

**Evaluating the Properties of Cementitious Panels
Incorporating Micro-Encapsulated Phase Change Materials
with Smart Curing Implementation**

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ABSTRACT

Evaluating the Properties of Cementitious Panels Incorporating Micro-Encapsulated Phase Change Materials with Smart Curing Implementation

Farshad Meftahi

The high demand for fast, reliable, and economical construction components pursued researchers to examine various potentials to improve energy efficiency for construction materials. Among various potentials, the application of micro-encapsulated phase change materials (MPCMs) demonstrated a high ability to modulate the inside temperature of the buildings. These materials have the capacity to absorb and release heat within a defined temperature range. Few studies enlighten the high potential of the inclusion of these materials with cementitious mixtures. Nevertheless, the chemical stability and thermal responsiveness of MPCMs under various curing conditions to be used in cementitious mixtures remain uncertain. Very limited research has explored the application of MPCMs in the inclusion of cementitious materials in the heat-curing process. Hence, this study evaluates the performance of MPCMs in inclusion with cementitious materials through various curing regimes with the aim of optimizing the process for using most of the energy capability of these materials for energy-saving purposes. In this research, an innovative curing method by utilizing MPCMs in cementitious mixtures as sawtooth curing was introduced. There was a possibility of producing a low energy-intensive cementitious mixture incorporating MPCMs in the heat curing while maintaining mechanical strength. It is anticipated that the findings of the thesis will help the in-situ engineers choose the proper mixture for producing construction panels with the inclusion of MPCMs to ensure outstanding mechanical performance with less energy usage.

CO-AUTHORSHIP STATEMENT

Substantial parts of this thesis were either published in or submitted for publication to peer-reviewed technical journals and an international conference. All experimental work, data analysis, and writing of initial versions of all publications listed below were carried out by the candidate himself. The contribution of this research advisor and any other co-author; if applicable, consisted of either providing advice, and/or helping in the development of the final versions of publications:

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List of Abbreviations

MPCMs	Micro-encapsulated Phase Change Materials
OPC	Ordinary Portland Cement
C-S-H	Calcium Silicate Hydrate
PC	Portland Cement
AMB	Ambient Temperature
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction
UTM	Universal Testing Machine
UPV	Ultra-Pulse Velocity
MPa	Megapascals
CM	Centimeter
AA	Alkali Activated
AAB	Alkali Activated Binder
AAM	Alkali Activated Mortar
Agro	Agricultural
HR	Heating Rate
CR	Cooling Rate
MIP	Melting Initiation Point
MEP	Melting Ending Point
SIP	Solidification Initiation Point
SEP	Solidification Ending Point
EDX	Energy-dispersive X-ray spectroscopy

CHAPTER 1: INTRODUCTION

1.1 Background

Two significant human society threats of the 21st century are climate change and global warming, which can relate to global greenhouse gas (GHG) emissions and energy consumption (Guan et al., 2021; Hansen et al., 2000). Population growth induced a significant need to provide accessible and habitable buildings, which caused an increase in using natural resources and consequently higher energy consumption to lessen this need. In general, 40% of global energy consumption is attributed to buildings which play an essential role in global warming and energy costs. Approximately one-third of the carbon dioxide (CO₂) emissions of the world can be attributed to the construction industry. The energy consumption and CO₂ emissions of the residential sector can reach 27% and 17% of the global values, respectively (Gielen et al., 2019; Pérez-Lombard et al., 2008). Innovative technologies for reducing construction time, especially during the long cold winter were introduced to offset the demand for new housing. One of these methods is heat curing, which comes into effect primarily for producing precast concrete, the most used and produced material for construction globally (K. P. Mehta, 2001; P. K. Mehta et al., 2014; Meyer et al., 2009). Several benefits have been achieved using the heat curing method, such as improving the concrete quality to obtain lower shrinkage, lower creep, and higher mechanical properties. Although this method has many advantages, its high energy demand is one of the main obstacles. During the last decades, researchers tried to find alternative, including the modification and optimization for the heat-curing process or using supplementary materials to increase strength gain (Elliott et al., 2019; Mohammed et al., 2018; Yee et al., 2001). On the other hand, other researchers investigated unconventional

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methods (such as phase change materials) to reduce concrete carbon footprint while enhancing their thermal performance leading to a more sustainable building.

Phase Change Materials (PCMs) is a smart materials introduced recently to the construction field as a potential solution for many issues related to energy and sustainability (Hale et al., 1971; Huang et al., 2021; Raoux et al., 2009; Zhou et al., 2012). PCMs can absorb latent heat and released during solidification/liquefaction in a predefined temperature range. They can improve thermal inertia when incorporated into other materials, such as cementitious materials, and maximize the thermal efficiency of the incorporating media. PCMs can be categorized into organic, inorganic, and eutectic compounds. Organic PCMs, such as paraffin wax, are the most adaptable in cementitious materials (Giro-Paloma et al., 2016; Raoux, 2009). To prevent the reaction between the paraffin with cement, researchers mostly use PCMs in the form of micro-capsules. Previous studies showed that approximately 40% reduction of the energy demand of concrete buildings incorporated such thermally efficient technologies can be achieved (Soares et al., 2013; Suresh et al., 2022). Moreover, some other attempts showed PCMs ability to mitigate concrete freeze-thaw damages and modulating inside temperature buildings in warm/cold areas (Liao et al., 2019; Yeon et al., 2018). However, Falzone et al. highlighted the negative impact for including such soft PCMs on the mechanical performance of cementitious materials (Falzone et al., 2016). Moreover, Fabiani et al. proofed the dramatic effect of PCMs breakage and the release of paraffin delaying hydration (Fabiani et al., 2018). Furthermore, Wei et al. investigated the long-term durability and mechanical properties of cementitious mortars containing PCMs (Wei et al., 2017). They found a 25% reduction in PCMs stability due to the chemical reaction of PCMs with sulfate ions. In general, choosing the proper PCM and its energy efficiency will depend on the hosting media properties (S. R. L. da Cunha et al., 2020; Frigione et al., 2019). Although PCM can bring many

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advantages and disadvantages, there needs to be more study on their life cycle design and reactions in construction materials, especially in cementitious mixtures (Adesina et al., 2019).

Although MPCMs are great smart materials with various potentials, there has been very few studies on the performance of inclusion of MPCMs with cementitious mixtures. In this thesis, there has been a vast attempt to identify the thermal responsiveness and chemical stability of MPCMs in different environments and their applications to utilize their ability to optimize the heat curing process with the aim of energy saving.

1.2 Thesis Objective

The main goal of this thesis is to investigate the performance and stability of micro-encapsulated PCMs (MPCMs) incorporated in cementitious materials under various curing regimes (i.e., ambient, and elevated temperatures) with the aim of energy optimization. This objective will be achieved through the following stages:

1. Deep analysis of the physical and chemical response of MPCMs in simulating conditions close to cementitious mixtures.
2. Evaluating the performance of MPCMs incorporation in mortars under ambient and heat curing conditions.
3. Introducing a novel method of elevated temperature curing to benefit from MPCMs addition and increase the energy efficiency of the process for optimizing the production.

To help address the above objectives, the scope of this research includes identifying the thermal and chemical characteristics of MPCMs, and mechanical properties of cementitious mortars with the inclusion of MPCMs addition by sand weight cured in ambient, standard heat conditions, and smart heat curing condition.

1.3 Structure of Thesis

This thesis has been prepared according to the guidelines of the Faculty of Graduate Studies at Concordia University. It comprises five chapters, two of which display the progress in the experimental program, starting with enhancing the fundamental knowledge about phase change materials and their production techniques, introducing and evaluating their potential in a new application, and assessing various methods of cementitious materials curing. Substantial parts of the thesis have been either published, accepted, or submitted for possible publication in peer-reviewed journals and national and international conferences.

Chapter two contains a state-of-the-art review of the current knowledge on PCMs properties, their relationships, the influence of various production and implementation techniques in construction materials, and the studies that have been done on cementitious mixture's heat curing. **Chapter three** discusses the peer review and analysis of MPCMs, their interaction in high alkaline environments, and different thermal conditions on their efficiency. **Chapter four** demonstrates the effect of MPCM incorporation in the cementitious mortars in ambient and heat curing conditions. Moreover, based on the gathered data in this chapter, a novel concept of heat curing by reducing a significant amount of energy is proposed and evaluated. Finally, general and specific conclusions drawn from the research study, along with recommendations for future research, are included in **Chapter five**.

1.4 Original Contributions

This research introduces a series of fundamental investigations related to phase change materials and their role in enhancing the performance of different construction materials under various exposure conditions. An examination of the stability of the MPCMs through simulating the construction mixture environment in chemical and the physical response has been done. Afterward, the influence of ambient and heat curing conditions and the efficiency of available PCMs products was explored. A new strategy for steam curing to reduce energy consumption while achieving adequate performance with a more negligible environmental impact is proposed. Specific original contributions of this dissertation include the following:

1. Develop an extensive database on the available phase change materials and their applications in the construction sector, particularly in ambient and heat curing.
2. Identifying the thermal and chemical stability of MPCMs in elevated temperatures and alkaline solutions. Mainly, it was found that: (i) the exposure time and temperature have a significant effect on the performance of the MPCMs, (ii) MPCMs in high alkaline environments lose their structural stability and consequently lose their performance; (iii) there is a stability in the energy absorbed and released from MPCMs, but the rates are equal.
3. Identifying the interaction mechanisms between cementitious mixtures and MPCMs in ambient and heat curing. Mainly, it was revealed that: (i) the state of the phase change materials (i.e., solid or liquid) is going to control the performance of the sample in heat curing; (ii) the stability of MPCMs has a vital role in the thermal performance of the product; (iii) during heat curing, MPCMs absorbed heat and released it gradually to reduce the heat damages.

4. Developing a heat curing technique to save energy with the MPCMs' potentials for the first time. It was found that: (i) there is a possibility to maximize the use of heat stored in MPCMs through proper heat profile in heat curing. (ii) there is a possibility to extend the heat period by using the heat stored inside the MPCMs to maintain the temperature for proper heat curing. (iii) there is a possibility to save +30% energy usage of heat curing of cementitious materials incorporated with MPCMs through heat curing.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Cementitious materials are a crucial component of the built environment and are extensively used in the construction industry. These materials are used to create structures that are strong, durable, and resistant to environmental conditions. Cementitious materials have been used for centuries and have evolved to meet the changing needs of the construction industry. This paper aims to provide an overview of cementitious materials, including their composition, properties, and applications, and to discuss recent advances in their development and use. Cementitious materials typically comprise a mixture of Portland cement, aggregates, and water (Mehta et al., 2014). Portland cement is the primary binding agent in cementitious materials, and it is made from a mixture of calcium, silicon, aluminum, and iron. The exact composition of Portland cement varies depending on the source of the raw materials used in its production (ACI Committee 116, 2010). Aggregates are typically made from sand, gravel, or crushed stone, providing strength and durability to the final product. Water is added to the mixture to initiate the chemical reaction between the cement and aggregates, forming a solid and durable material. In recent years, there has been a growing interest in developing alternative cementitious materials that can reduce the environmental impact of cement production. These alternative materials include fly ash, slag, and other industrial byproducts. These materials can be used as partial replacements for Portland cement, reducing the amount of cement needed in a mixture and reducing the carbon footprint of the final product (Gartner et al., 2004). Cementitious materials have several properties that make them ideal for use in the construction industry. One of the essential properties of cementitious materials is their

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compressive strength. Compressive strength refers to the ability of a material to resist forces that compress or squeeze it. Cementitious materials have high compressive strength, which allows them to support heavy loads and resist deformation (Neville et al., 2010).

Another critical property of cementitious materials is their durability. Cementitious materials resist environmental conditions like moisture, temperature changes, and chemical exposure, making them ideal for use in structures exposed to harsh conditions, such as bridges and tunnels (Mehta et al., 2014).

In addition to their physical properties, cementitious materials have chemical properties that make them useful in construction. Cementitious materials' most essential chemical properties are their ability to bind with other materials, such as aggregates and fibers, creating solid and durable structures (Scrivener et al., 2015). Cementitious materials are used in various applications in the construction industry. One of the most common applications of cementitious materials is in concrete production. Concrete is a mixture of cementitious materials, aggregates, and water, and it is used to create a wide range of structures, including buildings, bridges, and roads (Neville et al., 2010). Cementitious materials are also used in the production of mortars and grouts. Mortars are used to bond bricks and other building materials together, while grouts are used to fill gaps between tiles or masonry blocks. In addition to these traditional applications, cementitious materials are used to produce new and innovative building materials, such as fiber-reinforced composites and self-healing materials (Banthia et al., 2005).

2.1.1 Recent advances in cementitious materials

In recent years, there has been a growing interest in developing new and innovative cementitious materials that can reduce the environmental impact of cement production. One of the most promising recent advances in cementitious materials is the development of new types of cement

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that can reduce carbon emissions. Traditional Portland cement significantly contributes to global carbon emissions, accounting for up to 7% of all human-made carbon dioxide (CO₂) emissions (Gartner et al., 2004). Researchers have been working to develop new types of cement that can reduce the amount of CO₂ emitted during production. One promising type of cement is called calcium sulfoaluminate cement (CSA). CSA cement has a lower carbon footprint than traditional Portland cement and can be used in various applications, including concrete, mortars, and grouts. CSA cement can also create lightweight and high-strength concrete, making it ideal for use in bridges and buildings (Scrivener et al., 2015). Another promising type of cement is called geopolymers. Geopolymer cement is made from industrial byproducts such as fly ash, slag, and clay, and it has a much lower carbon footprint than traditional Portland cement. Geopolymer cement can also improve mechanical properties compared to traditional Portland cement, making it ideal for infrastructure projects (Davidovits, 1994).

In addition to new types of cement, researchers have also been exploring alternative binders that can replace Portland cement altogether. These alternative binders can provide similar mechanical properties to Portland cement while reducing the carbon footprint of the final product. One promising alternative binder is called alkali-activated materials (AAMs). AAMs combine industrial byproducts such as fly ash, slag, and metakaolin with an alkaline activator such as sodium hydroxide. AAMs can provide similar mechanical properties to Portland cement while reducing carbon emissions and waste in the construction industry (Provis et al., 2014). Another alternative binder is called magnesium oxide cement. Magnesium oxide cement is made from magnesium oxide, produced by heating magnesium carbonate. Magnesium oxide cement has a lower carbon footprint than Portland cement and can provide high strength and durability, making it suitable for infrastructure projects (Yan et al., 2019). In addition to new types of cement and

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alternative binders, researchers have also been exploring novel manufacturing methods for cementitious materials. These methods can reduce the energy required for production and improve the sustainability of the final product. One such method is called 3D printing. 3D printing allows for creating of complex shapes and structures using cementitious materials, reducing waste and improving production efficiency. 3D printing can also be used to create structures that are difficult or impossible to achieve using traditional manufacturing methods (Le et al., 2018). Another novel manufacturing method is called carbonation curing. Carbonation curing involves exposing cementitious materials to carbon dioxide gas, which reacts with the materials to form calcium carbonate. This process can improve the strength and durability of cementitious materials while reducing the final product's carbon footprint (Li et al., 2020).

2.1.2 Precast concrete

Precast concrete is a type of construction material that is prefabricated offsite and transported to the construction site for assembly. The use of precast concrete has become increasingly popular in recent years due to its many advantages, including quality control, speed of construction, and cost-effectiveness (Shaikh et al., 2016; Hearn et al., 2015; Gambhir et al., 2013). Precast concrete is used in various applications, including commercial buildings, bridges, parking structures, and residential construction (ACI, 2019; Gardner et al., 2019; Shah et al., 2012). This paper will review the use of precast concrete in the construction industry, its advantages, and its limitations. The manufacturing process for precast concrete involves casting concrete into a mold and allowing it to cure. The mold is typically made of steel or fiberglass and is designed to match the desired shape and size of the final product. Once the concrete has cured, the precast element is removed from the mold and transported to the construction site for installation. One of the primary advantages of precast concrete is the high level of quality control that can be achieved during manufacturing.

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The controlled environment of the precast concrete plant allows for precise control of factors such as mix design, curing time, and finishing. This results in a higher quality product with consistent dimensions, surface finishes, and color (Shaikh et al., 2016; Gardner et al., 2019). Another significant advantage of precast concrete is the speed of construction. Precast elements can be manufactured offsite while the construction site is prepared, reducing the overall construction time. Additionally, precast elements can be quickly installed at the construction site, minimizing disruption to traffic and the surrounding area (Hearn et al., 2015).

Precast concrete can be used in a variety of construction projects, including:

- **Building structures:** Precast concrete elements can be used to construct walls, columns, beams, and floors in buildings. These elements can be customized to meet the project's specific design requirements.
- **Bridges:** Precast concrete can manufacture bridge components, such as beams, decks, and abutments. These components can be precast offsite and then transported to the construction site for assembly, reducing construction time and traffic disruptions.
- **Infrastructure:** Precast concrete can be used for various infrastructure projects, including tunnels, culverts, and retaining walls. Precast elements can be manufactured to precise specifications, ensuring high accuracy and consistency.

The methodology of precast concrete involves several steps, including:

- **Design:** The design of precast concrete elements is based on the project's specific requirements. The design team determines the elements' size, shape, and configuration and prepares detailed drawings and specifications.

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- **Molds:** Precast molds are fabricated to the exact specifications of the design. The molds can be made of various materials, including steel, fiberglass, or rubber.
- **Casting:** The concrete is mixed and cast into the molds, which are then placed in a curing environment, such as a heated chamber or a steam room. The concrete is left to cure until it reaches the required strength.
- **Transportation:** Once the precast elements have cured, they are transported to the construction site. The elements are loaded onto trucks or trailers and transported to the site, where they are unloaded and placed into position.
- **Assembly:** The precast elements are assembled on-site using a crane or other lifting equipment. The elements are combined using various techniques, such as welding, bolting, or grouting.

Precast concrete is also cost-effective in many applications. Using precast elements can reduce the labor required at the construction site, resulting in lower construction costs. Additionally, the high level of quality control during the manufacturing process reduces the need for rework, further reducing costs (Gambhir et al., 2013). While precast concrete has many advantages, its use has some limitations. One of the primary limitations is the size and weight of precast elements, and transportation of significant precast elements can be challenging and may require specialized equipment.

Additionally, precast elements may require special handling and lifting equipment at the construction site. Another limitation of precast concrete is the limited flexibility in design. Once a precast element is manufactured, it cannot be easily modified or adjusted on-site, which may limit the ability to change the design during construction.

2.1.3 Energy and environmental issues

Cementitious materials, such as concrete, are widely used in the construction industry due to their durability and strength. However, producing cement and concrete requires significant energy, directly impacting carbon emissions and the environment. This paper will explore the energy consumption of cementitious materials, including the manufacturing process, transportation, and usage. The manufacturing process of cement and concrete involves several steps requiring significant energy. The first step in the process is extracting raw materials, such as limestone, from quarries. This involves using heavy machinery and vehicles, which consume large amounts of energy. The raw materials are then transported to a cement plant, where they are crushed and ground into a fine powder. This process also requires significant energy, as the machinery used to crush and grind the raw materials is enormous and energy intensive. The next step in the manufacturing process is the production of clinker, the main cement component. This process involves heating the raw materials to high temperatures, which consumes a lot of energy. The clinker is then ground into a fine powder mixed with other materials to create the final product, cement. This final step also requires significant energy, as the machinery used to mix and transport the materials is extensive and energy intensive. After manufacturing, the cement and concrete products must be transported to their final destination. This transportation process also requires significant energy, as cement and concrete are heavy and require large trucks and vehicles. The transportation process can also result in carbon emissions, as the vehicles transporting the materials consume fossil fuels. Once cement and concrete products reach their final destination, they are used in construction projects such as buildings, roads, and bridges. The energy consumption related to these products' usage depends on the project's design and construction. For example, buildings designed to be energy-efficient can reduce the energy consumption associated with

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heating, cooling, and lighting. Using lightweight and durable materials such as geopolymer cement can also reduce the energy consumption related to construction projects (Scrivener et al., 2015).

