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Original Article

Performance Review of C18 Paraffin Phase Changing Building Materials in Different Climate Zones

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Abstract *- Environmental conditions impact the performance of building materials; therefore, the performance of the material used can be considered one of the major factors that directly affect the building's lifespan. The need for durable materials to mitigate the effect of environmental factors on buildings has been a research point, which has led to the development of phase-changing materials. PCM are building materials designed to adapt and harness the environmental elements, such as heat and cold, which typically harm a building, to make buildings even more efficient. C18 paraffin is a shape-stabilized phase change material that is the most widely applied PCM in building envelopes worldwide. This study reports the performance of C18 paraffin-based PCM material; this PCM is the most widely used PCM across the globe. The performance assessment is carried out on four distinct climatic zones defined by the ASHRAE 169-2013 climatic zone guidelines. The performance evaluation is reported based on the energy requirements of the PCM for three different diameters of C18 PCM, which are 5cm, 10cm, and 15cm. The paper reports varying degrees of performance based on energy requirements for the use of C18 PCM in the different climatic zone for heating and cooling needs in the buildings, however despite the difference in the energy requirements performances of the PCM in different climatic zones, studies still report findings which show C18 PCM has more energy efficiency compared to conventional building materials in all climatic zones for energy requirements of cooling and heating.*

Keywords *- Building life cycle, Environmental condition impact, Phase-changing material, Sustainable building construction.*

1. Introduction

There has been a threat to the global environment, which is generally described as a phenomenon known as global warming. The global warming phenomenon is closely associated with the emissions of greenhouse gasses which eventually lead to a harsher environmental impact on the climate around the world [1]. The building and construction industry has been reported to be one of the leading contributors to global warming, with an estimated 40% of the overall global energy consumption, leading to about 50% of the total greenhouse gasses emitted globally [2]. This has led to an alarming need to find sustainable methods of building and construction; also, the climatic factors, which have always been lifecycle determinants of buildings and structures, have been critically impacted by the global warming phenomenon and will continue to do so if nothing is done to mitigate it.

Reducing energy consumption while ensuring optimal indoor comfort in buildings has been a huge research field that has led to the development of technologies such as PCM. PCM allows buildings to have the capabilities to adjust their characteristics to enable them to adjust to the current climatic conditions, and they can do so reversibly while responding to climatic stimulation at any given time. This characteristic of reversible change to climatic stimulation is the primary defining factor which is why the name *Phase Changing Materials* was given to them [3]. It is noteworthy to know that PCM as a term applies to several categories of materials that transcend the building and construction industry, some of the industries which have found application for PCM are products: preservation industry, the electronic industry, aerospace industry, solar energy industries, and the building and construction industries.

PCM has, over the years, gained more relevance and growth due to the applicability of the materials in different industrial usage. The widespread adoption of PCM has been associated with its optimal efficiency in creating solutions to challenges; adapting to climatic stimulation [4]. According to De Gracia & Cabeza [5], PCM in the building and construction industry has been primarily concerned and used with two main aspects; HVAC energy consumption reduction through active PCM application strategies and the second aspect is global and local thermal discomfort reduction through passive application strategies of PCM. Studies have shown PCM applications in HVAC to show a significant decrease in energy consumption by up to 30% in HVAC systems using some forms of PCM, especially in the colder climatic regions of the world [6].

Building and construction applications of PCM have been reported to be possible within the range of several melting points of temperature, where PCM materials which have a 20 degrees celsius to 30 degrees celsius range of melting points are shown to take advantage of LHS [7], and this has been associated with the fact that they have a very good amount of heat storage capacity in considerably low volumes which has little to no impact on the increase in surface temperature which then implies it does not negatively impact the thermal comfort. PCMs have been theoretically proven to be applicable in four phases of change in matter with regards to the building and construction sector, these four stages in the change of matter or materials are: solid to liquid, solid to solid, gas to solid, and gas to a liquid, and the most widely implemented PCM phase changing of matter or material is the solid to liquid phase changing [8].

