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Life Cycle Assessment (LCA) of Phase Change Materials (PCMs) for building applications: A review

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ABSTRACT

The environmental impact of Phase Change Materials (PCMs) incorporated in building envelopes is an extensively studied area of research, typically assessed by employing a Life Cycle Assessment (LCA) approach. The aim of this paper is to conduct a literature review on the LCAs for PCM- incorporating structures, in order to present the current state of the art, the research challenges, and what is to be looked forward in the near future. A brief recap on the development of PCMs and the fundamentals of their operation in buildings is presented. The principles of LCA, according to the International Standards, and the suitability of its application on PCMs are also discussed. This study presents some significant findings regarding the application of LCA to PCM- incorporated building systems. In particular it has been shown that there is consistency among the findings of the studies, however the findings were found to depend on the goal and scope definition of each LCA. Additionally, taking into consideration all the life-cycle phases of PCM- incorporated building constructions, they were found to be more environmental-friendly compared to other conventional thermal insulating materials.

Contents

Abbreviations: ALV_{brick}, Alveolar brick; CONCR, Pre-cast concrete; D, Disposal; EI99, Eco- Indicator 99; $Energy_{cons}$, Energy consumption; $Energy_{manuf}$, Energy for manufacturing; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; M, Manufacture; O, Operation; Opt., Optimum formulation; PCM, Phase Change Material; PCM_{ester}, Ester as PCM; PCM_{paraff}, Paraffin as PCM; $PCM_{salt\ hydr}$, Hydrated salts as PCM; PU, Polyurethane; REF_{brick}, Reference conventional brick; REM, Rammed Earth Matrix; TES, Thermal Energy Storage; VDSF, Ventilated Double Skin Facades

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1. Introduction

A Phase-Change Material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Similarly to conventional sensible storage materials, the temperature of PCMs rises as they absorb heat. However, unlike conventional materials, PCMs absorb and release heat at a nearly constant temperature. Thus, they are able to store 5–14 times more heat per unit volume than sensible storage materials [27]. They are a form of thermal energy storage (TES) system that when incorporated into the building envelope, enables the smoothing of the diurnal temperature fluctuations, and also achieves reductions in the building's energy consumption. However, the material to be used in the building envelope has to satisfy specific requirements. The PCM's melting temperature is required to be close to the human health and comfort temperature levels, according to the indoor thermal comfort conditions ($\approx 25\,°C$). Availability and cost are usually the main disadvantages for the selection of a suitable material, and still today, problems such as phase separation, subcooling, corrosion, long-term stability, and low heat conductivity, especially in the case of inorganic PCMs, have not been resolved and are under research [4].

Life Cycle Assessment (LCA) is one of the most valuable approaches for implementing a comprehensive environmental impact analysis of any product or system. This methodology is based on all the 'cradle- to-grave' inputs and outputs, starting from the extraction of the raw materials, the manufacture, the use and the maintenance to the end of the life of the product or system. Given the complexities of interaction between buildings and the natural environment, LCA represents a comprehensive approach for the examination of the environmental impacts of an entire building or a building system [30]. Accordingly, the LCA of PCMs for building applications has been proved an effective tool for counter-balancing the positive environmental impacts from the operational phase of the PCMs versus the negative environmental impact produced during the rest of its life- cycle stages.

The aim of this paper is to review the current scientific state of the art regarding the LCA of PCM for building applications, by presenting a review paper on the subject. Section 2 of the paper introduces the theoretical background, the classification of PCM, and their suitability as building thermal energy storage (TES) systems. The principles of LCA methodology, according to the International Standards (ISO 14040 and ISO 14044), are presented in Section 3. Section 4 reviews the previous works on LCA of PCMs in building applications, and some significant conclusions regarding the application of LCA methodology in investigating the environmental performance of PCMs in building envelopes are given in Section 5.

2. Basics and classification of Phase Change Materials

2.1. *Basics of Phase Change Materials*

PCMs, have the ability of storing and releasing large amounts of energy through melting and solidifying at specific temperatures, due to their high heat of fusion. In building applications during times of temperatures above the melting point, the PCM absorbs heat leading to its melting, while during periods of lower temperatures – typically night-time, the heat is released leaving the PCM in its solid state. Therefore, PCMs are classified as TES systems that in combination to high levels of thermal insulation, can provide buildings with a higher thermal inertia, smaller range of diurnal temperature variations, and reduced energy consumption. PCMs increase the ability of a building to act as a heat sink, so PCMs have been characterised as a thin version of "mass" [13].

A number of substances have been tested as potential PCMs, however only few of them have been further developed for commercial purposes. This is attributed to a number of thermophysical barriers of PCMs that make their applications in buildings difficult. For their use in buildings, the PCM's melting temperature is expected to be close to the human thermal comfort temperature levels, or around 19–25 °C. Additionally, it is anticipated that the PCM will be undergoing cycles, from solid- liquid to liquid- solid, continuously and without losing its property. Typically, PCMs are encapsulated so that the PCM substance cannot escape during melting [13]. Known PCMs that satisfy these requirements include:

- Organic PCMs, such as alkanes, fatty acids and organic mixtures.
- Inorganic PCMs such as hydrated salts and inorganic eutectic systems.

2.2. *Classification of Phase Change Materials*

Abhat [1] gave a useful classification of the substances used for TES (Fig. 1), while Lane [17], Lane [18], Dincer and Rosen [8], and Cabeza et al. [3] delivered complete reviews of PCMs, including their classification, characteristics, advantages and disadvantages and experimental methodologies for their thermophysical characterisation.

Organic materials are categorised into paraffins and non- paraffins, mainly fatty acids. Typically, organics present a congruent melting, or do not experience phase segregation, little or no supercooling, and non-corrosiveness. Paraffins consist of a mixture of mostly straight chain n-alkanes $CH_3–(CH_2)–CH_3$. The melting point and latent heat of fusion of parafins increase with the chain length. Paraffins are safe and reliable, and the fact that they are stable below 500 °C, show little volume changes on melting and have low vapour pressure in the melt form, results to paraffins also having long freeze–melt cycle. Despite these advantages, paraffins have low thermal conductivities, are flammable, are non- compatible with the plastic containers. According to Sharma et al. [27] only commercial grade paraffins can be offered for building applications due to cost considerations. Fatty acids have higher heat of fusion values compared to paraffins, undergo cycles without losing their properties, and do not experience the super-cooling effect. Nonetheless, their sharper phase change is offset by the disadvantages of being 2–2.5 times more expensive than paraffins and mildly corrosive [27,28].

Inorganic PCMs have a smaller range of melting points, however they are found to be more suitable for building application due to their wider range of phase change. In particular, salt hydrates have a number of advantages that make them attractive for applications in buildings; high latent heat of fusion per unit volume, small changes in volume on melting, high thermal conductivity, compatible with plastics, not very corrosive, and slightly toxic [27]. On the other hand, inorganic PCMs also exhibit high degree of sub-cooling due to their poor nucleating properties, delay at the start of solidification, and segregation. Accordingly, their thermal storage efficiency is decreasing with each cycle [22]. While the temperature range of phase change of inorganic PCMs is more suited for building applications, their costs and non-sustainable origins, turn the scientists' interest more towards the development of organic PCMs.

3. Principles of Life-Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is considered to be the most effective approach for implenting environmental impact analysis of any product or system. The life cycle of a system has a significant effect on its total environmental performance, while the energy