Energy, environment, and sustainable development are critical issues currently being faced by humankind (**Figure 2.1**). One of the most used materials in the current century can be named concrete, whose production grows yearly due to its low cost and severe demand. In this respect, it can be mentioned that concrete production is responsible for almost 8% of global anthropogenic GHG emissions and 3% of global energy demand, which evaluating proposed mitigation strategies in the sector is indispensable in the development of low- or zero-carbon emissions pathways (Miller et al. 2016, Monteiro et al. 2017). High energy consumption and greenhouse gas emissions are severe problems in exploiting and consuming non-renewable fossil fuels with a high environmental impact. Energy production is known to be the largest emitter of greenhouse gases, representing approximately 75.2%.

The incidence of CO₂ emissions in the construction industry is very noticeable, and this rate can be measured and quantified, both in energetic terms and in terms of CO₂ emissions. Some authors, such as Goldenberg, calculate that a third of the energetic expense, and therefore of the production of this gas, comes directly or indirectly from the construction activity. Others, like Webb or Edwards and Hyett, more precisely state that participation of close to 50% of the total energetic cost in developed countries is closely linked or is a consequence of the construction industry if we add to the outcome the maintenance of building expenses and their consumption in heating, refrigeration, and lighting, etc.

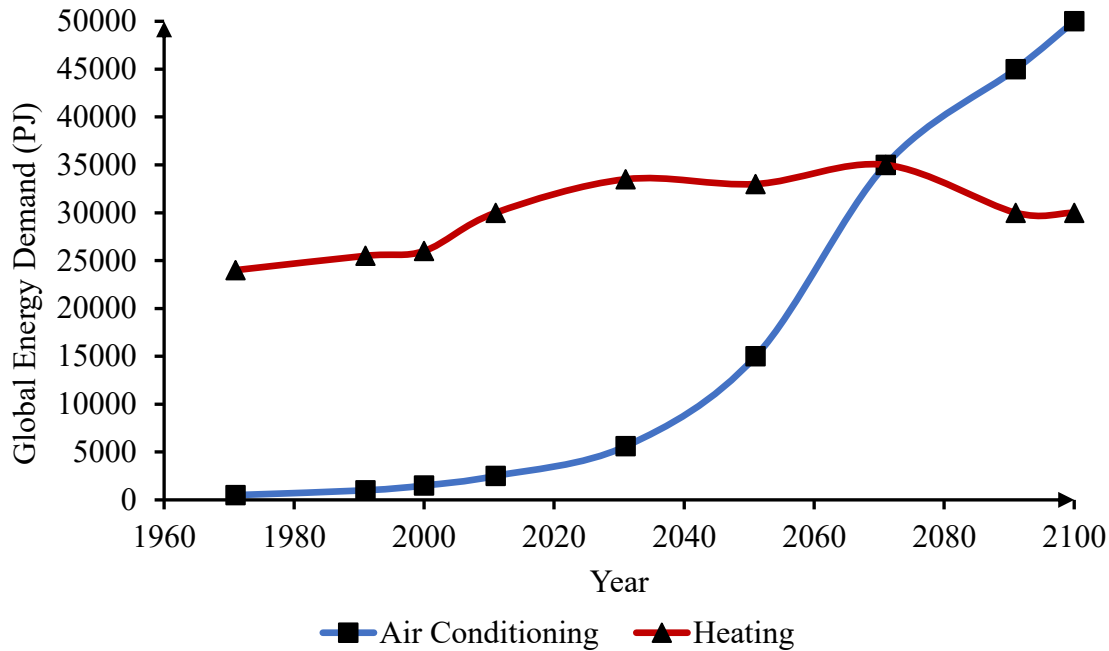


Figure 2.1 Yearly global Energy demand of households concerning heating and cooling. (After Miller et al. 2016)

Of the three main sectors in which the energetic expense of a country is divided (consumption for maintenance and air conditioning of buildings, transport, and industry), the first one has a direct and immediate relation with construction. This one, maintenance energy, has already received the favorable attention of state institutions, which have emphasized the implementation of alternative energies and the intense use of thermal insulators, and responsible consumption. These decisions can be made regarding the two other energy consumption sectors, transport, and industry; there is little information on building construction. Therefore, the aim of this research has been, firstly, to find a direct relationship between CO₂ emissions and construction through the detailed study of a practical case, considering at the same time the two other chapters, transport and industry, affected by it, and secondly, to provide a solution proving that the correct selection of particular materials can reduce the consumption of CO₂ in standard construction, as is shown in the case study of these terraced houses drastically reduce the energy expenditure of the refrigeration of buildings.

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Energy consumption is essential in the construction industry, and precast concrete construction is no exception. Precast concrete construction involves casting concrete components offsite and transporting them to the construction site for assembly. The process is efficient, as it reduces the amount of on-site work and minimizes waste generation. However, precast concrete construction requires significant energy during manufacturing, transportation, and assembly. This paper explores the energy consumption associated with precast concrete construction and proposes strategies for reducing energy consumption in this construction technique.

Precast concrete construction involves several stages that consume energy. The first stage is manufacturing the precast concrete components. This involves batching the concrete mix, pouring it into molds, and curing the components. The process requires energy to operate the batching plant, mix the concrete, and maintain the curing conditions. The energy consumption in this stage depends on the type of precast component, its size, and the manufacturing process used (Mourshed et al., 2015). The second stage is transporting the precast components from the manufacturing plant to the construction site. Precast components are bulky and heavy, requiring specialized trucks or trailers. The energy consumption in this stage depends on the distance between the manufacturing plant and the construction site, the type of transportation used, and the route taken. Transportation also contributes to carbon emissions, a significant concern in the construction industry (Lee et al., 2015). The third stage is assembling the precast components on the construction site. This stage involves hoisting the components into place, aligning them, and connecting them to the building structure. Hoisting requires cranes or other lifting equipment, which consumes energy. The energy consumption in this stage depends on the components' size and weight, the building's height, and the assembly process's complexity (Mak et al., 2016).

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Overall, precast concrete construction consumes more energy than traditional on-site concrete construction. This is because precast concrete construction involves additional energy consumption during the manufacturing and transportation stages, which offset the energy savings from reduced on-site work (Choi et al., 2017). However, precast concrete construction has several advantages over traditional on-site construction, such as improved quality control, faster construction time, and reduced waste generation (Riley et al., 2016). Therefore, reducing energy consumption in precast concrete construction is essential for improving its sustainability.

There are several strategies for reducing energy consumption in precast concrete construction. One strategy is to use sustainable materials in the precast components. Sustainable materials, such as recycled aggregate and fly ash, require less energy to produce than traditional materials and can reduce the carbon footprint of the precast components (Tam et al., 2019). Using sustainable materials can also improve the durability and strength of the precast components, resulting in a longer lifespan and reduced maintenance costs (Hadi et al., 2018). Another strategy is to optimize the manufacturing process. The manufacturing process for precast components can be optimized to reduce energy consumption. This can be achieved by using more efficient mixing equipment, optimizing the curing conditions, and reducing the amount of water used in the batching process (Lu et al., 2020). Optimization can also reduce the waste generated during manufacturing, further improving the sustainability of precast concrete construction (Yang et al., 2018). Transportation can also be optimized to reduce energy consumption. This can be achieved by reducing the distance between the manufacturing plant and the construction site, using more efficient transportation methods, and optimizing the route (Tang et al., 2021). Transportation can also be combined with other construction projects to reduce the trips needed and improve transportation efficiency.

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Finally, the assembly process can be optimized to reduce energy consumption. This can be achieved by using more efficient hoisting equipment, optimizing the placement of the components, and reducing the energy required for connecting the components to the building structure (Lee et al., 2019). Also, prefabricated building systems can reduce on-site work and energy consumption (Choi et al., 2019). Reducing energy consumption in precast concrete construction has several benefits. First, it improves the sustainability of the construction process by reducing the carbon footprint and energy consumption. This is essential for meeting the increasing demand for sustainable construction practices and reducing the environmental impact of the construction industry (Lin et al., 2017). Second, reducing energy consumption can lead to cost savings. Energy is a significant cost factor in precast concrete construction's manufacturing, transportation, and assembly stages. By reducing energy consumption, construction companies can reduce operating costs and improve profitability (Wong et al., 2017). Third, reducing energy consumption can improve the quality and durability of precast concrete components. Sustainable materials and optimized manufacturing processes can result in more robust and durable precast components requiring less maintenance and a longer lifespan (Chen et al., 2021). Fourth, reducing energy consumption can improve the safety of the construction process. By using more efficient hoisting equipment and optimizing the assembly process, construction companies can reduce the risk of accidents and injuries on the construction site (Li et al., 2020).

2.2 Application of Smart Materials in cementitious materials

the incorporation of smart materials in cementitious materials has the potential to improve their energy efficiency and sustainability significantly. Thermoelectric materials, such as bismuth telluride, can convert waste heat into electrical energy, while phase change materials, such as paraffin wax, can regulate the indoor temperature and reduce the energy consumption of the

HVAC systems. Piezoelectric materials, such as lead zirconate titanate, can generate electrical energy from the mechanical vibrations caused by the traffic or wind loads on the structures. In contrast, self-healing materials, such as microcapsules filled with healing agents, can repair the cracks or damages in the structures and reduce maintenance costs. However, applying smart materials in cementitious materials still faces several challenges. First, the high cost and low availability of some smart materials, such as piezoelectric materials, may limit their widespread adoption in the construction industry. Second, the compatibility and stability of some smart materials, such as phase change materials, with the cementitious matrix need to be carefully studied to avoid any adverse effects on the mechanical and durability properties of the structures. Third, the long-term performance and reliability of the smart materials need to be tested under various environmental conditions and loading scenarios to ensure their effectiveness and safety. Researchers have been exploring using smart materials in cementitious materials to improve their energy efficiency and sustainability. Smart materials can change their properties in response to external stimuli, such as temperature, light, or magnetic fields (Bhaskar et al., 2015). These materials have been successfully applied in various fields, such as aerospace, electronics, and biomedical engineering. In this article, we review the recent advances in the application of smart materials in cementitious materials for energy purposes.

2.2.1 Thermoelectric materials in cementitious materials

Thermoelectric materials have gained attention recently as a potential solution for energy harvesting in cementitious materials. These materials can generate electricity from the temperature difference between two surfaces, making them a promising option for energy production in buildings and infrastructure. The use of thermoelectric materials in cementitious composites has been explored in several studies (Hao et al., 2019; Luo et al., 2020; Wang et al., 2018). Hao et al.

(2019) investigated using carbon-based thermoelectric materials in cementitious composites for energy harvesting. They found that adding carbon-based thermoelectric materials improved the electrical conductivity of the cementitious composites, resulting in increased power output. The researchers also noted that using these materials did not negatively impact the mechanical properties of the composites. Luo et al. explored the use of bismuth telluride (Bi_2Te_3) as a thermoelectric material in cementitious composites. They found that adding Bi_2Te_3 significantly increased the thermoelectric performance of the composites, leading to higher power output. The researchers also noted that Bi_2Te_3 did not significantly impact the composites' mechanical properties (Luo et al., 2020). Wang et al. reviewed using thermoelectric materials in cementitious materials for energy harvesting. They noted that several thermoelectric materials, including bismuth telluride, lead telluride, and silicon germanium, had been investigated for cementitious composites (Wang et al., 2018). The researchers concluded that using thermoelectric materials in cementitious composites showed promise for energy harvesting applications, but further research was needed to optimize the materials and improve power output. Overall, using thermoelectric materials in cementitious composites for energy harvesting is a promising area of research. While there are challenges to overcome, such as optimizing the materials and improving power output, the potential benefits make it an area of interest for researchers and industry professionals.

2.2.2 Piezoelectric materials in cementitious materials

Piezoelectric materials can convert mechanical energy into electrical energy and vice versa, making them a promising solution for energy harvesting in cementitious materials. Several studies have explored the use of piezoelectric materials in cementitious composites (Cai et al., 2018; Chao et al., 2020; Li et al., 2020). Cai et al. investigated using lead-free piezoelectric materials in cementitious composites for energy harvesting applications (Cai et al., 2018). The researchers

found that adding piezoelectric materials improved the electrical properties of the composites and resulted in a significant increase in energy harvesting efficiency. They also noted that using lead-free piezoelectric materials could reduce the environmental impact of cementitious composites. Chao et al. developed a novel piezoelectric cementitious composite using zinc oxide (ZnO) nanoparticles (Chao et al., 2020). The researchers found that adding ZnO nanoparticles significantly improved the piezoelectric properties of the composites, resulting in a higher energy conversion efficiency. They also noted that the piezoelectric cementitious composite could be used in smart infrastructure systems for structural health monitoring and energy harvesting. Li et al. investigated using flexible piezoelectric nanogenerators (FPNGs) in cementitious composites for energy harvesting applications (Li et al., 2020). The researchers found that adding FPNGs improved the energy harvesting efficiency of the composites and demonstrated the potential for self-powered structural health monitoring of cementitious structures. Overall, using piezoelectric materials in cementitious composites can potentially improve infrastructure systems' energy efficiency and sustainability. While there are challenges to overcome, such as optimizing the piezoelectric properties and ensuring long-term stability, the potential benefits make it an interest for researchers and industry professionals.

2.2.3 Self-healing materials in cementitious materials

Li et al. developed a self-healing cementitious composite using microcapsules filled with healing agents (Li et al., 2019). The researchers found that adding microcapsules significantly improved the healing efficiency of the composites, resulting in a reduction of crack width and length. The researchers also noted that adding microcapsules did not significantly impact the mechanical properties of the composites. Qin et al. investigated using bacterial-based self-healing materials in cementitious composites (Qin et al., 2020). They found that adding bacterial spores and nutrients

improved the self-healing ability of the composites, leading to a reduction in crack width and length. The researchers noted that the use of bacterial-based self-healing materials had the potential to be a sustainable solution for the repair and maintenance of cementitious structures. Wang et al. explored using shape memory polymers (SMPs) as self-healing material in cementitious composites (Wang et al., 2017). They found that the addition of SMPs improved the healing ability of the composites, resulting in a reduction in crack width and length. The researchers also noted that the use of SMPs had the potential to improve the fatigue resistance of cementitious composites. Overall, using self-healing materials in cementitious composites has the potential to improve the durability and lifespan of these materials.

2.2.4 Phase change materials in cementitious materials

Human civilization has seen many ages, from Stone Age to the modern age, and with it developed the requirement for constructing structures. In ancient times, construction methods were relatively simple. Usually, naturally available materials were used with no impact on the environment. The requirements of humans have changed in this era of development, and there is a need for smart materials to help minimize unprecedented pollution levels due to construction. So, practitioners worldwide require novel and more efficient material which affects the environment the least. The future's requirement points towards efficient materials applicable in multiple fields, low embodied energy, proven cost-effective, and environment friendly. The existing materials are failing on one or the other requirement; hence, searching for new materials for construction has become imperative. This has led to extensive research on novel construction materials; all over the world. Thus, it is high time to do extensive research on materials. There must be materials that possess all the qualities of a building material and can be used in many applications. Researchers have been working on this for a long time now.

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This revolution brought several smart materials and advanced methods for construction and production materials. Smart materials change their properties per the required application when the surrounding environment changes, and it has a purpose and an engineered method to achieve that. The constraints like required strength, increasing pollution, and lack of availability have cornered practitioners to look for new smart materials. These new methods and materials have found their place in the construction industry on a large scale since smart materials are so versatile in applications that they are found in numerous fields such as aerospace, environment electronics, civil, electrical, medicine, hospitality, agriculture, mechanical, sports, marine, defense, etc.

The previous researchers in the field of smart materials focused on applying them to reduce energy in buildings. A few types of research mentioned life cycle energy in materials and how we can control the influential factors in Building materials to reduce energy and CO₂ and reach for long life and high-performance building.

On the other hand, development in material technology in the last couple of decades demonstrated that the incorporation of phase change materials (PCMs) into the most used building material in the world (i.e., concrete) is an intelligent method to reduce building energy assumption problems (Adesina et al., 2019). PCMs are smart materials that can absorb or release large amounts of thermal energy during phase transitions (**Figure 2.2**). These materials have been widely used in various applications, such as thermal energy storage, building insulation, and temperature regulation (Hao et al., 2019). Recently, researchers have been investigating the incorporation of PCMs in cementitious materials to improve their energy efficiency and thermal comfort (Nawari et al., 2015). Adding PCMs, such as paraffin wax, into cementitious materials can regulate indoor temperature and reduce the energy consumption of HVAC systems (Soltani et al., 2019). Application of PCMs in the mentioned materials may be a potential method for improving the

above problems caused by steam curing. The ability to incorporate different materials inside the concrete mixtures nominates them as a proper host for PCMs.

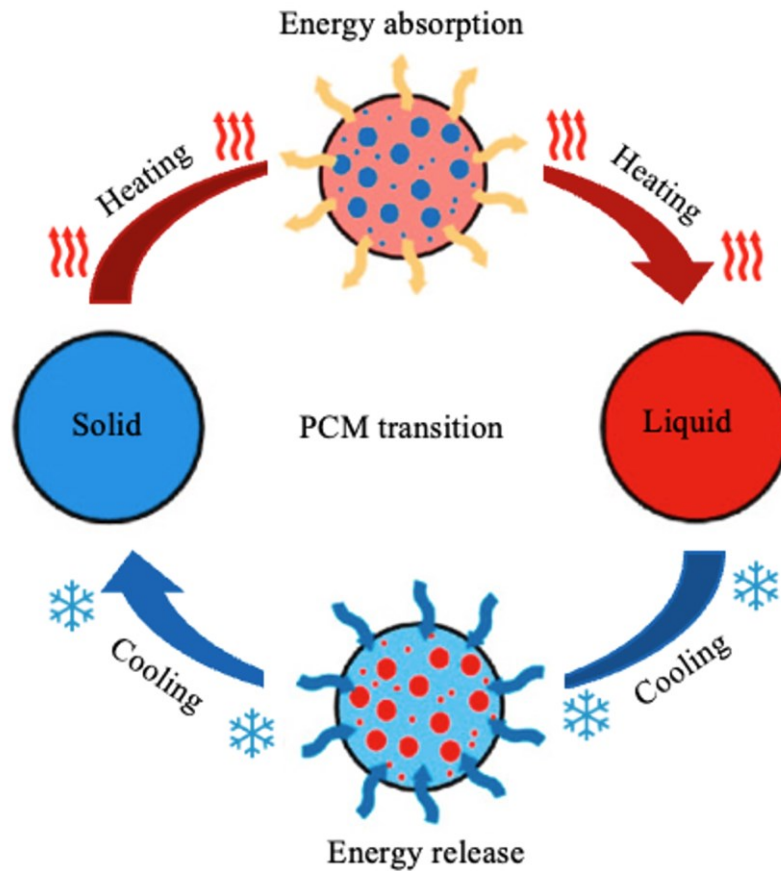


Figure 2.2 phase change materials function in heat and cool

The main property of phase change materials is the storage of heat energy in a latent form, leading to greater heat storage capacity per unit volume than conventional building materials. When the ambient temperature rises, the chemical bonds of the material will break up, whereby the material will change from solid to liquid. This phase change is an endothermic process and, as a result, will absorb heat. As the ambient temperature drops again, the PCM will return to the solid state, giving off the absorbed heat. This cycle stabilizes the interior temperature, cuts off-peak cooling loads, and decreases heating loads, not by affecting the thermal resistance of the building envelope but by influencing the (surface) temperatures.

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Including such phase change materials in building constructions, some specific thermal, physical, kinetic, and chemical properties are desired:

- From a thermal point of view, a suitable phase change temperature range, high latent heat of fusion, and a good heat transfer towards the PCM are desired. The desired phase change temperature will depend on climatic conditions and the desired comfort temperature.
- From a physical point of view, a favorable phase equilibrium, i.e., no phase segregation, a high density, and small volume changes at the phase change, are desired for easy incorporation in existing building materials or structures.
- From a kinetic point of view, no supercooling and a sufficient crystallization rate are desired to make optimal use of the properties and possibilities of PCMs. Supercooling, i.e., lowering the temperature of a liquid below its freezing point without becoming a solid, could strongly affect the performance of the PCMs based on the chosen suitable phase change temperature by influencing this temperature.
- From a chemical point of view, the long-term chemical stability of the PCM, despite cycling, compatibility with construction materials, non-toxicity, and no fire hazard, is desired.