1.1. Problem Statement

PCM has been used alone or as a hybrid with conventional building materials in the construction of buildings for decades; they have been applied on an industrial scale in building materials such as concrete and gypsum boards and have, for the most part, been applied in building and construction concerning thermal storage functions. PCM has been highly applauded as a sustainable building material in building and construction and has been considered by some as ideal building material which should be taken advantage of [9]. However, the performance of PCM in buildings and structures across multiple climatic conditions establishes their output and properly quantifies their “ideal” nature as construction materials. Some studies have also reported variability in the performance of PCM in buildings when subjected to different climatic conditions, according to Beltrán et al. [10], PCM as building materials are as efficient as the climatic and environmental variables which surround them; which either deter their performance or complement their performance. There is a need for comprehensive studies to carry out life cycle analysis of PCM in buildings across multiple climatic regions.

Environmental factors have always played a role in measuring and considering the lifecycle of buildings and structures. Understanding building materials' performance in varying climatic regions is necessary. PCM as a building material has been developed as materials with the primary function of adjusting to climatic conditions as they change to adapt to the climatic conditions and also harness the environmental elements as energy sources to be utilized in some cases. This study aims to carry out the variability of the performance of paraffin PCM in different climatic regions of the world while using the ASHRAE 169-2013 climatic zones guidelines. Performance evaluations are based on the energy requirements for heating and cooling depending on the months of the year which require energy to carry out either cooling or heating in the buildings. Four distinct climate zone classifications are used based on the ASHRAE 169-2013 climate guidelines.

2. Literature Review

2.1. Environment and Buildings

Buildings are interfaces for people and their usage between them in their indoor and outdoor environments [11]. It makes it paramount for buildings to be able to provide the needs of safety and comfort to the occupants of the buildings, which are suitable for the intended purposes of the building. The outdoor environmental elements are subject to impact on the performance of buildings against ensuring the needs and comfort of occupants, as well as the sustainability of the lifecycle of the buildings too [12]. Environmental elements and how they impact the performance of buildings, as well as their lifecycle, have always been a field of study by building research scientists and other specialists in climate and earth studies, these concerns on the impact of environmental elements and climate have been particular more concerning in recent times due to the records of alarming climate and environmental changes happening globally [13].

Climate and environmental changes are primarily occurring at regional and local levels; hence, environmental elements and climatic factors that impact buildings' performance and life cycle are subject to variation concerning the climate's local or regional environment. Factors that impact the life cycle and performance of buildings include constant environmental elements, slight changes in environmental elements, and severe or significant changes in environmental elements. In other words, all forms of environmental or climatic factors impact the performance of buildings regardless [14]. This point emphasizes the need to review the impact of environmental elements and climatic factors on buildings at local or regional levels to properly and adequately understand the impact on buildings and the building materials used in designing and constructing them.

The typical areas of a building that are most affected by environmental elements concerning the lifecycle and performance of buildings are emissions, energy usage, malfunction, and building inefficiencies, among other effects. These effects of environmental and climatic elements need to be properly and adequately quantified to enable risk reduction of such negative impacts [15]. The building materials and the functions of the buildings as they were designed for purpose also add to the extent of the impacts of the environmental and climatic elements interacting with the building as a whole. Complex interactions between the building materials and environmental elements result in further experiences that the occupants of the buildings experience in aspects such as cooling and heating.

2.2. Life Cycle Assessment (LCA)

The evaluation and assessment of the impact of environmental factors and climate on buildings and building materials are done using several methods, most of which have advantages and disadvantages. One such method of evaluating environmental elements' impact on buildings is the use of Life Cycle Assessment (LCA); LCA is a process of evaluating environmental loads and other environmental aspects on the entire lifecycle of a building [16]. LCA assessment is an all-inclusive evaluation of a system's life cycle; in this case, the system is a building. LCA considers the raw materials used in a building, the maintenance and reuse of the materials, and the recycling of the materials, up until the final disposal of the components of a building. LCA is a widely used method for the evaluation of building lifecycle, and this is attributed to the available framework of LCA and impact assessment quantification standards [17].

One of the highly used LCA assessment tools is the ISO 14040, which is designed based on four outlined analytical steps: goal and scope definition, creation of an inventory of life cycle, impact assessment, and final results interpretation. LCA standards of life cycle assessment in building ensures the examination of environmental input into the building and environmental output from the building. According to ISO 14040, LCA is defined as an assessment tool for assessing environmental elements and aspects impacts and potential impacts on a building as a product of building materials. LCA assessment compiles an inventory of necessary inputs, analyses the inventory's output on buildings, and evaluates the environment. The four-stage analytical process of ISO 14040 is described in Figure 1 below.

