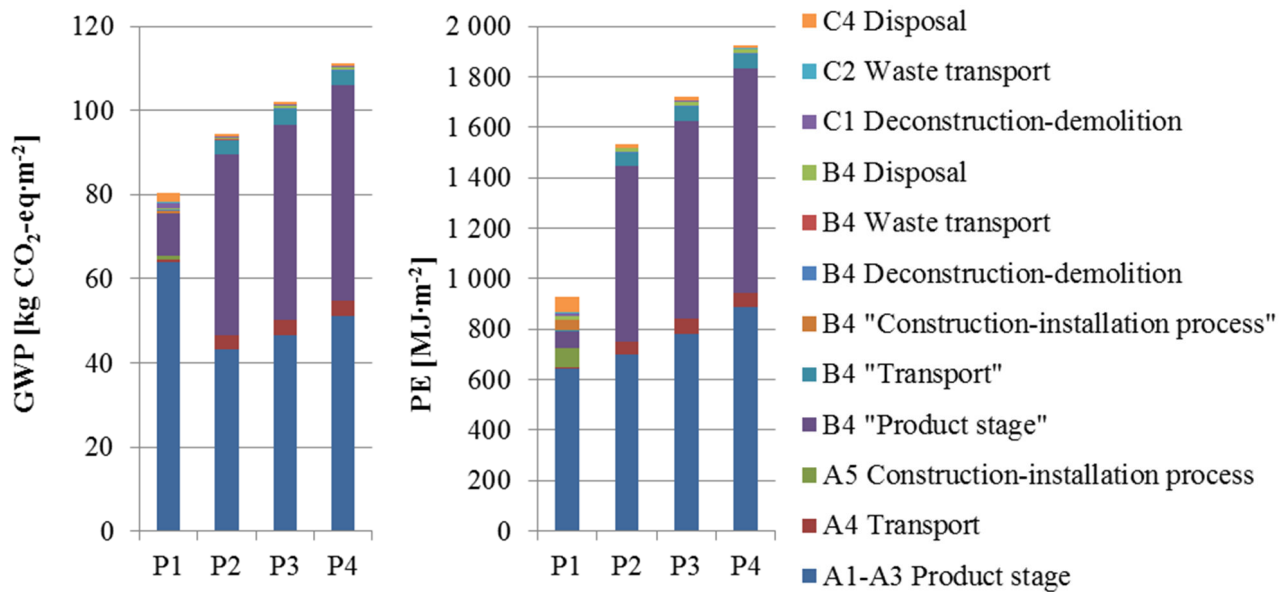


Figure 4. Total environmental impacts of the evaluated partitions divided according to EN 15978 framework.

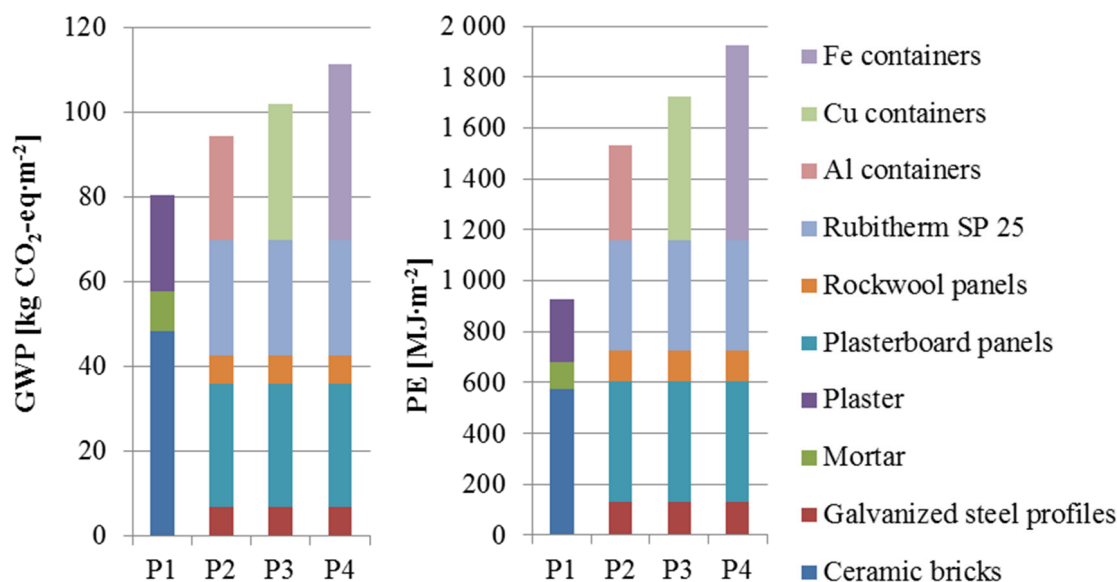


Figure 5. Total environmental impacts of the evaluated partitions divided per individual construction materials.

The results show that the reference brick partition P1 is the least environmentally demanding in the comparison. It has 17-38% lower environmental impacts in GWP and 65-107% lower environmental impacts in PE compared to PCM-based P2, P3 and P4 partitions. Figures 4 and 5 indicate two main reasons for the difference. First reason is higher replacement rate (lower durability) considered for the light-weight partitions with PCM (P2-P4). It is most pronounced in the left chart in Figure 4. The chart shows that P1 has 16-29 % higher initial environmental impacts (modules A1-A5) in GWP compared to P2-P4. However the initial advantage of PCM-based partitions is turned over due to the amount of replacement materials added during their use (module B4). Moreover, this is connected to the second reason for the “failure” of PCM-based partitions: High environmental impacts of both the evaluated PCM and the metal containers. Figure 5 shows that environmental impacts of the plasterboard partition serving as the basis of P2-P4 are 47 % (GWP) or 22 % (PE) lower than environmental impacts of the brick partition P1. On the other hand, solely the

combination of PCM with stainless steel container has environmental impacts comparable to the P1 (15% lower in GWP, 29% higher in PE).

CONCLUSIONS

The research presented in this paper aimed at multi-criteria evaluation of suitability of selected metals in the role of PCM containers. First part of the research was the experiment evaluating the corrosion of metals exposed to PCMs. The experiment has shown that tested metals suffer little weight changes and no visual changes in organic PCMs such as Linpar 17. Calculated variations in CR (see Figure 2, right) were very low. They were probably caused by measurement errors (due to accuracy limits of the measuring equipment). In contrast, the metals exposed to inorganic PCMs have shown relevant weight and visual changes (see Figure 1, right and Figure 2, left) reflected in higher CR values. Overall the experimental results indicate that tested metals (excluding stainless steel) are not suitable as containers for long-term storing of PCMs (especially inorganic) due to danger of corrosion. The worst performing combination was inorganic PCM Rubitherm SP25 and copper. The best was organic PCM Linpar 17 and stainless steel.

The results of the environmental assessment further confirm that evaluated hypothetical application of PCMs in metal containers is not suitable replacement of traditional construction materials. The reasons are relatively high environmental impacts of the containers (especially steel) and their lower durability compared to the traditional construction materials, such as bricks.

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