Organic phase change materials are generally chemically stable, do not suffer from supercooling, are non-corrosive, are non-toxic, and have a high latent heat of fusion. Organic PCMs can be subdivided into paraffin (i) and non-paraffins (ii).

Inorganic PCMs generally have a relatively high heat of fusion, good thermal conductivity, and are cheap and non-flammable. However, most are corrosive to most metals, undergo supercooling, and undergo phase decomposition. The most common inorganic PCMs are hydrated salts.

Eutectic mixtures or eutectics, i.e., a mixture of multiple solids in such proportions that the melting point is as low as possible, have, in general, sharp melting points. Their volumetric storage density is slightly higher than organic compounds. However, limited data on their thermal and physical properties are available (**Figure 2.3**). Eutectics may be divided into three groups according to the materials of which they consist of: (i) organic–organic, (ii) inorganic–inorganic, and (iii) inorganic–organic eutectics (**Figure 2.4**).

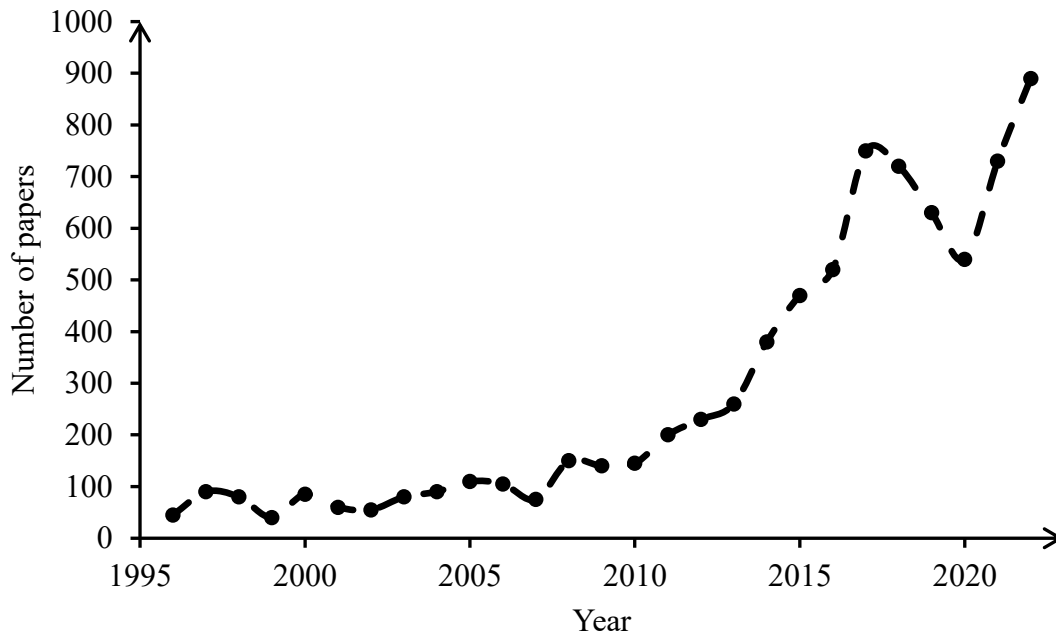


Figure 2.3 papers on PCM published during the last two decades.

The constant need for new constructions, the wish of the end-user for individuality, the poor productivity of the construction sector compared to other sectors, the low efficiency regarding material use, the low level of automation in design and construction, the lack of skilled workers as well as the growing scarcity of natural resources are all current challenges the construction industry must face. Managing sustainability is critical to developing corporate sustainability and fundamentally about strategic organizational development and change.

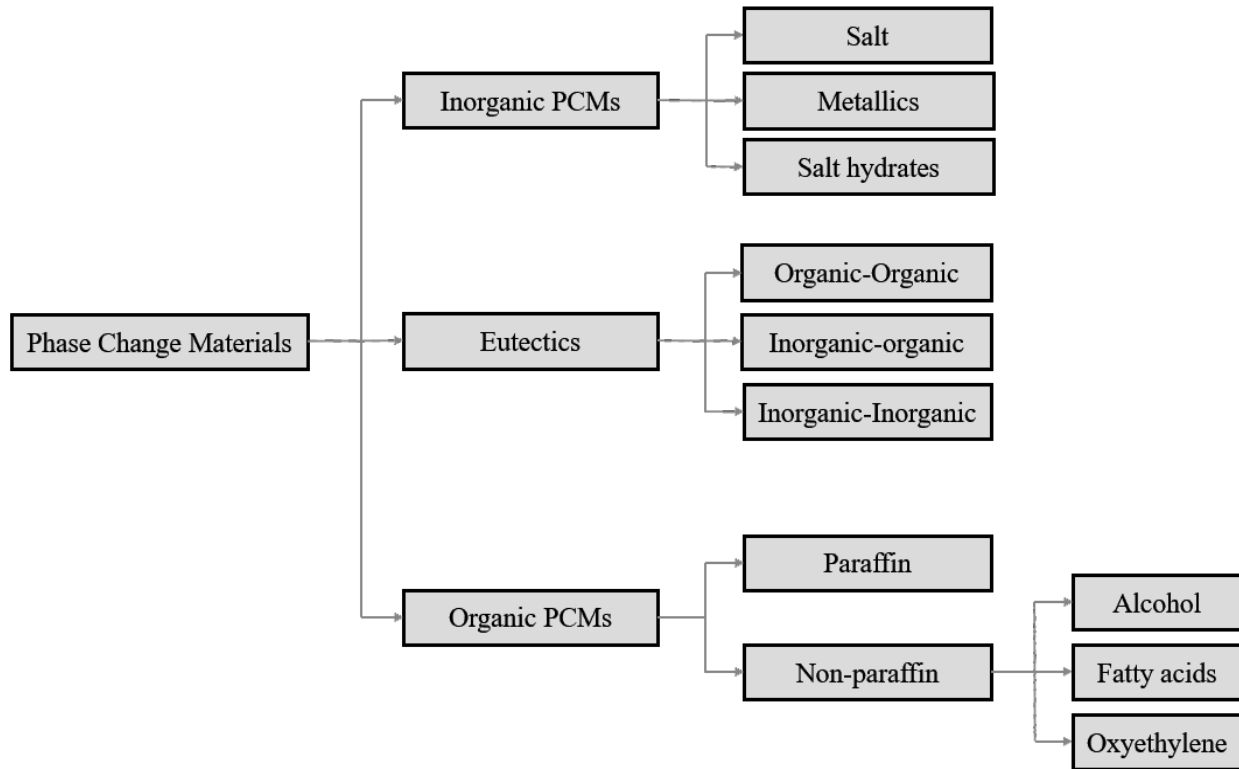


Figure 2.4 Overview of the main phase change materials

Some recent studies on applying phase change materials in cementitious materials can be mentioned as follows.

Sharifi et al. presented an experimental study of incorporating phase change materials (PCMs) into cementitious materials for thermal energy storage (Sharifi et al., 2015). The authors selected two types of PCMs, paraffin, and fatty acids, with melting temperatures between 21–24 °C and 27–29 °C, respectively. The PCMs were encapsulated into high-density polyethylene (HDPE) containers and mixed with cementitious materials to form composite materials. The thermal properties of the composite materials, including thermal conductivity, specific heat capacity, and thermal energy storage capacity, were measured, and compared to those of conventional cementitious materials. The results show that incorporating PCMs into cementitious materials significantly increases thermal energy storage capacity, especially when a high percentage of PCM (up to 50%) is used.

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However, using PCM also decreases the thermal conductivity of the composite material, which could negatively affect the heat transfer performance. The authors suggest that this could be addressed by using additives to improve the thermal conductivity of the composite material. Overall, the study demonstrates the potential of using PCMs in cementitious materials for thermal energy storage applications.

Ekmekyapar et al. investigated the effect of incorporating microencapsulated phase change materials (MPCMs) on the properties of cementitious composites (Ekmekyapar et al., 2014). The PCM used in the study was paraffin wax, which was microencapsulated with a melamine-formaldehyde shell to prevent leakage and chemical reactions with cement. The study found that incorporating PCM into the cementitious composites decreased compressive strength, but the reduction was limited and acceptable for most practical applications. The authors also found that the addition of PCM had a positive effect on the thermal properties of the composites, increasing their thermal energy storage capacity and reducing their thermal conductivity. The results indicated that the optimum content of PCM was around 5% by weight of the cementitious composite. The authors suggested that using MPCMs in cementitious composites has the potential for energy-efficient building applications, such as reducing the energy consumption of buildings by controlling indoor temperature fluctuations. The study also highlights the importance of the microencapsulation process to ensure the stability and compatibility of the PCM with cementitious materials. Overall, the study's findings demonstrate the potential benefits of using MPCMs in cementitious composites for thermal energy storage applications.

Noguchi et al. comprehensively reviewed using PCMs for thermal energy storage in building applications (Noguchi et al., 2015). The authors summarize the properties of different PCMs, including their melting point, latent heat of fusion, and chemical stability. They also describe

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various methods for incorporating PCMs into building components, such as walls, floors, and roofs, and discuss the advantages and limitations of each method. The authors reviewed the experimental and numerical studies on using PCMs in building applications, including their effects on indoor temperature control, energy consumption, and thermal comfort. They highlight the potential benefits of using PCMs in buildings, such as reducing energy consumption for heating and cooling, improving thermal comfort, and increasing renewable energy sources. The review also covers the challenges associated with using PCMs, such as their low thermal conductivity, the tendency to leak or degrade over time, and their high cost compared to traditional building materials. The authors discuss some of the strategies that have been proposed to overcome these challenges, including the use of additives to improve thermal conductivity, the development of novel encapsulation methods, and the optimization of PCMs composition and application.

Zhang et al. worked on the thermal performance of cementitious composites with MPCMs for building applications (Zhang et al., 2017). The PCM used in the study was paraffin wax, which was microencapsulated with a shell made of polyurethane. The study found that incorporating MPCMs into cementitious composites improved thermal energy storage capacity and reduced thermal conductivity, resulting in improved thermal performance. The authors also found that the addition of PCMs had a slight impact on the compressive strength of the composites, but the reduction was within acceptable limits for most practical applications. The study identified the optimum PCMs content to be 10% by weight of the cementitious composite. The authors suggest that using MPCMs in cementitious composites has the potential for building applications, particularly for reducing energy consumption for indoor temperature control. The study also highlights the importance of the microencapsulation process to ensure the stability and compatibility of the PCM with cementitious materials.

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Nguyen et al. investigated the effects of incorporating phase change material (PCM) on cementitious composites' mechanical and durability properties (Nguyen et al., 2016). The PCM used in the study was a mixture of paraffin wax and high-density polyethylene added to the cementitious composites at different weight fractions. The study found that the addition of PCM had a slight effect on the compressive strength of the cementitious composites, with a reduction of up to 15% at higher PCM weight fractions. However, the addition of PCM had no significant effect on the composites' flexural strength or modulus of elasticity. The authors also investigated the durability properties of the composites, including their water absorption, chloride ion penetration, and freeze-thaw resistance. The study found that adding PCM had no significant effect on the composites' water absorption or chloride ion penetration. However, the addition of PCM improved the freeze-thaw resistance of the composites, with a reduction in mass loss of up to 30% compared to the control specimens.

Zhang et al. investigated the thermal performance of a cementitious composite incorporating MPCMs. The MPCMs used in the study was a mixture of paraffin wax and expanded graphite encapsulated in a shell material to form microcapsules (Zhang et al., 2013). The study used a series of experiments to investigate the thermal properties of the composite, including its thermal conductivity, heat storage capacity, and heat release/retrieval characteristics. The results showed that the incorporation of MPCMs significantly improved the thermal performance of the cementitious composite, with a reduction in thermal conductivity and an increase in heat storage capacity. The study also investigated the composite's heat release/retrieval characteristics, which are essential for understanding the practical application of PCMs in building materials. The results showed that the composite had good heat retrieval characteristics, with a high percentage of the

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stored heat released when the temperature of the composite dropped below the melting point of the PCMs.

Huang et al. reviewed the mechanical and thermal properties of fiber-reinforced geopolymer mortar (FRGM) with the addition of PCMs for potential use in energy-efficient building applications (Huang et al., 2022). The study used two types of PCMs, paraffin wax and erythritol, at different weight percentages and incorporated them into the FRGM mix. The mechanical properties of the resulting FRGM with PCMs were tested, including compressive strength, flexural strength, and tensile strength. The thermal properties of the FRGM with PCMs were also investigated, including thermal conductivity, thermal diffusivity, and specific heat capacity. The results showed that the addition of PCMs had a slightly negative effect on the mechanical properties of the FRGM, but the reduction was within an acceptable range for practical applications. The thermal conductivity of the FRGM with PCMs was reduced by up to 38% compared to the control sample without PCMs. The thermal diffusivity and specific heat capacity of the FRGM with PCMs were also improved. The study also conducted an energy storage and release test on the FRGM with PCMs to evaluate its effectiveness in energy storage and energy-efficient building applications. The results showed that the FRGM with PCMs had good energy storage and release characteristics, with a large amount of energy being stored during the melting process and released during the solidification process.

Bo et al. studied preparing and characterizing PCMs for building applications. The study focuses on organic PCMs, including paraffin and fatty acids, as they are widely used in building applications due to their high latent heat of fusion, good thermal stability, and chemical compatibility with building materials (Bo et al., 2018). The authors used a two-step process to prepare the PCMs, including melting and solidifying to achieve a homogeneous mixture and then

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encapsulating the PCM in a high-density polyethylene (HDPE) matrix to prevent leakage and improve handling. The authors characterized the prepared PCMs using a range of analytical techniques, including differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR). The results showed that the prepared PCMs had high latent heat of fusion, good thermal stability, and chemical compatibility with building materials. The authors also evaluated the thermal performance of the prepared PCMs in a simulated building environment. The PCMs were applied to the ceiling of a test room, and the temperature was measured over a while. The results showed that using the PCMs reduced the peak temperature by 6 °C and delayed the onset of temperature rise by 2 hrs.

Given the context of earlier experiments and research, which were briefly discussed earlier, it becomes evident that there exists a significant gap in the understanding of the behavior of PCMs, particularly when incorporated into organic PCMs within cementitious materials. This knowledge void serves as the driving force behind this thesis, prompting a rigorous exploration. The primary aim of this research is to contribute to the advancement of energy-efficient practices within the production of precast cementitious products. This is achieved through a comprehensive series of experiments focused on harnessing the energy-saving potential of PCMs, while considering their inherent properties. As a result, the upcoming chapters of this thesis are meticulously structured to address this overarching goal.

CHAPTER 3: EVALUATING THE THERMAL RESPONSES AND CHEMICAL STABILITY OF PHASE CHANGE MATERIALS EXPOSED TO THE ALKALINE ENVIRONMENT UNDER CYCLIC TEMPERATURE

Abstract

The utilization of smart materials in the construction industry significantly changed many design concepts. Among various innovative materials, Micro-encapsulated Phase Change Materials (MPCMs) are widely used to modulate the thermal response for various materials by absorbing and releasing heat in a specific temperature range. MPCMs have shown a potential to optimize the heat curing process for cementitious products minimizing temperature fluctuation and curing period. However, under such harsh conditions (i.e., high temperature, relative humidity, and high alkalinity) the thermal responses and chemical stability of MPCMs incorporated in cementitious materials yet need to be evaluated. In this study, the response for MPCMs exposed to cyclic temperatures and different alkaline environments simulating the cementitious matrix was examined. Results reveal that although a reliable thermal response of MPCMs in various temperature ranges was adequate, an extensive chemical reaction between MPCMs and the alkaline environment occurred. The performance of MPCMs in alkaline environments at certain temperature levels was highlighted.

3.1 Introduction

With the population increase and remarkable industry development, energy demand increased significantly, encouraging researchers to look for new methods to save energy in different sections (Palacios et al., 2020). The building sector is the primary energy consumption, and it is dedicated to around 40% of the fossil fuel consumption in western countries (Balali et al., 2020). To reduce energy consumption, improving thermal energy storage of facades for the heating and cooling of buildings is essential. For this reason, many researchers have focused on the materials used for constructing various buildings (Belussi et al., 2019; Heniegal et al., 2021). Phase Change Materials (PCMs), one of the recent smart materials invented, are considered the most effective technique for improving the energy storage capacity of building envelopes (Qu et al., 2021). PCMs are categorized as organic, inorganic, or a mixture of both. In cementitious materials, primarily organic type (paraffin bases) is being used (Cabeza et al., 2011). However, application of the PCMs can be problematic due to the potential delay of cementitious materials hydration as being in contact with paraffin. Hence, several encapsulation techniques were proposed to prevent this issue, including microencapsulation, macro-encapsulation, shape stabilization, and lightweight aggregate (LWA) impregnation (Berardi et al., 2019). Among those methods, micro-encapsulation PCMs presented a better promising performance in terms of mechanical stability (Khadiran et al., 2015; Ramakrishnan et al., 2017). Paraffin MPCMs in exposure to a specific temperature range can absorb the energy as latent heat by changing phase through solidification or liquefaction. Many researchers have used the ability of MPCMs in the construction sector. Adesina et al. (Adesina et al., 2020) found that the incorporation of PCMs by 20 wt.% into the cementitious mixtures could reduce setting time by more than 15%. Other authors reported a reduction in mechanical properties when utilizing MPCMs in cementitious materials (Cui et al., 2015; Fernandes et al., 2014).

Bondareva et al. (Bondareva & Sheremet, 2022) worked on the heat transfer performance of concrete blocks containing PCMs for thermal comfort in buildings. It was found that partitions with PCMs inclusion for passive cooling of buildings in a vertical direction could absorb more energy than horizontal direction due to natural convection. . Marani et al. (Marani & Madhkhan, 2021) showed that incorporating concrete panels with PCMs in the interior building walls can reduce temperature variation by a 5.4oC.

On the other hand, although there have been many studies on the performance of the cementitious mixtures with the inclusion of MPCMs, there are few studies on the performance of MPCMs in terms of chemical stability and thermal responses. This may explain the low performance of some mixtures incorporating MPCMs (Jayalath et al., 2016; Pilehvar et al., 2019; Sahu et al., 2017). This study is anticipated to cover the knowledgeable gap on the proper conditions of applying PCMs in cementitious material to obtain the best energy performance. In addition, an energy analysis was performed through MATLAB software to magnify the thermal responses of MPCMs. The thermal responses and chemical stability of MPMCs are yet needs to be identified. There has been very few studies that covered this topic, especially with respect to cementitious and non-cementitious mixture specifications.

3.2 Experimental Work

3.2.1 Materials

Powder MPCM with a melting point of 57 °C, considering the normal steam curing condition for mortars, was used in this experiment (Yang *et al.*, 2021). The physical and chemical properties of the MPCMs are shown in **Table 3.1**. The particle size distribution and microstructure of the MPCMs can be seen in **Figure 3.1**. Sodium hydroxide solution was prepared by dissolving NaOH

pellets (AR grade, purity $\geq 99\%$) into deionized water to obtain 6M and 12M molarities for MPCMs' chemical stability check purposes. This solution is one of the primary activators for alkali-activated mixtures. The selected molarities was to simulate the normal and high alkaline environment to test MPCMs' stability.