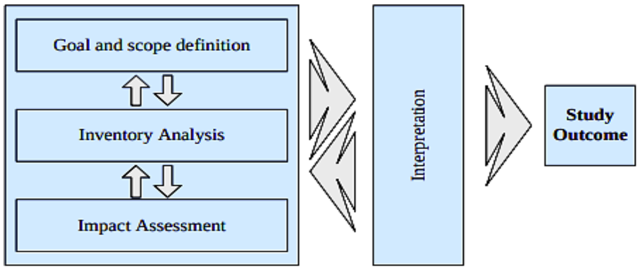

Fig. 1 ISO 14040 analytical process [17]

The application of LCA to buildings as a product defines the building as such, where the material processes of the entire building are assessed at all levels using the available tools. Where LCA is concerned with sustainability, for instance, tools such as BREEAM frameworks of sustainability assessments are used to assess the components of the building and their lifecycle. The particular system or level of the building to be assessed using LCA standards requires a particular understanding of the level, where instances of any building material and component combination (BMCC) need adequate definition according to the function they are intended for or serve on a building as a system or a product [17]. Ideally, LCA should be a process that is started and incorporated in the design process of a building and the decision-making of buildings as a decision support tool for ensuring efficiency in material selection for the building being designed, which considers factors such as cost relative to function and lifecycle value on a building. The use of LCA in the design process of buildings is to find a balance between value, price, and longevity as a criterion for the designers and architects to achieve in their building designs and constructions to enable optimal performance of the buildings. It is paramount for building designs to consider alternatives to designs using materials that assessment has shown as non-optimal for the performance of a building, as the environmental impacts on a building are unstoppable and are inevitable to impact the building in both short term and long term [18].

Studies have shown the building use phase is responsible for about 80% to 90% of the total energy requirements and consumption of a building throughout its life cycle. About 10% to 20% of the energy used in a building’s life cycle is consumed during the production and extraction of materials used in construction. An estimate of less than 1% of the energy usage in the building life cycle is used at the treatment given to the building by the end of the life cycle [19].

2.3. Buildings Life Cycle Analytical Process

Buildings are complex systems made up of several materials to which each may be chosen to fulfill a function or more; such functions include thermal insulation and structural support, and the function of a building as a system is achieved through the combination of several building materials. Changing the materials in a building may ultimately alter the entire function design, such as the fire protection of a building, sound and acoustics properties, and building weight [20]. To carry out a proper lifecycle assessment of a building, there is a need for a complex assessment of the different elements of a building in the form of building materials and how they interact with one another. It is generally done by comparing building materials and their functional equivalents [21].

The average lifetime consideration of buildings when carrying out building materials life cycle assessment is 50 years. The overall assessment of materials’ LCA is between several factors, such as energy consumption and passive conditioning during the life cycle of a building. Over the years, LCA analysis of building materials has been done using different approaches tailored for specific building materials categories. An example of this is the assessment of LCA for building materials in Spain based on the energy investment of specific building materials for each square meter of the materials used in a standard building scenario [22].

2.4. Principles of Life Cycle Assessment

Life cycle assessment (LCA) principles, as previously described, is a process that evaluates the total performance of building materials and the significant effect and impacts it has on the environment and the environment has on it. General lifecycle assessments indicate the process of raw materials extraction, transportation, and the maintenance of materials in its assessment; however, according to the ISO 14040 standards, the guidelines for LCA are as follows [23]:

2.4.1. Goal and Scope Definition Phase

This phase of LCA is a phase that is used to define the goals expected to be achieved through the use of building materials. The material generally defines the LCA process's goal and scope under investigation. This phase is also carried out with an adequate definition of the building system boundaries as a functional unit, the categories of the impact to be analyzed, and the relevant scenario of the building system being analyzed [24].

2.4.2. Inventory Analysis Phase

The inventory analysis phase of LCA is the phase that requires the input and output of data of the materials being investigated. The input data in an LCA investigation include data on the raw materials and the energy required for the materials. The output data in inventory analysis are fundamentally the waste materials released into the natural environment, including gaseous waste, liquid waste, and solid waste as a consequence [25].

2.4.3. Impact Assessment Phase

It is the third phase of the ISO 14040 LCA analysis standard. The primary objective of the impact assessment phase is to provide further information on the definition and environmental understanding surrounding the input and output data regarding the impacts they have on the environment and the material. The impact assessment phase converts the data into indicators of the impact and effects on the material. This phase involves the characterization and classification of the building materials [26].