Table 3.1 Properties of the used MPCM 57 °C

	MPCM 57
Classification	Organic mixture
Appearance	White, dry powder
Solubility	Insoluble
Phase change	55 - 59 °C
Moisture	$\leq 3\%$
Paraffin Wax	79.6%
Melamine Resin	17.4%
Heat of fusion	172 J/g
Size range	4.99 μm to 82.8 μm
Mean particle size	30.7 μm
Solid content	98.1%
Shell material	Melamine

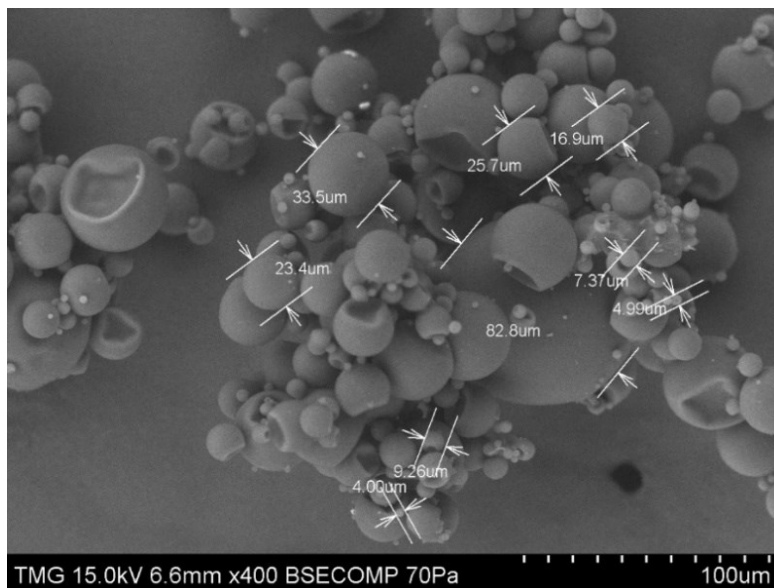


Figure 3.1 Particle size distribution of MPCMs (SEM analysis)

3.2.2 Testing and specimens' preparation

3.2.2.1 Thermal responses of MPCMs

The MPCMs were subjected to different temperature ranges in an environmental chamber to monitor their thermal responses and latent heat with respect to their phase change periods. In this respect, samples of MPCMs were instrumented with type T thermocouples in glass containers subjected to cyclic temperatures with the maximum temperature exposure of 60 ± 1 °C as a simulation for steam curing conditions (Yang et al., 2021). The thermal responses were collected with a data acquisition system every 1 minute.

Table 3.2 shows the temperature ranges applied to the MPCMs' samples. Three primary cycles concerning the melting and the solidification limit of the used MPCMs were applied. These temperature ranges cover the MPCMs' thermal response scenarios through the inner and outer phase change range. Scenarios are named from T1 to T4, considering the T1 as the main one to determine the needed time for the rest of the scenarios.

Table 3.2 MPCMs 57 Stability check-in heat variations

Mood	Temperature range (°C)	Time
T1	72-42	30 min, 1, 1.5, 2, 3, and 5 hrs.
T2	55-72	2 hrs.
T3	59-42	2 hrs.
T4	55-59	2 hrs.

3.2.2.2 Chemical stability of MPCMs

MPCMs samples were subjected to sodium hydroxide solutions with 6M and 12M molarities for simulating high pH environments and distilled water at ambient and high-temperature environments for up to one week. The ambient temperature was 23 ± 2 °C, and the high-temperature environment reached maximum of 80 °C. Specimens were monitored for color, size, and agglomeration changes hourly with a camera during the experiment. The specimens were

analyzed before and after the experiment with a scanning electron microscope (SEM) to track changes.

3.3 Results and Discussion

3.3.1 Thermal response

Based on the MPCM 57 °C manufacturer's manual, the phase change of paraffin should start by melting at 55 ± 0.5 °C to reach 59 ± 0.5 °C for the complete melting stage and solidifying at 55 ± 0.5 °C to reach 51 ± 0.5 °C for the complete solidification stage. Moreover, it was stated that the ± 2 °C from 57 °C is the gap between the solidification and melting of the MPCMs. These statements have been set to be investigated through the thermal response test.

According to the results of T1 (**Figure 3.2**), it was found that the MPCMs require at least two hours of temperature holding period to achieve a complete phase change. The available paraffin inside the MPCM's particle cannot be fully melted/solidified in cycles with less than two hours temperature holding period and will not reach the maximum energy storage capacity for MPCM. Hence, if the exposure time is less than two hours, paraffin will not reach the complete melting point in the first cycle (i.e., the total melting and solidification period is called a cycle). It intended to reach the equilibrium in the phase change in the subsequent cycles. A gradual upward deviation in the temperature absorbed by the paraffin in the cycles before the equilibrium point was seen (**Figure 3.2**) indicating that the paraffin's tendency is to absorb heat than release it, which was also seen in all the scenarios. The equilibrium in phase change was clear after two hours of exposure for the first cycle and continued through the rest of the cycles until the end of the investigation period. This indicated that the appropriate time to change the paraffin phase entirely

is +2 hours in this scenario (**Figure 3.4**). Therefore, it can be concluded that the exposure time significantly affects the energy storage efficiency of MPCMs.

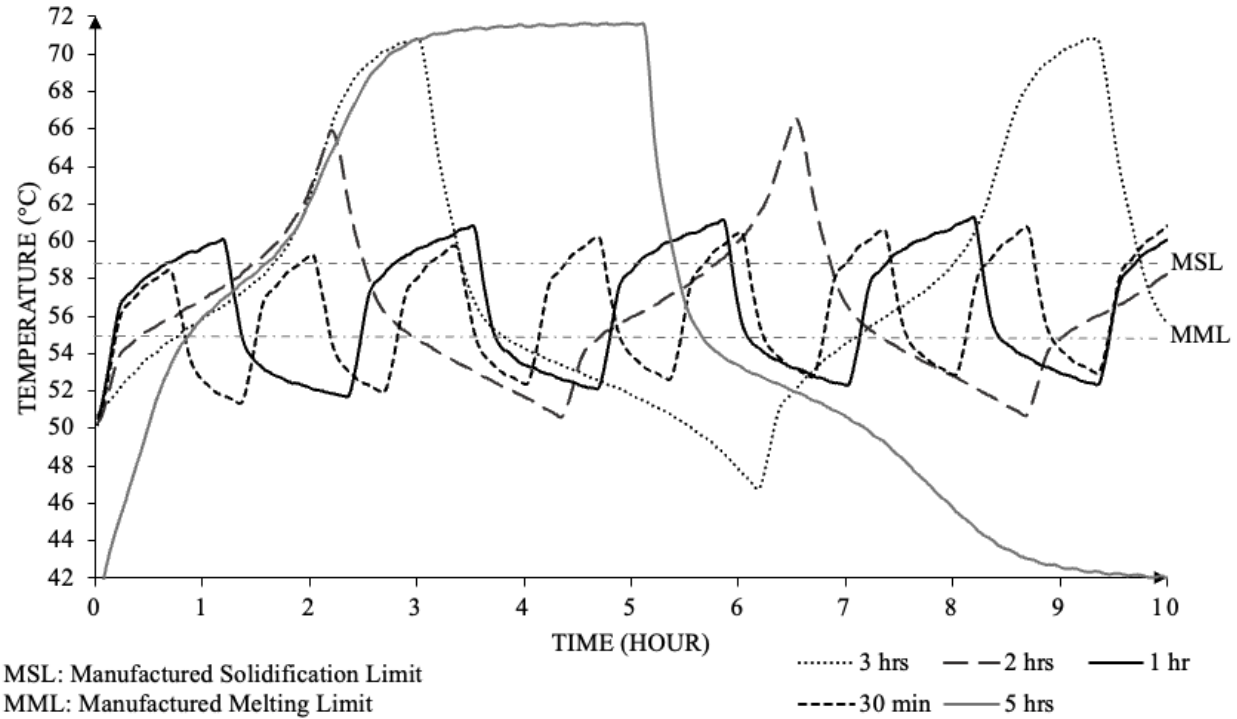


Figure 3.2 Thermal response of MPCMs in T1

The primary and final points in the changing phase period were named as the initiation and ending point. Moreover, the change in the phase of the paraffin through the scenarios can be represented by the change in the curve's slope. It was found that the heating and cooling rates of T1 in all exposure times differed. Based on the observations, paraffin has quicker heat absorb capability than releasing heat by +1 °C (**Figures 3.3 and 3.4**). This fact caused the difference between the melting and solidification period. For instance, in T1 with 30 minutes and 2 hours holding period, the heating rate dropped from 35 °C/hr to 6 °C/hr and from 35 °C/hr to 4 °C/hr (**Figures 3.3 and 3.4**). Accordingly, the heating and cooling rates during the phase change period decreased by 88% and 92%, respectively. In a comparison between the T1 with 30 min and 2 hours holding period, it was observed that the period between the melting initiation point (MIP) and melting ending point

(MEP) or solidification initiation point (SIP) and solidification ending point (SEP) had been increased significantly. This phenomenon illustrated the increase in the latent heat capacity of paraffin by increasing the exposure time. This capacity remained steady in the exposure with temperature holding period times over 2 hrs. **Table 3.3** presents detailed information on the thermal responses of MPCMs in T1 exposure scenario. Based on the findings, MPCMs lowered the heating rate through the phase change period by six times. This reduction was enhanced by 50% with the extension in the temperature holding period from 30 minutes to 5 hours in T1 demonstrating the importance of exposure time on the effectiveness of MPCMs' latent heat capacity. The heating and cooling rates were in a linear relationship through phase change periods.

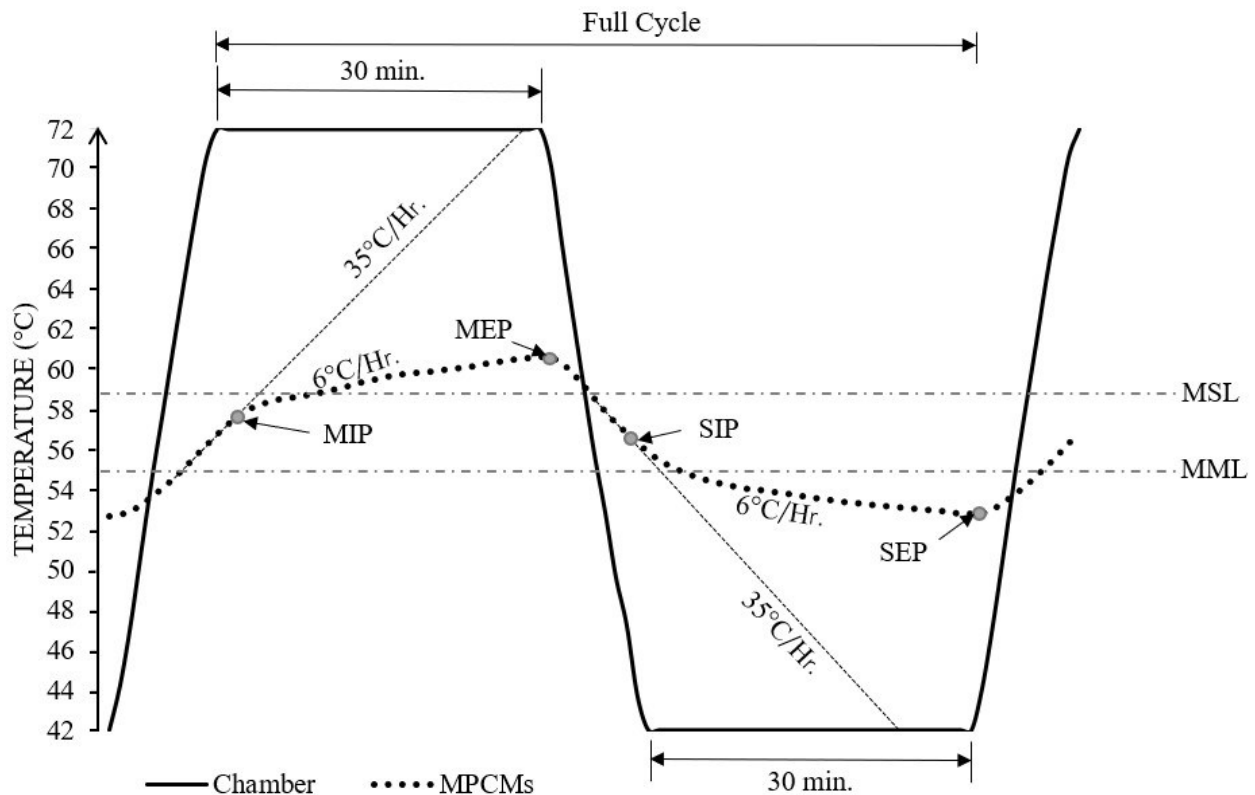


Figure 3.3 Thermal response of MPCMs in T1 - 30 min.

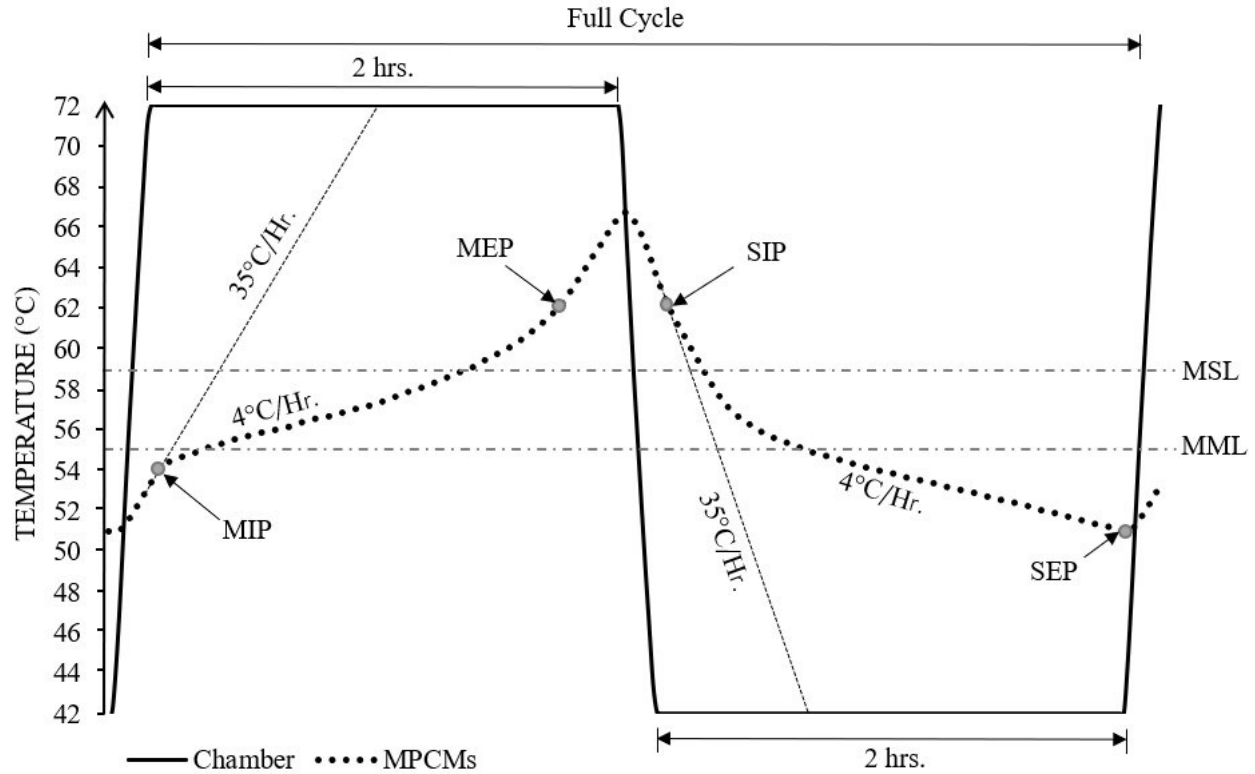


Figure 3.4 Thermal response of MPCMs in T1 - 2 hrs.

Table 3.3 Thermal responses of MPCMs in T1 mood

Mood	Duration (hr.)	MIP (°C)	MEP (°C)	HR (°C/hrs.)		SIP (°C)	SEP (°C)	CR (°C/hrs.)	
				Before	After			Before	After
T1	0.5	58	60	35	6.0	56	52	35	6.0
	1.0	58	62	35	5.8	56	52	35	5.8
	1.5	57	64	35	5.3	59	51	35	5.3
	2.0	54	62	35	4.0	62	51	35	4.0
	3.0	51	62	35	3.7	59	47	35	3.7
	5.0	51	61	35	2.9	56	50	35	2.9

The rest of the scenarios were adjusted based on the findings of T1. Scenarios T2 and T3 simulate the conditions of having small temperature variation (i.e., fluctuation) either on the melting or solidification of paraffin to have phase change. Based on the results of T2, it was found that although there was enough time for paraffin to liquidity, a significant amount of paraffin could not solidify during the phase change. This fact was related to the small temperature fluctuation

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range for the solidification period. Accordingly, paraffin could not fully achieve an equilibrium in the phase change in the first couple of cycles and presented an upward trend in absorbing energy rather than releasing it. Eventually, the balance between the phases was seen after the fifth cycle. This fact was confirmed in the T3 in the solidification phase as well. In this scenario, paraffin could not change from solid to liquid form entirely due to the low-temperature fluctuation range for the melting phase. In this respect, MPCMs could reach the equilibrium from the fifth cycle, similar to the T2.

Although the paraffin could not transform fully to liquid during heating, it presented an upward trend in thermal response. This indicated the MPCM's tendency to absorb energy more than release it. A similar fact was seen in the T1 in the cycle of less than 2 hours temperature holding period. As the holding period was identical for T2 and T3 (i.e., 2 hours) (**Figures 3.5, 3.6**), it was found that the exposure temperature significantly affects the energy capacity of MCPMs. To use the higher latent heat capacity of MPCMs, the chosen environment should ensure adequate temperature fluctuation ranges beyond the melting and solidification points.

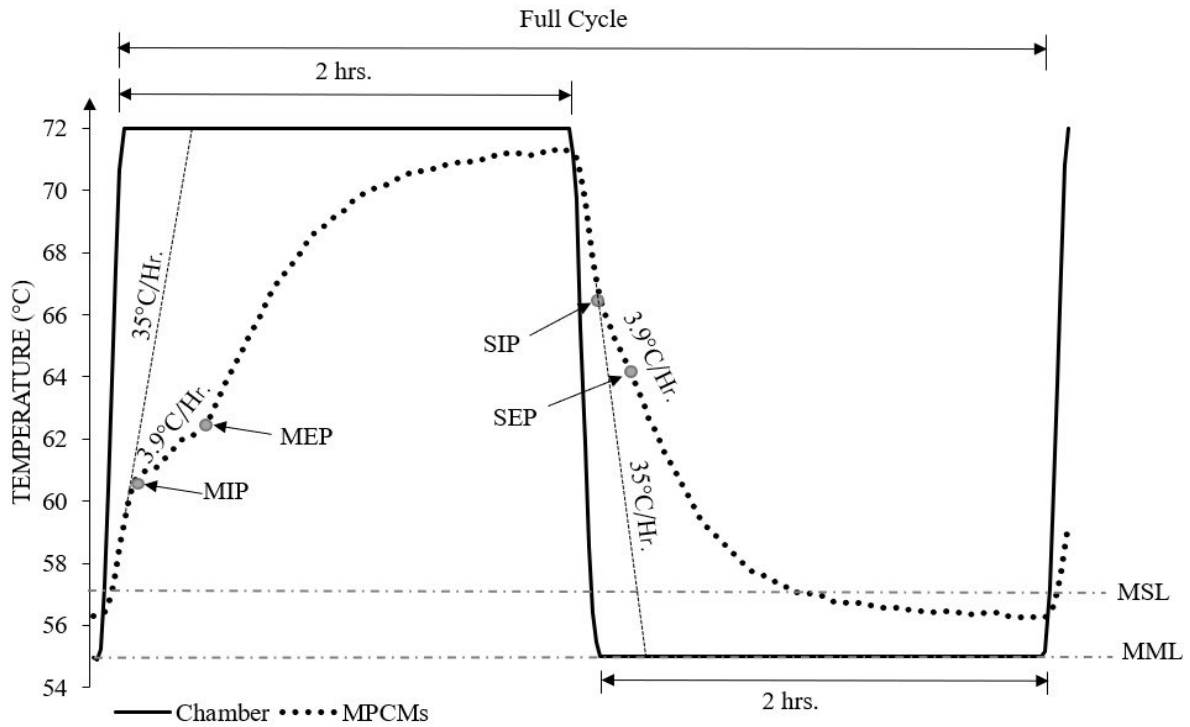


Figure 3.5 Thermal response of MPCMs in T2 – 2 hrs.

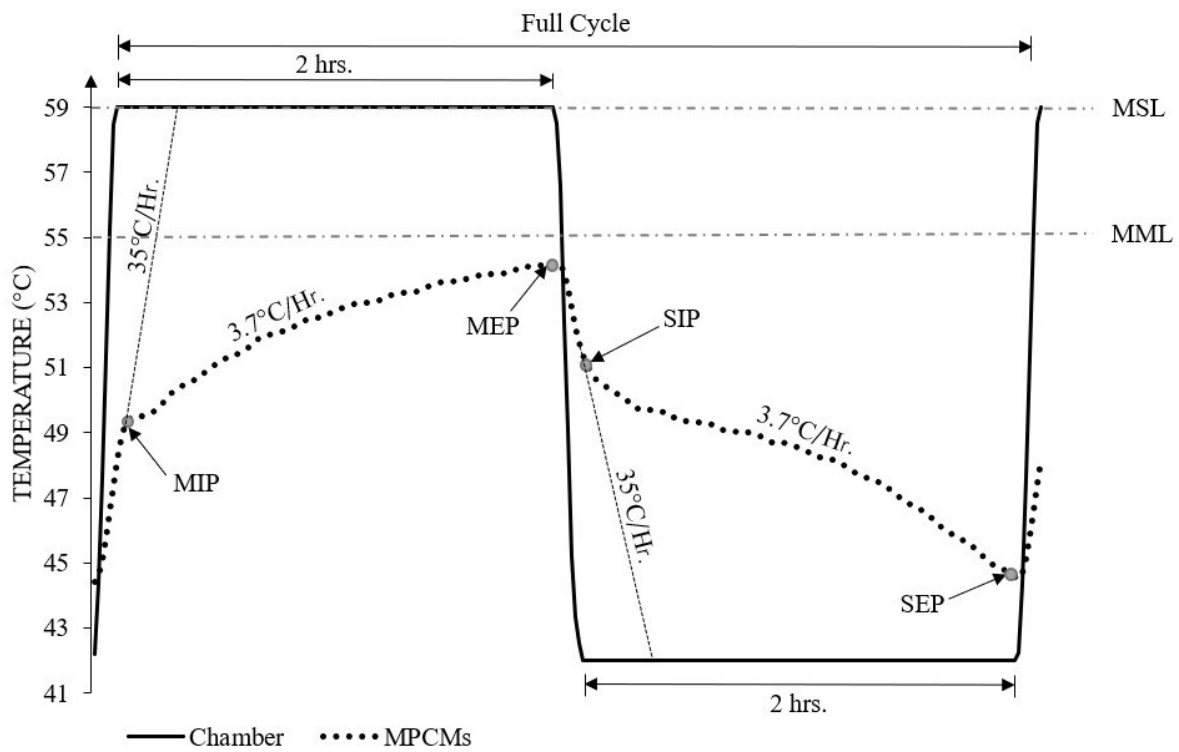


Figure 3.6 Thermal response of MPCMs in T3 – 2 hrs.

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Comprehension of the MCPMs' thermal response can also be focused on paraffines' response in the melting and solidification in short temperature gaps. To challenge this point, T4 mood was designed (**Figure 3.7**). In this mood, the MPCMs have been subjected to a short temperature gap of 55°C to 59°C for evaluating the thermal response at the phase change limits. According to the findings, MPCMs presented an upward trend similar to the previous moods, indicating more desire for absorbing energy. Through this phenomenon, the equilibrium in the phase change reactions could be achieved after a couple of cycles. The MIP and SIP were at 56.7°C and 56.5°C, respectively.

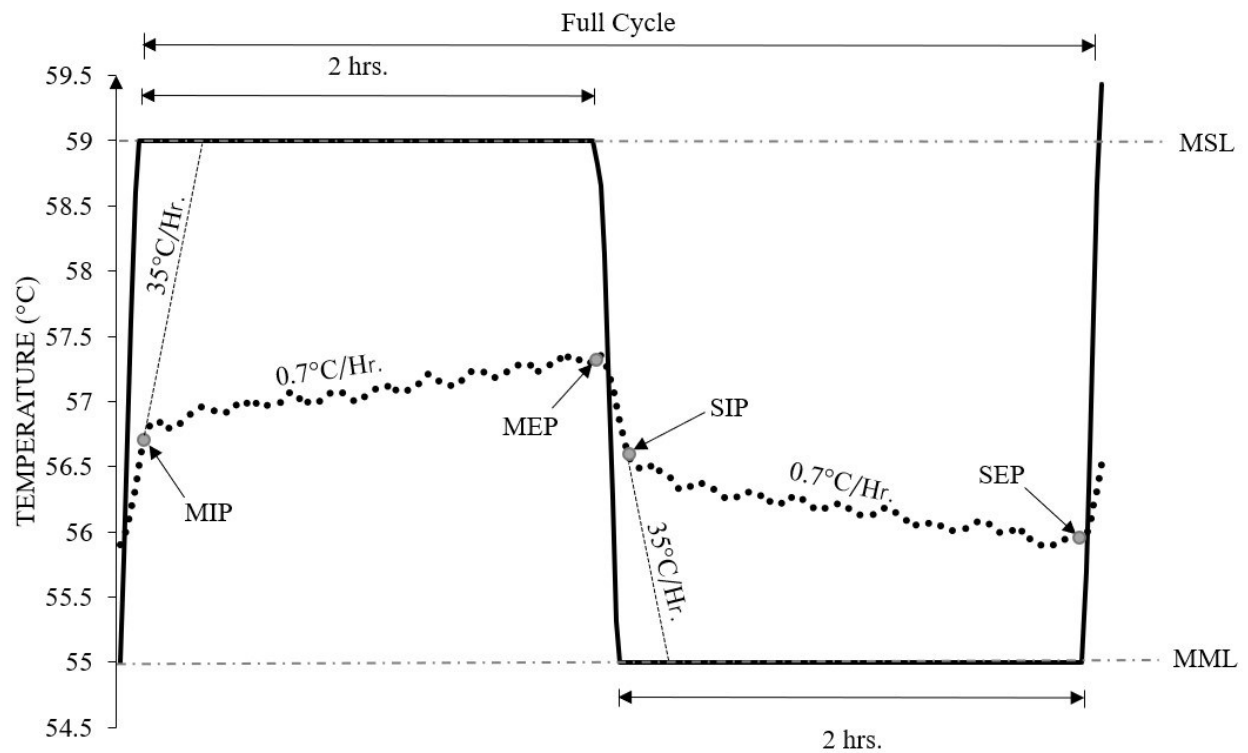


Figure 3.7 Thermal response of MPCMs in T4 – 2 hrs.

A balance between the energy stored and released in paraffines was found in MIP, MEP, SIP, and SEP analysis. Although this tendency to absorb heat was seen, the gap between the melting point and the higher temperature (59°C) was double than of the lower temperature (55°C). This

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demonstrated the difference between the melting and solidification points of paraffines. These particles could consolidate more in this exposure temperature.

Moreover, this fact presented that the ending melting or solidification points could not be reached through this mood. Hence, lower latent heat capacity was utilized. A higher exposure temperature gap from the phase change range is essential to increase this capacity.

Other thermal scenarios have also been tested on the MPCMs including different exposure times and temperatures, however, same outcomes were found. Through the long-term investigation of the thermal responses, MPCMs exhibited superb reliability in the thermal response. The equilibrium in the phase change reaction was achieved after the initial cycles and continued steadily.

3.3.1.1 Energy analysis

The energy analysis was carried out on the T1 with 30 minutes holding period using MATLAB software to analyze the data. Based on the results of T1, one of the cycles after the equilibrium was analyzed. Different areas of the thermal response were selected to evaluate deeply. These areas are named 1, 2, 3, and 4, presenting the energy given, the energy taken, the energy absorbed, and the energy released, respectively (**Figure 3.8**). **Table 3.4** presents the amount of energy numerically. Equality in the energy given and taken through the one cycle of this scenario was observed with a 2.5% difference.

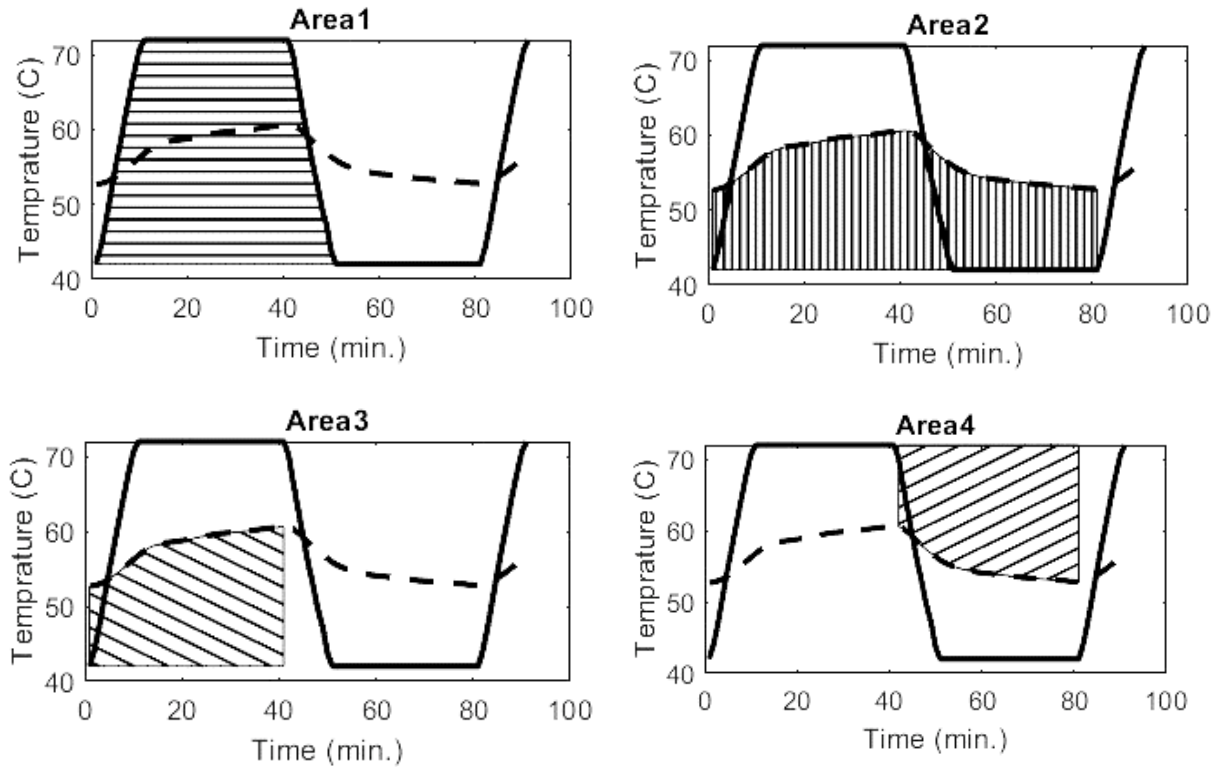


Figure 3.8 Energy analysis of MPCMs in the oven at one T1 – 30 min cycle.

Furthermore, the amount of energy absorbed and released through MPCMs during the same cycle was equal, with a slight deviation (less than 4%). Based on these establishments, a direct relation in the energy cycle in this scenario could be seen. In the simulated environment, the energy given as the heat absorbed by the MPCMs is the latent heat through the melting process of paraffines. This energy was later released during the cooling period through the solidification process of paraffines to compensate for the energy loss of the environmental chamber. Based on this significant finding, it can be stated that in closed environments such as steam curing chambers, MPCMs can be incredibly effective in saving energy.

Table 3.4 The area of each section analyzed with MATLAB software.

Area 1	Area 2	Area 3	Area 4
1.201005000000000e+03	1.172692000000000e+03	6.573520000000002e+02	6.846600000000001e+02

3.3.2 Chemical stability

The chemical stability was carried out on samples mentioned in **Table 3.5**. The evaluated samples were named S1 to S10. The composition of samples is written as the three main testing materials of MPCMs, NaOH, and H₂O, along with the exposure conditions. Two methods of evaluation of visual scale available in **Table 3.6** and SEM photos have been taken for samples to analyze the results. The visual scale was designed to evaluate the samples through agglomeration, color change, and workability factors.

Table 3.5 Exposure conditions applied to specimens in chemical stability check.

Sample	Composition	Exposure condition
S1	MCPMs + H ₂ O	Ambient
S2	MCPMs + H ₂ O	80 °C
S3	6M NaOH	80 °C
S4	12M NaOH	80 °C
S5	MCPMs + 6M NaOH	Ambient
S6	MCPMs + 12M NaOH	Ambient
S7	MCPMs + 6M NaOH	60 °C
S8	MCPMs + 12M NaOH	60 °C
S9	MCPMs + 6M NaOH	80 °C
S10	MCPMs + 12M NaOH	80 °C

Table 3.6 Visual scale for stability check of MPCMs subject to heat and alkaline solutions

Scale	Description
1	No defect Workable
2	Low agglomeration Workable
3	High agglomeration Partially workable
4	Permanent deformation Not workable

Based on the observations, MPCMs presented a scale of 1 in the combinations with water at ambient (S1) and heat conditions (S2). MCPMs' particles are hydrophobic and have a lower specific gravity (≈ 0.6) than water (≈ 1). This made the MCPMs to be floated on the water. This was true for all the samples mixed with alkaline solutions (NaOH). The alkaline solutions were

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also examined for changes in the presence of heat (S3 and S4). According to the results, the pH of alkaline solutions increased as being heated. This may be attributed to the evaporation of water from the solution increasing the concentration of NaOH. In S5 and S6 analyses, low agglomeration of MPCMs was observed with no desolation after 48 hrs (scale of 2). This agglomeration was attributed to the minor reactions between the alkaline solution and the MPCMs. The MPCMs' shell was made of Melamine. According to Al-shannaq et al.'s work (Al-Shannaq, 2022) on the various methods of synthesis of phase change materials microcapsules, NaOH is being used as a catalyzer between the Melamine and formaldehyde to form M-F prepolymer. This reaction requires heat to be completed.

The low reaction of MPCMs with the used alkaline solution can be due to the interaction between NaOH and the melamine shell. This reaction was seen clearly as the temperature increased. In S7 and S8, as the temperature increased from ambient to 60°C, a significant agglomeration was caught by the end of the experiment with a scale of 3. This phenomenon was higher in S8 as the solution had a higher pH. The highest agglomeration was seen in samples of S9 and S10, which were subjected to 80°C for 48hrs. By increasing the heat, the solutions became more alkaline as the solution's water evaporated. This in-fact significantly increased the reactions between NaOH and MPCMs' shells (+30%). According to the visual inspections, a non-reversible expanded particle reaction remained by the end of the experiment (scale of 4). The sequences of the mentioned information are shown in **Figure 3.9**.

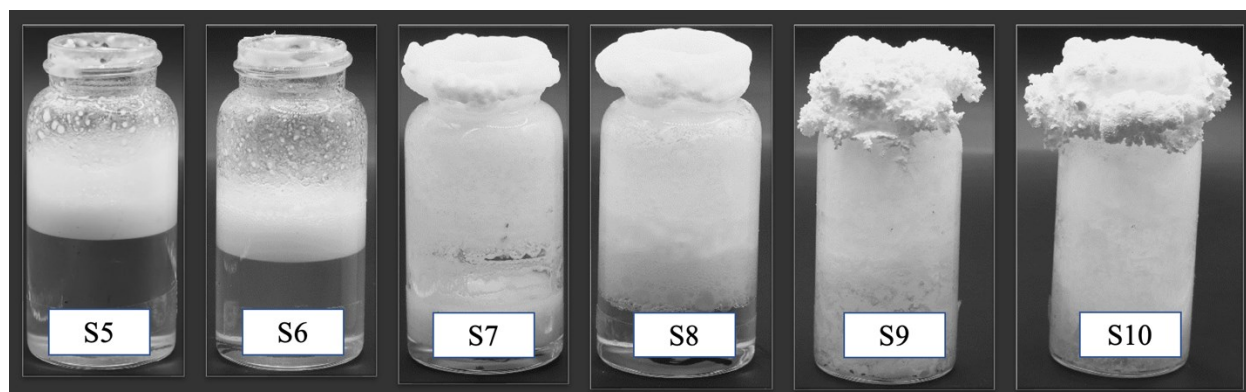


Figure 3.9 MPCMs specimens subjected to chemical stability.

Scanning Electron Microscopy (SEM) was used to obtain more details about the mentioned deformation. According to the photos, the MPCMs' particles have a spherical shape with a mean particle size of $30.7\ \mu\text{m}$ (**Figure 3.1**). No change was seen in the mixture of MPCMs with water in ambient and heat conditions (**Figure 3.10**). A significant difference in the microstructure of MPCMs with the increase in temperature and pH was observed.

The melamine shell of MPCMs in reaction with MCPMs dissolved partially at the ambient condition, which was followed by magnificent shell destruction as temperature increased to 80°C . This reaction was more intense in the solutions with higher alkalinity (12M). As a result of this reaction, the paraffines have pushed out of their shells and reacted as needles out of the shells (**Figure 3.11**). These needles have become sharper with the increase in temperature and pH. Ultimately, no MPCMs particles could be observed at the end of this experiment because of this reaction (**Figure 3.12**).