2.4.4. Interpretation Phase

It is the final step of the ISO 14040 standard of LCA analysis. This phase is where the analysis results are summarized and discussed as a basis for the report's conclusion. This phase also handles the decision-making and recommendations in line with the LCA's goal and scope definition phase [27].

2.5. ASHRAE Standards and Global Warming

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is an organization incorporated to advance heaven, ventilation, and air conditioning (HVAC) in indoor environments and control technology. ASHRAE was an organization formed in 1959 by the American Society of Heating and Air conditioning Engineers (ASHRAE); the aim and objective of the organization were to standardize and present guidelines necessary for technical standards on indoor environment and control technology for HVAC. The organization, ASHRAE, also serves as a liaison with the general public [28].

Climate zones are a very important aspect of evaluating the performance of building applications and their energy efficiencies according to variations in standards, regulations, and certifications. ASHRAE 169-2013 is a regulation of climatic zoning according to the standardization of ASHRAE as n organization. ASHRAE 169-2013 is regulatory climatic zoning used to evaluate the performance of targets in climatic zones to enable the design and implementation of strategic methods to achieve optimal energy conservation and reduction of CO2 emissions. ASHRAE 169-2013 was a result of the review of total climatic conditioning of 54 countries concerning 85% of the total primary global energy consumption (ASHRAE, 2013). According to Walsh et al. [29], building performance can be qualitatively evaluated based on climatic zoning parameters and performance metrics.

According to the ASHRAE 169-2013 climatic zones, there are 18 different climatic zones with cooling and heating degrees ranging from 0 to 9000. A total classification of four climatic subcategorizations was used for this study, as subcategories were identified for the ASHRAE 169-2013 having four groups of climatic zones which are as follows: Type 1 climatic zones which do not require heating, Type 2 climatic zones which do not require cooling, Type 3 climatic zones which require both cooling and heating, and Type 4 climatic zones which require neither heating nor cooling. The climatic zone types labeled Type 1, Type 2, Type 3, and Type 4 conform to the ASHRAE 169-2013 climatic zones of 1A, 2A, 3A, and 4A, respectively.

3. Methodology

This paper is a study on the review of the performance of PCM in different climatic zones. The climatic zones used in the reports on the performance of different PCM are based on the climatic zone classifications of ASHRAE 169-2013 climatic zone categorizations. Four peculiar climatic zones are chosen for this study to confirm the applicability and performance of different PCM materials in different climatic zones. These chosen climatic zones represent the distinct ranges of different climatic zones worldwide. The reported PCM is the paraffin PCM-based materials, paraffin-based PCM are categorized as Shape-stabilized phase-change materials (SSPCM), and this is considered the most utilized PCM in the construction industry [30]. This study carries out its analysis on the chosen ASHRAE 169-2013 climatic zones 1A, 2A, 3A, and 4A because these are the four climatic types according to the ASHRAE standards that have very distinct energy consumption demands, where 1A zones are characterized as very hot and humid, 2A is characterized as hot, 3A is characterized as warm and humid, and 4A is characterized as mild and humid.

3.1. Paraffin PCM

The reported PCM material used in this study is the Shape-stabilized phase-change materials (SSPCM) which are made of C18 paraffin to build building envelopes. The C18 paraffin PCM was used as an exterior building envelope wall.

The C18 paraffin PCM was implemented using three thickness diameters which are 5 cm, 10 cm, and 15 cm. Paraffin waxes-based PCM is the most common PCM material for thermal management due to the high rate of fusion per unit for high heat; paraffin PCM materials also have large melting points which enables a dependable non-corrosive chemically inert cycling in the materials. The reported paraffin PCM has the following properties melting range between 19 degrees Celsius to 26 degrees Celsius, solidification range of 20 degrees Celsius to 25 degrees Celsius, the density of 868 meters cube per KG, and thermal conductivity of 0.12 W/mK. Table 1 shows the comprehensive properties of the material.

3.2. Energy Performance Evaluation

The performance evaluation of the PCM materials applied in the study was evaluated using Stephen's problem heat transfer equation which is modeled as shown in equation 1 below:

$$\rho csolid\partial Tsolid\partial t = \partial\partial x(ksolid\partial Tsolid\partial x) \quad (1)$$

To ensure the numerical performance evaluation as applied in the study, verification applications were used; PCM melting and heat transfer (HTF). Structure gids were also applied to ensure computational accuracy, where the dimensionless distance is maintained at 1.5 for the first grid layers in the heat transfer zones. The maximum deviation using the performance evaluation method is 3.94%. Computational coupling, which factors the grid density at 10 grids/mm2, is applied to each climatic zone to evaluate heat transfer and the PCM melting.