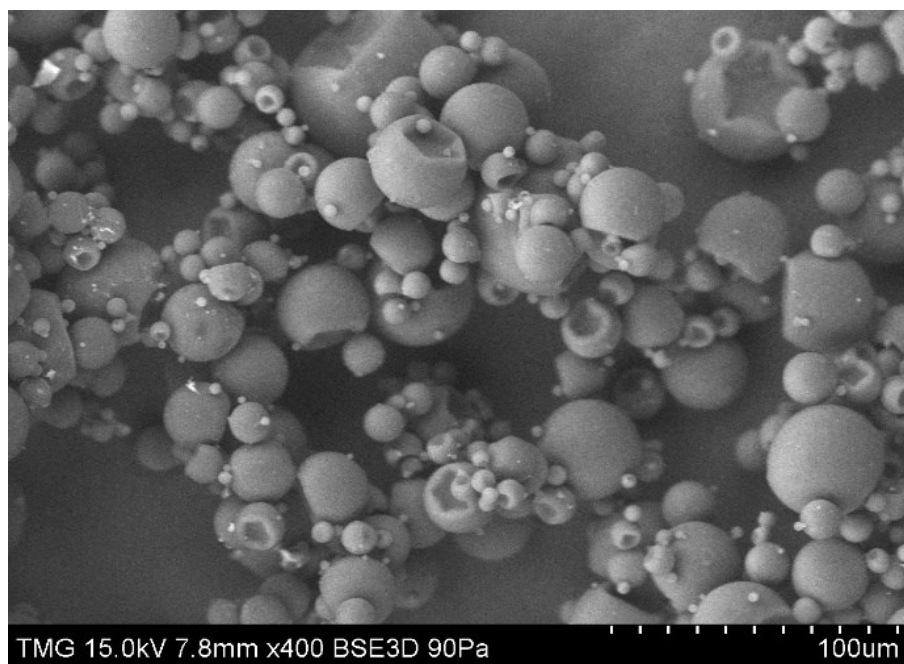


Figure 3.10 The reaction of MPCMs in water at 80°C temperature

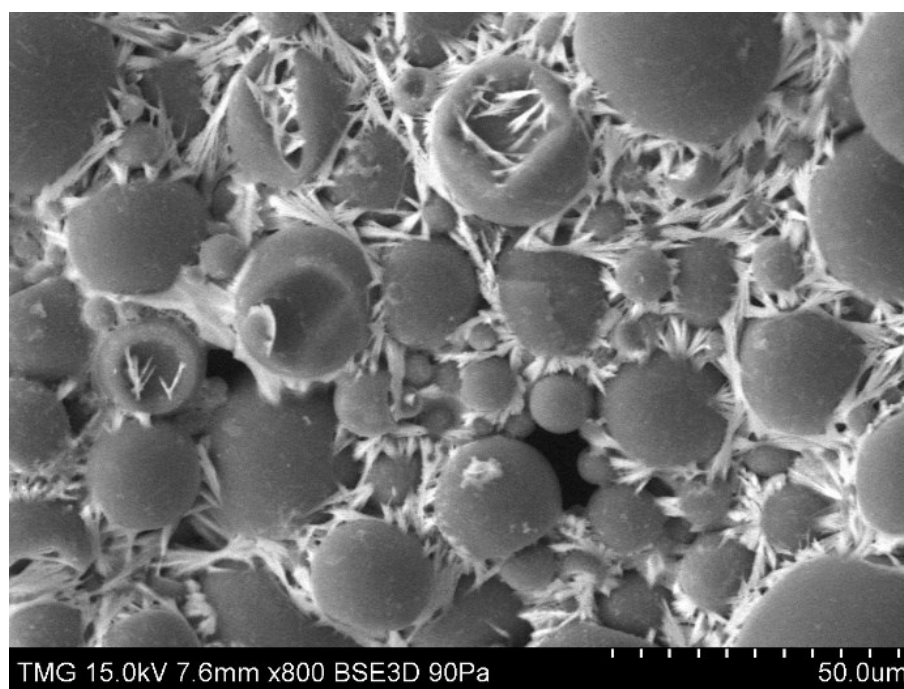


Figure 3.11 The reaction of MPCMs with 12M NaOH solution at ambient temperature

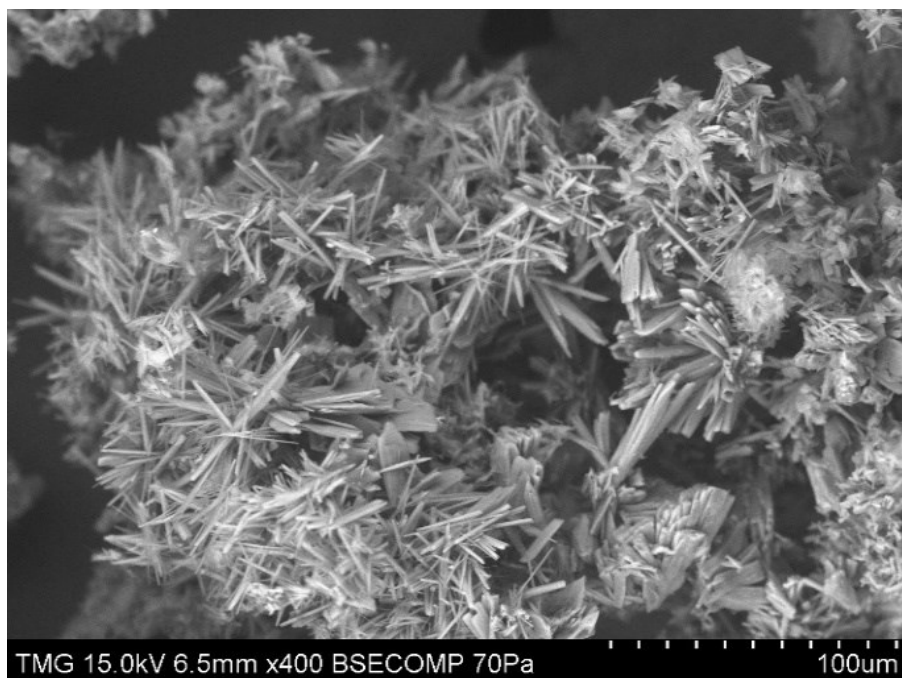


Figure 3.12 The reaction of MPCMs with 12M NaOH solution at 80°C temperature

The chemical formula of materials is listed in **Table 3.7**. The SEM for S10 is shown in **Figure 3.13**, and its chemical composition of MPCMs through the reactions with the alkaline solution in S10 can be observed in **Table 3.8** using Energy Dispersive X Ray (EDX) analysis. The high amount of C, O, and Na confirms this transformation of the MPCMs through this reaction. The lack of H in the chemical composition analysis indicated the evaporation of all the available water and de-solvation of NaOH with Melamine through this process.

Table 3.7 Chemical formula of the particles used in this experiment.

Name	Chemical formula
Melamine	$C_3H_6N_6$
Paraffin	C_nH_{2n+2}
Sodium Hydroxide	NaOH
Water	H_2O

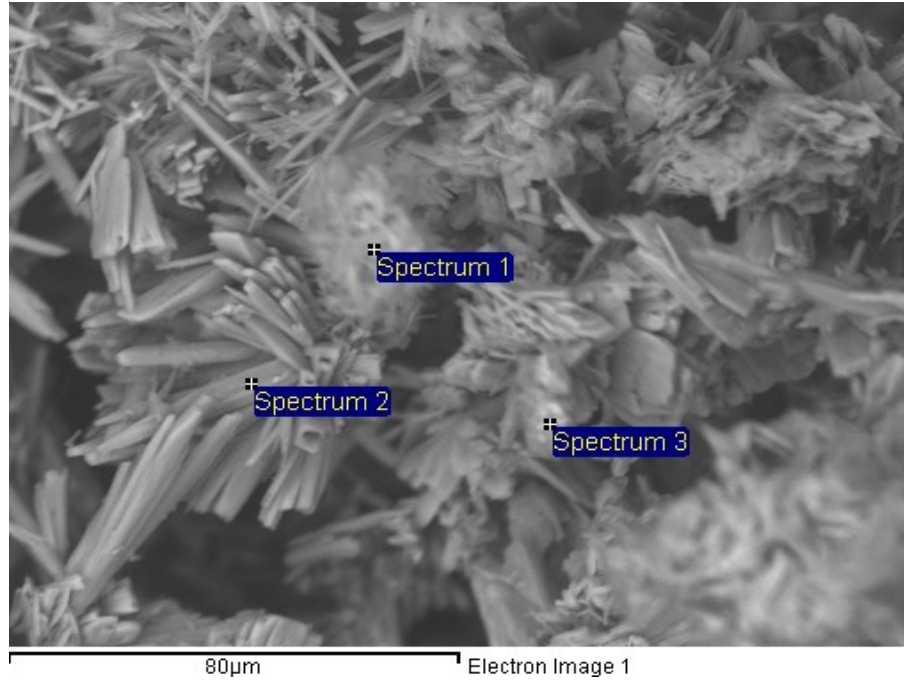


Figure 3.13 SEM photo of S10

Table 3.8 Chemical composition of S10 in EDX analysis

Spectrum	In stats.	C	O	Na	Al	Si	S	Ca	Total
Spectrum 1	Yes	43.11	42.82	13.56		0.50			100.00
Spectrum 2	Yes	46.59	41.25	11.80		0.35			100.00
Spectrum 3	Yes	39.49	39.90	10.48	0.35	1.43	0.48	7.88	100.00
Max.		46.59	42.82	13.56	0.35	1.43	0.48	7.88	
Min.		39.49	39.90	10.48	0.35	0.35	0.48	7.88	

3.4 Conclusion

The application of MPCMs nowadays is one of the great possible ways of saving energy through modulating heat inside the building. Understanding the characteristics, including thermal responsiveness and chemical stability, are essential to verify their reaction in cementitious building mixtures.

According to the thermal responses of the MCPMs through various temperature variation scenarios, the MPCMs showed outstanding thermal responsiveness reliability. Their

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responsiveness was highly dependent on the exposure temperature and time. As the temperature fluctuation extended beyond the phase change zone, the amount of energy stored increased.

Moreover, the exposure period has significant effect. An increase in exposure period provides more opportunities for MPCMs to use more latent heat capacity. The period between melting/solidification initiation and ending point varied concerning the applied exposure condition of the MPCMs' specimens. Hence, choosing the proper MPCMs' melting point for cementitious mixtures should be done cautiously concerning the site's weather conditions.

A direct relation between energy absorption and the release of MPCMs in closed environments was seen with MATLAB analysis. This indicates the equilibrium in phase change periods of MPCMs in temperature variations. Furthermore, Melamine based MPCMs presented low chemical stability in the alkaline environments caused by NaOH solutions, especially in the presence of heat. An unwanted reaction between the Melamine based MPCMs and NaOH solution will occur as a result and cause a permanent defect in the performance of MPCMs.

CHAPTER 4: THE POSSIBILITY OF PRODUCING LOW ENERGY INTENSIVE MORTAR WITH INCLUSION OF PHASE CHANGE MATERIALS

Abstract

The high rise in the population made the researcher look for methods for increasing the construction speed. Heat curing is one of the novel methods in rapidly constructing cementitious materials that consume much energy. Many researchers pursue new programs and utilize novel materials to modernize the old fashion heat curing. Micro-encapsulated phase change materials (MPCMs) are one of the promising materials that are newly used in eco-friendly buildings to modulate the interior temperature. This research evaluates the performance of OPC mortars with the inclusion of 0%, 6%, and 20% MPCMs⁵⁷ to produce precast elements. The focus of this study is the utilization of promising potentials of MPCMs upgrading traditional heat curing. The mixture's thermal responses, flowability, and compressive strength were examined through different ages. Innovative curing was introduced considering the use of higher latent heat capacity of the MCPMs. According to the results, 30% energy saving was obtained by sacrificing less than 3% mechanical strength of OPC mixtures containing MCPMs.

4.1 Introduction

Concrete is one of the most used materials in the current century, with a high annual increasing production rate. However, the long winter in cold regions may delay construction and extend the needed time to achieve adequate strength. This motivated producers to precast concrete elements,

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where concrete is mixed, cast and cured under a controlled environment. One of the main problems with precast concrete is the high amount of energy used in the heat-curing for elements to accelerate strength gaining rate, allowing rapid production. Such elevated temperatures promote binder hydration, resulting in high early-stage strength development (Detwiler et al., 1992; Kjellsen et al., 1996). However, the elevated temperatures make the concrete microstructure more heterogeneous in the initial stage (Lothenbach et al. 2007). Therefore, the elevated temperatures negatively affect the late-age properties of concrete (i.e., low strength and high permeability) (Escalante-García et al., 2001; Yang et al., 2003; Elkhadiri et al., 2008). These disadvantages are often called "heat damage" (Ma, Long et al., 2017).

The heat (steam) curing regimes are based on three parameters, preset time, curing temperature, and curing time. Different standards such as CSA (CSA, 2005), PCI, (Wilden et al., 2010), and AASHTO LRFD (AASHTO, 1998) provided standard curing approaches for concrete used in precast plants (Soo-Duck Hwang et al., 2012). The temperature in the isothermal curing section is the peak steam curing temperature and is set between 60°C and 80°C. Some researchers mentioned that the peak curing temperature should be around 66°C and not exceed 82°C (Türkel et al., 2005; Ba et al., 2011). Palomo et al. (Palomo A. et al., 2000), Li's team (Li et al., 2008), and Alghazali et al. (Alghazali et al., 2020) reported similar steam curing temperature ranges and associated damages.

On the other hand, developing new materials opens new opportunities to innovate. Using PCMs may be a potential method for improving steam curing. PCMs are a kind of heat storage material used in this field with an exceptional capability called "Thermal Energy Storage (TES)". PCMs store energy and release it later at a certain temperature with respect to their melting and solidification specifications. **Figure 4.1** shows the heat storage and latent heat composition in the

MPCMs. During the heat exchange period, the PCMs absorb heat as latent heat until they reach their melting point. At this point, the particles start to melt and transform to liquid gently until all the particles become liquid. The heat storage capacity reaches the maximum when all particles are liquid (**Figure 4.1**). (Kuznik et al., 2011).

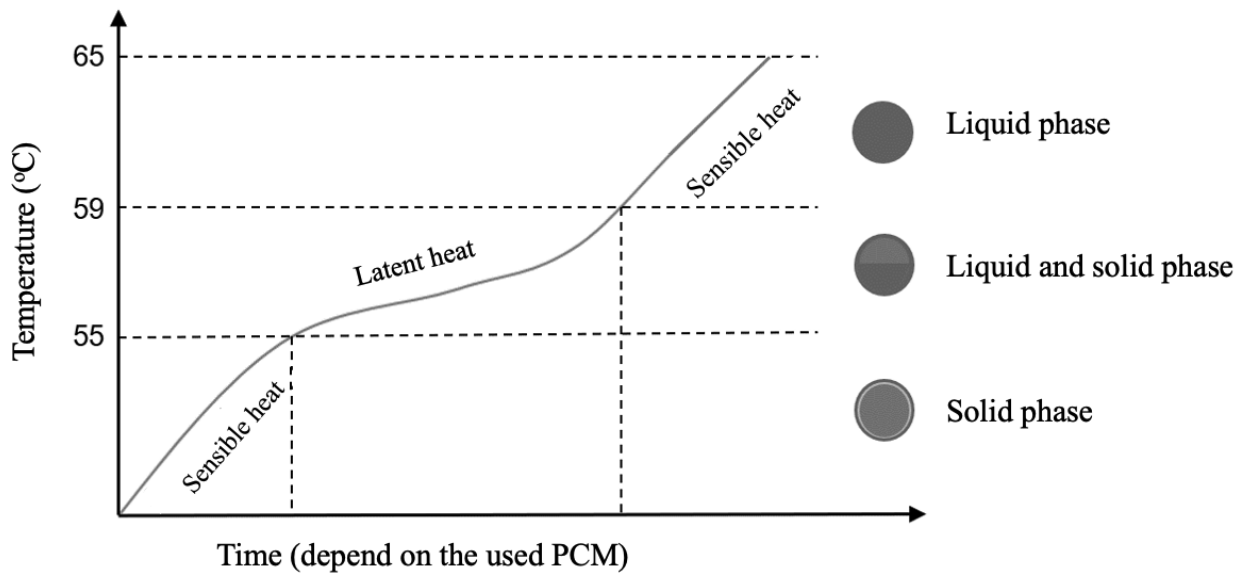


Figure 4.1 Heat storage as sensible and latent heat for MPCM 57 (after (Yang et al., 2016)).

This highlights the potential advantages of incorporating MPCM in cementitious materials and promising solutions. According to previous studies, PCMs can inhibit thermal cracking, enhance the capillary water absorption resistance, and improve early volume stability and freeze-thaw resistance of cement-based materials ((Fernandes et al., 2014; Yeon et al., 2018) (Bi et al., 2021)). However, PCMs incorporation may slightly reduce cementitious materials' mechanical strength (Djamai et al., 2019), (Xu et al., 2013).

Although there have been some studies on applying MPCMs in OPC mixtures for regulating interior building temperatures, there are few studies on using these materials in precast cementitious elements. Hence, this chapter extensively evaluates the potential for utilizing

MPCMs in heat curing, targeting lower energy consumption while maintaining adequate mechanical performance.

4.2 Experimental work

4.2.1 Materials and preparations

Ordinary Portland Cement (OPC) with a blain fineness of 360 m²/kg and a specific gravity of 3.15 was used in this study (**Table 4.1**). Natural River sand with particle size distribution that complies with ASTM C33 (Standard Specification for Concrete Aggregates) and fineness modulus of 2.3 was used (**Figure 4.2**). Soft inclusion of MPCMs (**Figure 4.3**) in a powder form with a phase change temperature of 57 ± 2 °C and a latent heat (ΔH_{PCM}) capacity of approximately 172 kJ/kg was selected (**Table 4.2**).

Table 4.1: Chemical and physical properties of cement

Item	Cement
SiO ₂ (%)	19.80
Al ₂ O ₃ (%)	4.90
CaO (%)	62.30
Fe ₂ O ₃ (%)	2.30
SO ₃ (%)	3.70
Na ₂ O (%)	0.34
MgO (%)	2.80
C ₃ S (%)	57.00
C ₂ S (%)	14.00
C ₃ A (%)	9.00
C ₄ AF (%)	7.00
Loss on ignition (%)	1.90
Specific gravity	3.15

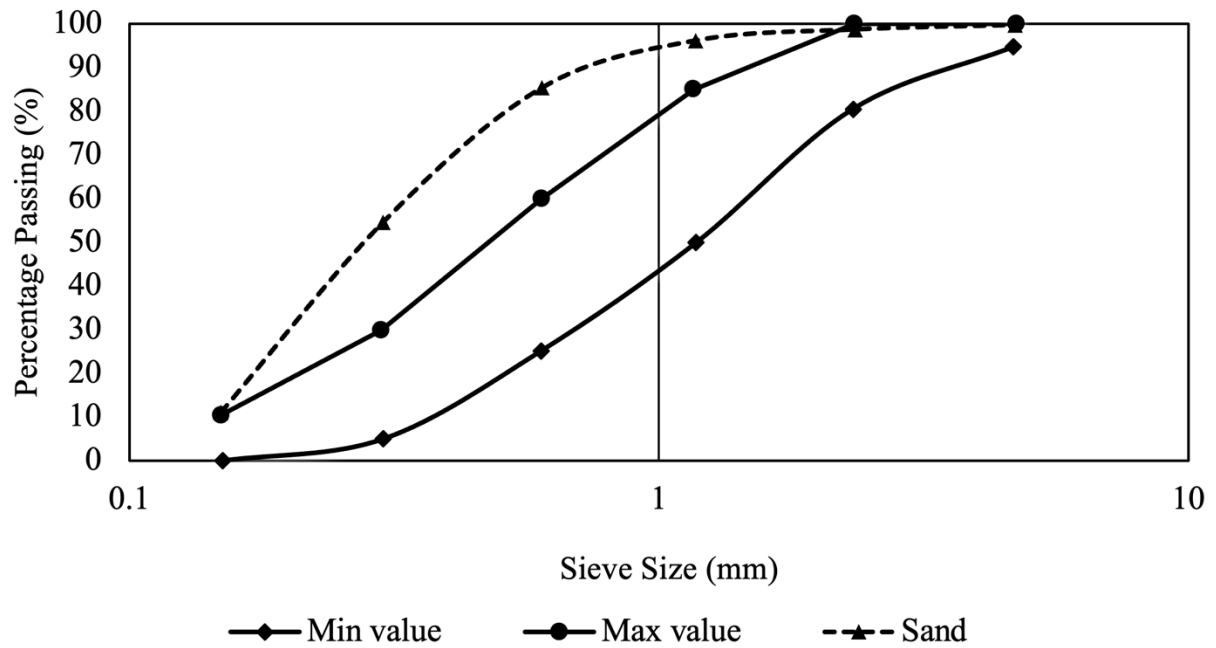


Figure 4.2 Sieve analysis of the used fine aggregate (based on ASTM C33)

Table 4.2 Properties of the used MPCM 57

MPCM 57	
Classification	Organic Mixture
Appearance	White, dry powder
Solubility	Insoluble
Phase change	55 - 59 °C
Moisture	≤3%
Paraffin Wax	79.6%
Melamine Resin	17.4%
Heat of fusion	172 J/g
Size range	4.99 μm to 82.8 μm
Mean particle size	30.7 μm
Solid content	98.1%
Shell material	Melamine

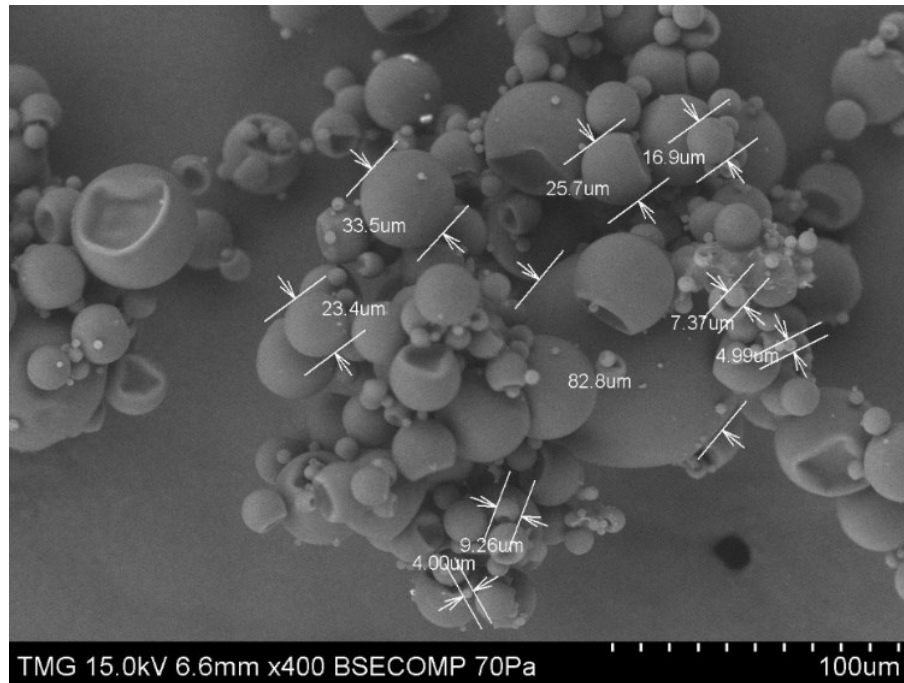


Figure 4.3 Particle size distribution of the used MPCMs through SEM analysis

Mortar mixtures incorporating MPCMs as a replacement partially based on sand weight and water at a w/c 0.45 (mass basis) as stated in ASTM C305 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency) with a minor adjustment keeping the flowability in the range of 15-18 cm according to ASTM C1437 (Standard test method for flow of hydraulic cement mortar). The cement-to-aggregate ratio was set at approximately 1:2.75, and the addition of MPCMs from 0 to 20% concerning the sand by weight. The MPCMs were added in the last mixing stage for less than 45 seconds to reduce the possibility of shell breakage of MPCMs (C.Y. Zhao et al., 2011, B. Kazanci et al., 2020). Three specimens were prepared for each test to obtain the mean value.