Table 1. Thermal properties of paraffin-based PCM sheets

Melting range (◦C)	**Solidification range (◦C)**	**Density (kg/m3)**	**Sensible heat (J/g K)**	**Latent heat (J/g)**	**Thermal conductivity (W/m K)**
19.0–26.0	20.0–25.0	868	3.26	62.24	0.12

4. Results and Discussion

C18 paraffin PCM has been reported to have considerable heat gains in the interior of the buildings analyzed, especially in winter when less energy has been consumed compared to buildings without PCM implementations. Heat gain and heat transfer have the most performance gain in the buildings with C18 PCM. Cooling scenarios with the C18 do not show a significant difference. The energy demands for Type 1 climate zone for 5cm C18 PCM were reported at 79% reduction in the energy requirement for cooling, and 94.2% energy requirement reduction for heating, in Type 1 climatic conditions for 10 cm and 15 cm had a significant thermal energy performance with no energy requirement for heating in the buildings, the energy reduction demand for heating was 100% for both 10cm and 15cm C18 PCM. Cooling energy reduction in 10cm and 15cm PCM was not as optimal as the case of heating, where the cooling energy requirement was 85% and 88% for 10cm and 15cm C18 PCM, respectively. Table 2 shows the Type 1 climate zone energy reduction for C18 PCM for cooling and heating.

Table 2. Type 1 climate zone energy reduction for heating and cooling

C18 PCM diameter	**Heating Energy Reduction**	**Cooling Energy Reduction**
5 cm	94.2%	76.4%
10 cm	100%	85%
15 cm	100%	87%

The energy demands for the Type 2 climate zone were as follows; the heating energy requirements were reduced by up to 95.6%. The cooling energy requirements were reduced by up to 85.7%. For individual material thickness, 15cm C18 PCM required no energy for thermal heating in the building, while the cooling energy requirement was reduced by 94.1%. Compared to Type 1 and Type 2 energy requirements for cooling, the Type 3 climate zone has a significantly higher reduction in the energy requirement for 5cm, 10cm, and 15cm for C18 PCM cooling energy requirements were 77.4%, 86.1%, and 90% energy requirement decrease respectively. Table 3 shows the energy requirement reduction for the Type 3 climate zone and individual C18 PCM diameters.

Table 3. Type 3 climate zone energy reduction for heating and cooling

C18 PCM diameter	**Heating Energy Reduction**	**Cooling Energy Reduction**
5 cm	83.5%	77.4%
10 cm	75%	86.1%
15 cm	57.7%	90%

Type 4 climate zone has the least difference in energy required between the C18 PCM diameters, the energy reduction in cooling requirements for 5cm, 10cm, and 15 cm are 80.9%, 85.6%, and 87.5%, respectively. The difference between the energy requirements for cooling 10cm diameter and 15cm diameter has the least difference in Type 4 climates. Table 4 shows the reduction of energy requirement for heating and cooling C18 PCM in Type 4 climate zones.

Table 4. Type 4 climate zone energy reduction for heating and cooling

C18 PCM diameter	**Heating Energy Reduction**	**Cooling Energy Reduction**
5 cm	56.5%	80.9%,
10 cm	73.7%	85.6%
15 cm	81.9%	87.5%

According to the results shown in Table 4 for Type 4 climate zones, the heating energy requirements in C18 PCM are higher than in the remaining 3 climate zones. The heating energy requirement reduction was lower in Type 4 climate zones than in all remaining 3 climate zones.

5. Conclusion

The use of C18 paraffin PCM in four different climatic zones has shown improvement in the energy demands in all four tested climatic zones. However, as seen in the results, the performance difference varies according to the climatic zone conditions. Some of the climatic zones were seen to have a better energy performance in heating than in cooling and some in cooling than in heating. According to these reports, the optimal C18 PCM climatic zone is the heating energy reduction seen in climate Type 1, which is the considerably warmer climate zone when evaluated annually. C18 PCM, according to this study, can be said to be more efficient in heat transfer gain in a building than in cooling transfer gain. However, the lower cooling gain in the C18 PCM is still better performing than conventional building material use. Hence this makes it a better building material than conventional building materials.

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