4.2.2 Curing condition

Specimens were separated into two groups: ambient cured and heat cured. The ambient temperature was around 23 ± 2 °C, and the relative humidity (RH) of $95\% \pm 3\%$. The regular heat

curing regime is illustrated in **Figure 4.4** according to CSA A23.4. Specimens were stored for three hrs at $23 \pm 1^\circ\text{C}$ and $95\% \pm 3\%$ RH (i.e., so-called pre-curing period). The top environmental chamber's temperature is set to 60°C for 10hrs. The heating and cooling rates were set to 20°C/hr. and 15°C/hr. , respectively. After 24hrs, all specimens were demolded and covered with plastic under the lab condition until the designated testing age (ASTM C192 - Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). Apart from the normal heat curing, different curing regimes with heating and cooling rates of $20\text{--}30^\circ\text{C/hr.}$ and $15\text{--}20^\circ\text{C/hr.}$, were applied to specimens.

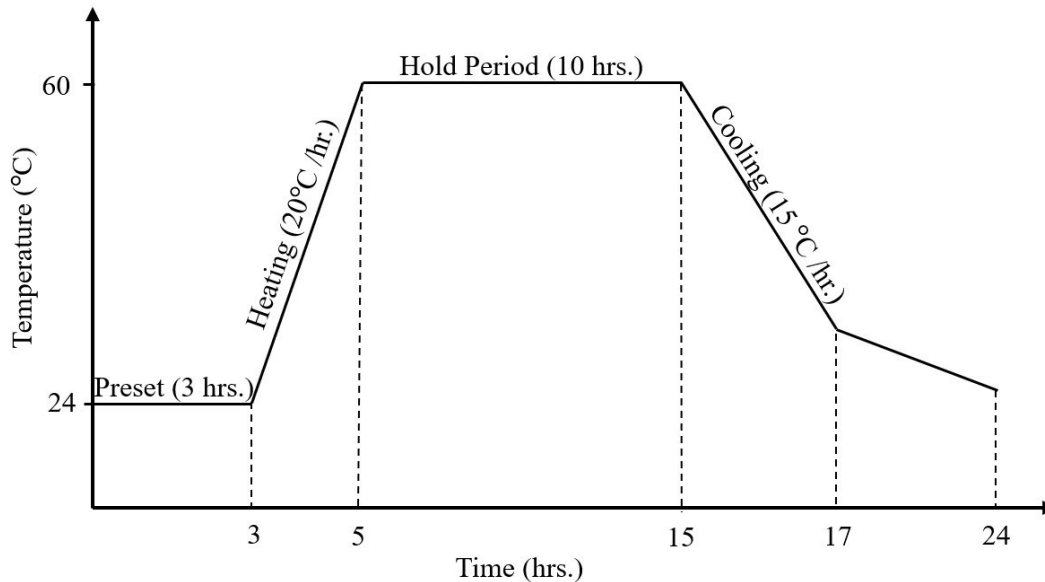


Figure 4.4 Different stages for heat curing regimes according to CSA standard curing regime

4.2.3 Testing procedure

The influence of MPCM inclusion on the temperature evolution was evaluated on a 50 mm cubic molds instrumented with type T thermocouples at the center connected to a data logger. Data collected during the whole period of heat curing reflected the temperature changes under semi-adiabatic conditions ($\pm 0.5^\circ\text{C}$ deviation based on replicate specimens).

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The flowability of the mixture was evaluated according to ASTM C1437 before and after MPCMs addition. Ultra-Pulse Velocity (UPV) for checking the density variation and quality of the specimens was carried out concerning ASTM C597 (Standard Test Method for Pulse Velocity Through Concrete).

The compressive strength of 50 mm cubic specimens was measured in ASTM C109 at 1, 7, and 28 days. The coefficient of variation (COV) in the measured strength was around 5% for specimens cast from the same batch.

The amount of energy used during the heat-curing process of each curing regime was analyzed. This experiment compared the energy absorbed and released through the samples with or without MPCMs to identify the optimum energy needed for preferred curing.

4.3 Results and discussion

This research evaluated the flowability of the mortars containing 0, 6, and 20% MPCMs. According to the results, although the used MPCMs were indicated to be hydrophobic, a significant decrease in the flowability of the mortar after the addition of MPCMs was seen. This reduction was 15% and 50% for MPCMs addition of 6% and 20%, respectively (**Fig. 4.5**).

This reduction can be attributed to the increase in particle disspreading and minimizing the cohesion of the mixture by the addition of MPCMs. This fact reduced the adhesion of water molecules in the microstructure of the paste and caused a reduction in flowability.

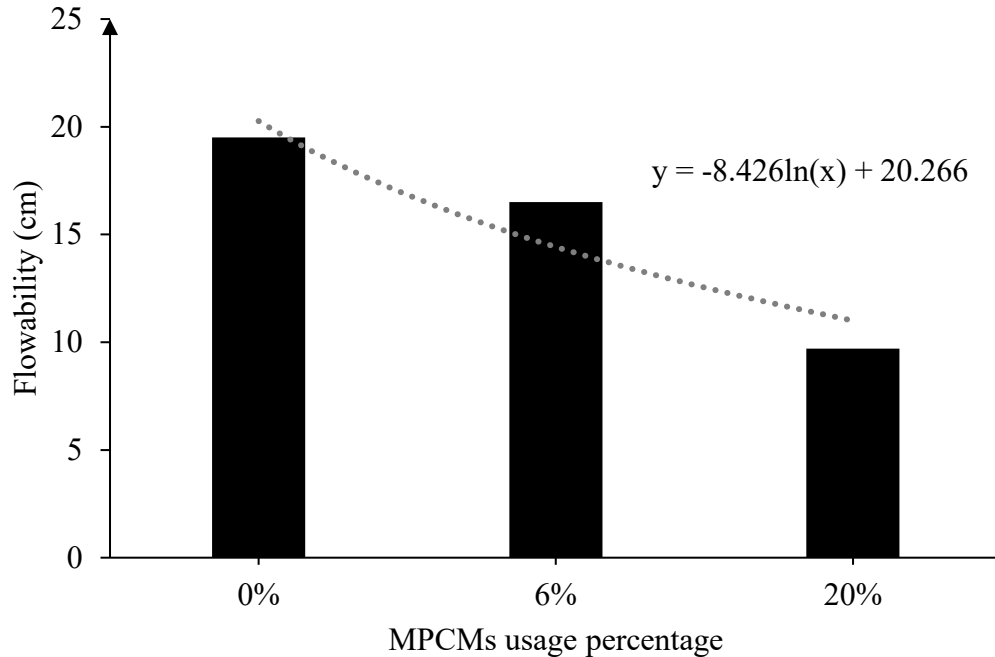


Figure 4.5 Flowability of OPC mortars with/without the inclusion of MPCMs

The analysis of the OPC mortars containing 6% and 20% MPCM showed that the inclusion of MPCMs can significantly increase the thermal capacity of the specimens in the heat-curing process. Adding MPCMs increased the cementitious materials' latent heat capacity, affecting the specimens' thermal response. Approximately a 10% delay in the thermal response of OPC mortars, including 20% MPCMs (**Figure 4.6**). This delay decreased the heating and cooling rates due to the extended phase change period at 57°C. The phase change occurred in the temperature periods of 55°C and 59°C. Specimens absorbed heat during the heating period (melting phase) and released heat through the cooling period (solidification phase). This phase transition of paraffin helped specimens maintain the internal temperature for longer. The heat curing process continued longer than specimens with no MCPM inclusion through this effect. Moreover, the delay in the thermal response of OPC mortars containing 20% MPCMs was double that for mixtures incorporating 6%.

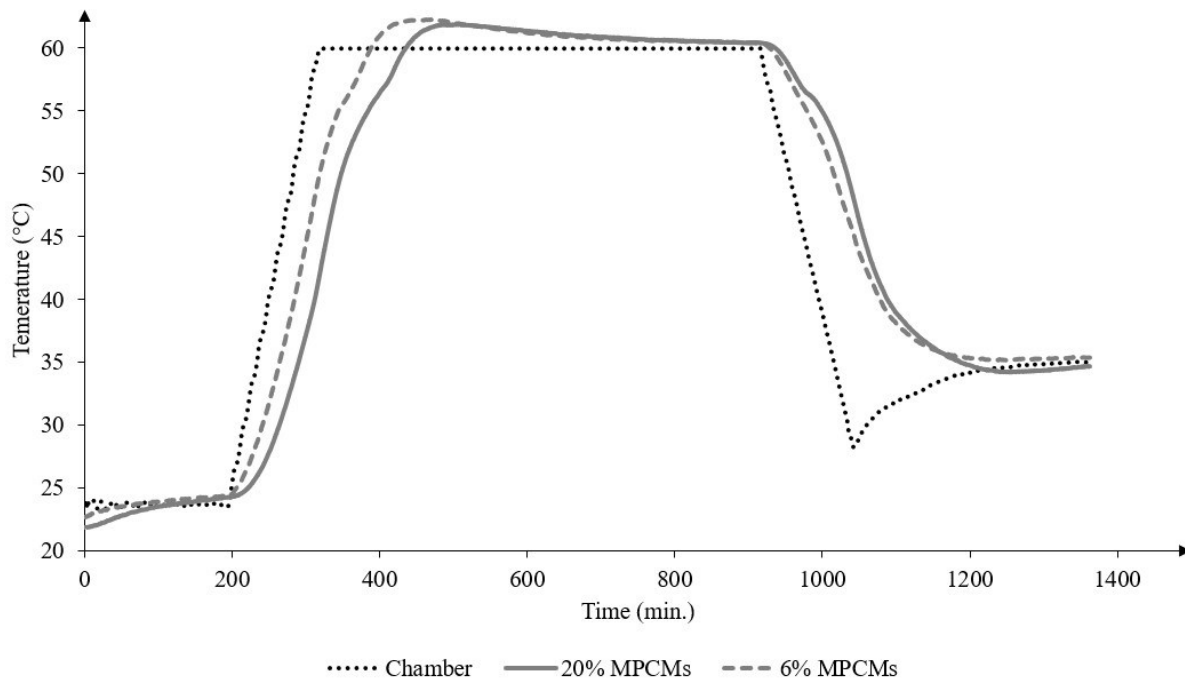


Figure 4.6 Thermal response of OPC mortars containing 6 and 20% MPCMs 57 in normal heat curing.

Although the inclusion of MPCMs improved the thermal capacity of the MPCMs, it enormously reduced the mechanical properties of the species. Including 6% and 20% MPCMs in OPC mortars resulted in 22% and 45% reductions in compressive strength compared with 0% MPCMs in one-day heat curing, respectively. With the help of heat curing, OPC mortars could achieve 14% more compressive strength in one day of curing compared with ambient curing. This amount was 17% and 23.5% for specimens containing 6% and 20% MPCMs (**Figure 4.7**). The compressive strength of the specimens at the age of 28 days was approximately equal in both curing conditions. This output is attributed to the high temperature increasing the hydration reactions in the first days of curing, leading to more compressive strength.

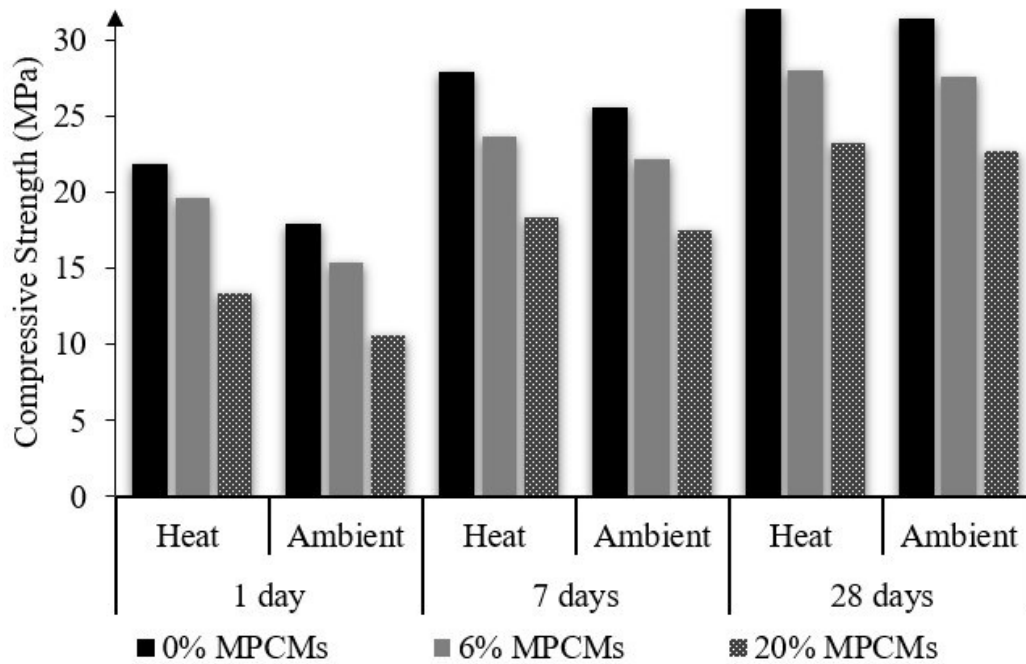


Figure 4.7 Compressive strength of OPC mortars with different MPCMs inclusions in heat and ambient curing

The hydration reaction rate for heat curing was then reduced and continued until 28 days. It was evident that including MPCMs in cementitious materials can increase the thermal capacity used in subsidiary heat curing. Considering the sharp drop in the compressive strength with the high inclusion of MPCMs, 6% MPCMs inclusion was chosen to run further investigations concerning the application of MPCMs in cementitious mixtures.

As mentioned earlier, the addition of MPCMs had affected the strength development. For instance, in control mixtures without MPCMs, the strength increased between 1 and 28 days by 45% and 72% respectively in heat and ambient curing condition. However, this fact for mixtures of containing MPCMs of 6 and 20% were 31% and 76% in heat condition and 56% and 120% in ambient condition. Although the strength development of specimens containing MPCMs were higher, the final strength was lower in compared with specimens of 0% MCPMs. In another word, the increase in the MCPMs content led to reduction of the final strength of the specimen. For

instance, at the age of 28 days, the specimens of 20% MPCMs had 37% lower compressive strength in heat and ambient curing condition compared to 0% MPCMs specimens. This amount for 6% MPCMs was 21% in both conditions.

4.4 Novel Heat Curing Technique

According to the high potential of inclusion of MPCMs in the OPC mortars, a novel heat curing, namely Sawtooth curing, was introduced. This type of curing is focused on utilizing the highest possible latent heat capacity of MPCMs for subsidiary heat curing with the aim of energy saving. In this respect, three potential Sawtooth heat profiles, including Sawtooth I, II, and III, were introduced (**Table 4.3**). Each of these profiles examines the specific thermal responses and mechanical performance with respect to the energy-saving terms.

Sawtooth I, II, and III contained respectively cycles of 120, 120, and 90 min., and the heating and cooling rates were respectively 15, 22, and 30 °C (**Figures 4.8-4.10**). These rates were selected based on the standard heat curing of the USA and Canada (I) and then modified in the II and III. Based on the thermal response results, each mood presented a different response with respect to its heating regime. A great temperature modulation was seen in all moods that kept the temperature of the specimens higher than 50°C.

The saving energy in all the moods was defined as the cooling period. The cooling periods were when the heat source (namely the environmental chamber) was simulated to be off. Hence, each sawtooth represented the possibility of utilizing MPCMs' latent heat energy usage during the on/off periods of the chamber. According to the thermal responses, there was a possibility of saving 20-30% energy utilizing sawtooth heat regimes.

Table 4.3 Sawtooth curing regimes specification

	Sawtooth mood		
	I	II	III
Total period (hrs.)	17	17	17
Heat period at 60 °C (hrs.)	4	5	6
Heating rate (°C/hrs.)	20	22	30
Cooling rate (°C/hrs.)	15	22	30
Saw rate (°C/hrs.)	15	22	30
Saw time (min.)	60 + 60	60 + 60	45 + 45
Temp. variation (°C)	60 to 45	60 to 38	60 to 37.5

The main difference between the regimes was the environmental chamber's temperature variation, which determined the chamber's efficiency at isolating the temperature inside. This criterion was chosen to simulate different scenarios as environmental chamber isolation properties (heat losing rate). Based on the data, specimens in sawtooth I could present 50% less temperature fluctuation than the other two moods. Specimens in sawtooth II and III showed similar thermal responses with approximately the same temperature fluctuation. This fact illustrated the significant effect of paraffin particles in modulating the heat inside specimens through the phase change function. Based on the moods' specifications, the total heating time at 60°C was 4, 5, and 6 hrs. for sawtooth I, II, and III, respectively. Sawtooth I and II had more heating periods due to higher thermal fluctuations. The sawtooth III was designed to use more heating periods (+1.8 hrs.) with the aim of increasing the mechanical strength. The total saving time (off time) at 60°C was 30%, 27%, and 38% for sawtooth I, II, and III, respectively. The sawtooth I presented the lowest heating and cooling rates during the phase change periods compared to the other two moods. According to the thermal response analysis of the sawtooth moods, a decline thermal response curve indicating an adjustment in latent heat energy usage was observed. The paraffin was intended to absorb and release heat during their phase change in the range of 57 ± 2 °C.

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A downward thermal response of OPC mortars containing MPCMs⁵⁷ during the sawtooth moods was seen. The slope of this curve (thermal response) was increased the most in sawtooth III, and this increase can be related to the rise in the temperature variation applied in this mood. The observations made equalizing the phase change function concerning the short heating period compared to the off time (cooling time) impossible. The MPCMs tended to modulate the embedded temperature of the specimens by releasing the latent heat, but this amount of energy was not obtained through the later heating periods. This phenomenon caused a decrease in the latent heat energy capacity through the later cycles and consequently caused a reduction in the overall slope of the curve.

Since the hearing duration in sawtooth II and III was higher than the sawtooth I, the amount of saved energy as latent heat in specimens was higher in the first cycle. Although the absorbed heat was higher in the first cycle in the mentioned moods, the specimens lost more energy due to the higher temperature fluctuation in later cycles (more energy loss in the sawtooth periods). A significant resistance in the thermal response of specimens between the melting and solidification points of the MPCMs was seen. The average temperature heating period accounting for the off times was recorded at 55°C in all the sawtooth moods. At this temperature point, the MPCMs presented the most resistance to temperature change as absorbing/releasing heat.

Figure 4.11 shows the comparison between the three sawtooth curing regimes in terms of heat transfer rates. As it can be seen from this figure, sawtooth III due to the higher heat rates, presented higher peaks and this fact made the PCMs to absorb more heat so that in the given period, they could not release this heat similar to sawtooth II. Although this heat fluctuation became more steadily in the second and third heat wave for the sawtooth III, sawtooth I presented less fluctuation among the three regimes. This statement can be beneficial in terms of heat damages and inducing

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cracks in the heat curing process of sawtooth I specimens in compare with the others. This fact was tested with SEM and mechanical experiments later.

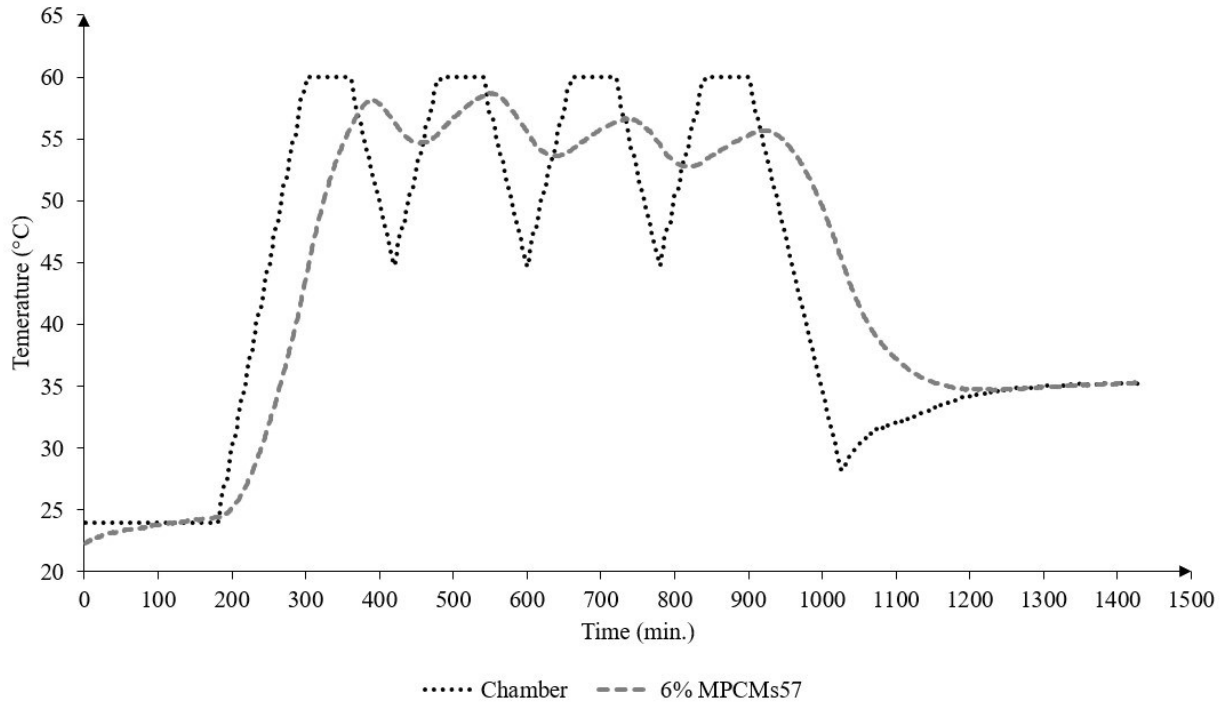


Figure 4.8 Sawtooth I applied on OPC mortar containing MPCMs57.

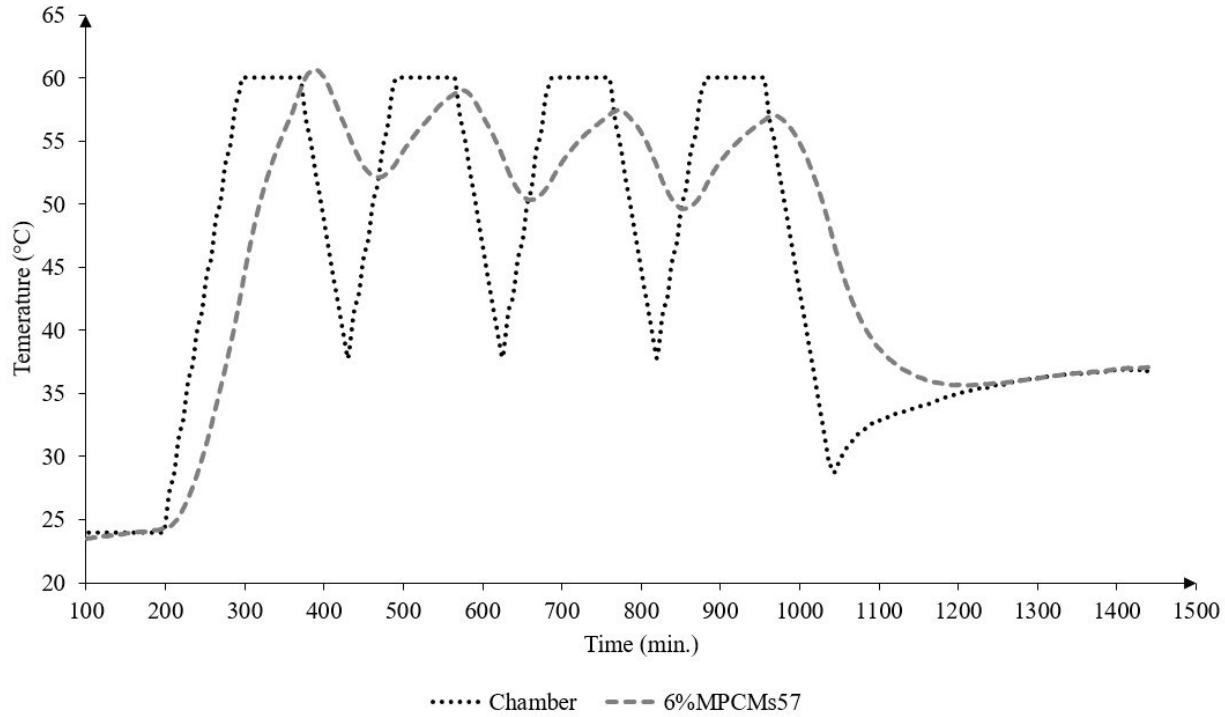


Figure 4.9 Sawtooth II applied on OPC mortar containing MPCMs57.

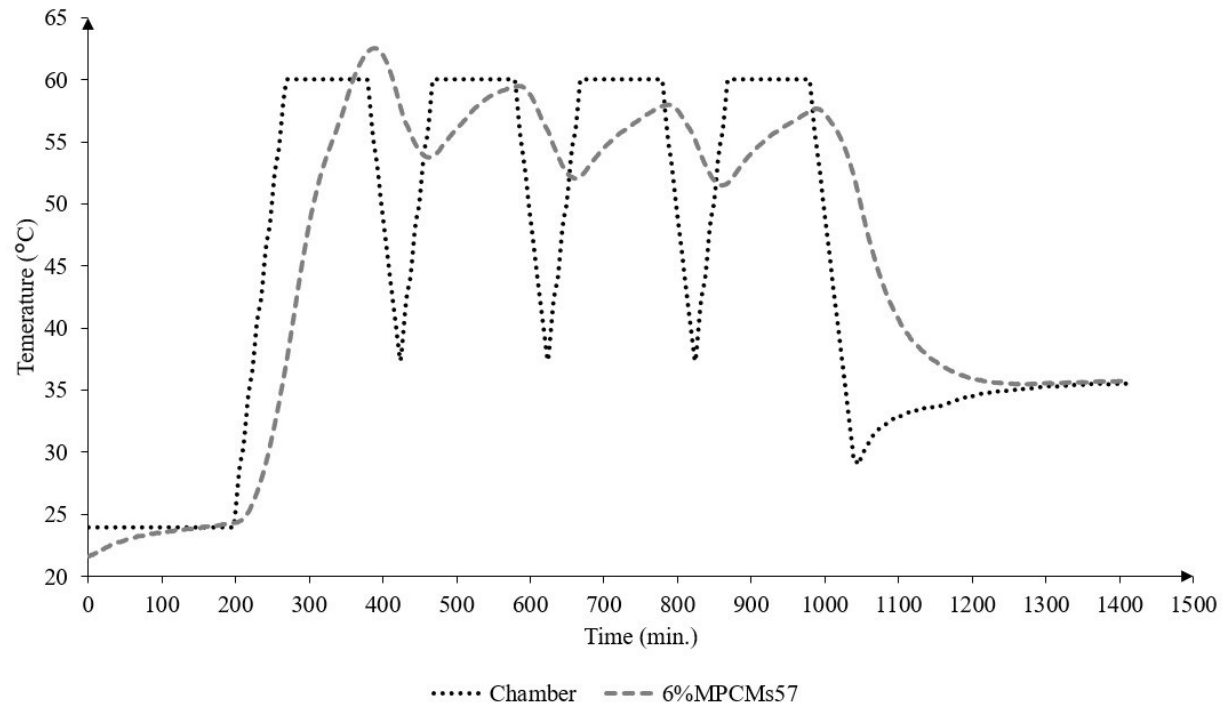


Figure 4.10 Sawtooth III applied on OPC mortar containing MPCMs57.

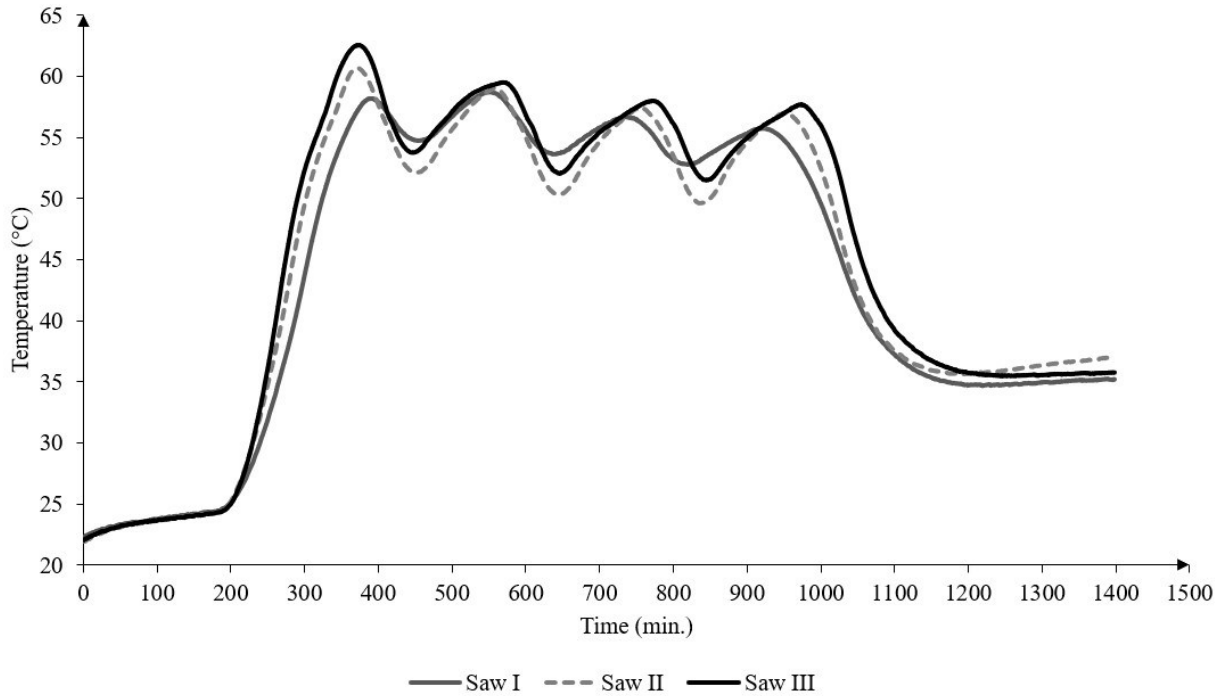


Figure 4.11 Comparison between Sawtooth regimes applied on OPC mortars containing MPCMs57.

Although there was less saving energy in sawtooth III, specimens presented a slightly lower mechanical strength among them. There was a small gap in mechanical strength between sawtooth I and II; however, sawtooth II used more energy during the curing regime (**Figure 4.12**). Furthermore, sawtooth II presented better mechanical strength in one day test than sawtooth III (+6%), although sawtooth III had almost 17% more curing time at 60°C. The difference in mechanical strength of these mortars can be attributed to the difference in heating time and heating/cooling rates. The mechanical strength of the OPC mortars improved as the heating time increased. In addition, with the reduction in heating/cooling rates, the chance to heat damage was reduced and, consequently, improved mechanical performance.

In comparison between the mechanical strength of the sawtooth and the normal heat curing regime, a minor difference between the two was seen. As mentioned earlier, the normal heat curing was

with constant 10hrs. at 60°C, and the sawtooth was approximately equal to continuous 10hrs. at 55°C, including the saving times. Specimens in sawtooth II moods presented an almost similar mechanical performance to specimens in normal heat curing ($< 2\%$ difference). This outcome demonstrates the high potential of sawtooth curing in compare with normal heat curing. Specimens with sawtooth I curing presented the best mechanical strength considering the energy usage compared to normal heat curing and other sawtooth curing. 30% saving energy was achieved with only a 3.5% mechanical strength reduction of specimens with sawtooth I curing compared to normal heat curing.

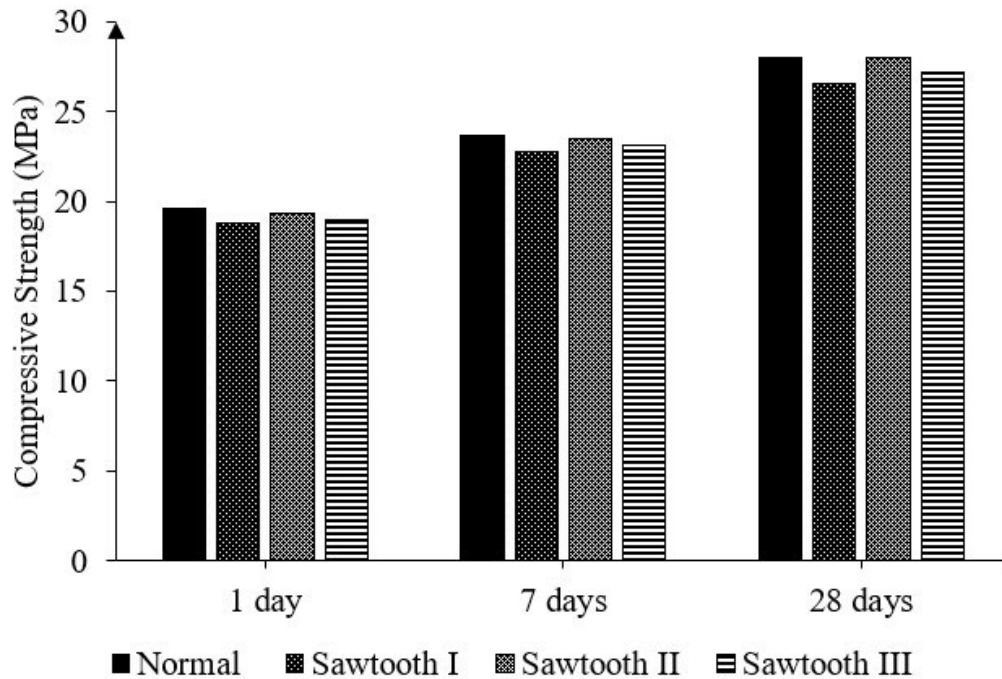


Figure 4.12 Compressive Strength of OPC mortars containing 6%MPCMs57 in sawtooth curing moods.

In the energy analysis related to cementitious materials, the specific heat capacity of the used materials and the change in the temperature over time is required. The specific heat capacity is the amount of heat needed to raise the temperature of a unit mass of the material by one degree Celsius.

Equation 4.1: $\text{Energy} = \text{mass} \times \text{specific heat capacity} \times \text{change in temperature}$

In energy analysis of the applied sawtooth and normal heat curing, as the used materials (specific heat) were the same, the only criterion to compare was the temperature change in the curing regimes. Based on the integration of the thermal responses' area, it can be realized that sawtooth I utilized the lowest energy usage (**Fig. 4.13**).

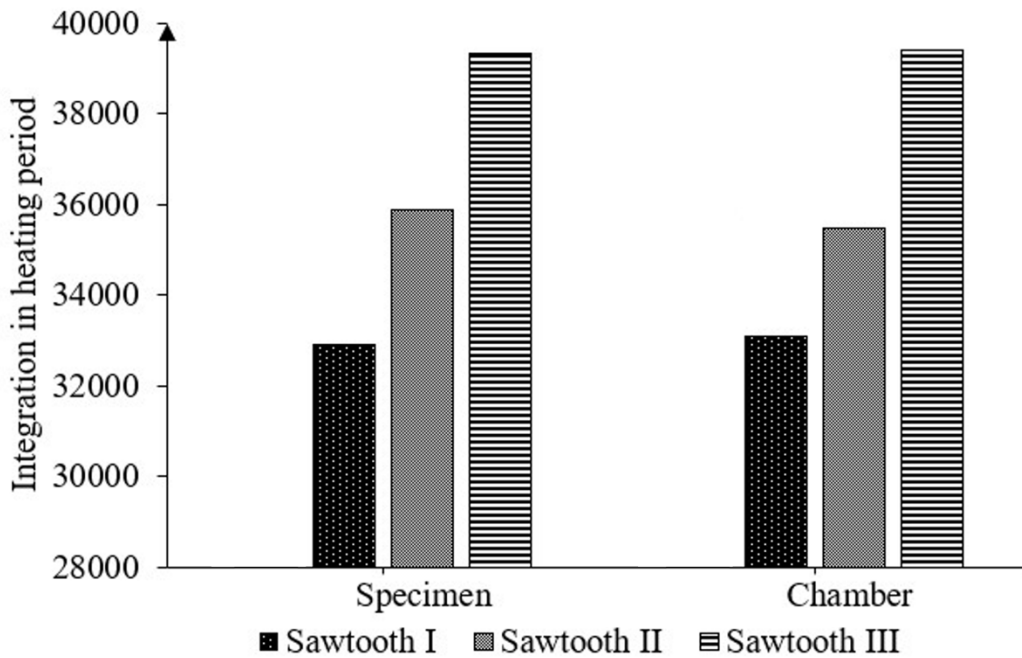


Figure 4.13 The integration of the thermal responses of applied sawtooth curing methods on OPC mortars

Although the samples in sawtooth presented very close accumulated energy in the whole curing period, sawtooth III contained more energy than the others. The difference between the heat available in the environmental chamber and the specimens' energy was highest in sawtooth II, indicating the excellent efficiency of the MPCMs concerning the applied curing regime. The temperature change and curing period in sawtooth III was more than the other regimes (highest

energy use). But since MPCMs were utilized in the specimens, this energy was mostly saved as latent heat to overcome the off periods.

In addition to the OPC usage, alkali-activated materials (AAMs) were examined. AAMs presented great potential during the last decades that can be the perfect candidate to substitute with OPC. In this respect, alkali-activated mortar containing 6% MPCMs57, similar to the used OPC mortar, was examined. Sodium hydroxide with six molarity was chosen as the activator due to its high potential to increase mechanical performance and ease of mixing. Ground blast furnace slag (GBFS), an industrial by-product commonly used in AAMs, was used in this experiment (**Table 4.4**). The slag-to-sand ratio of 1:2.25 and liquid-to-solid ratio of 0.55 to obtain a flowable mixture with high mechanical performance was chosen. The remedies contained 0%, 6%, and 20% MPCMs57 and were subjected to normal and sawtooth heat curing.

Table 4.4 Chemical and physical properties of GBFS

	GBFS
SiO ₂	32.97%
Al ₂ O ₃	17.97%
CaO	35.08%
Fe ₂ O ₃	0.72%
SO ₃	0.72%
Na ₂ O	---
MgO	10.31%
C ₃ S	---
C ₂ S	---
C ₃ A	---
C ₄ AF	---
Na ₂ O _{eq}	---
Loss on ignition	0.58%
Specific gravity	2.88
Major crystalline phases	Gehlenite
Specific Surface Area	3.15 m ² /g

Based on the results, the increase in the MPCMs usage had a similar effect on the flowability of AAMs mortars. The increase in MPCMs usage decreased the flowability of the specimens (**Figure 4.14**). 51% reduction was seen in the AAMs mortars containing 20% MPCMs⁵⁷ compared with the 0% inclusion. The fact behind the opposite relation between MPCMs usage and the flowability of the specimens can be attributed to the increase in the voids and reduction of the water contact with the aggregates. It should be mentioned that based on the results of the trials, the increase in mixing time led to an increase in the flowability of the mixtures containing MPCMs. This fact was due to the high potential of shell breakage of the MPCMs and the release of paraffin wax into the mixtures. This phenomenon may increase the flowability of the mixture significantly and delay the hardening time.

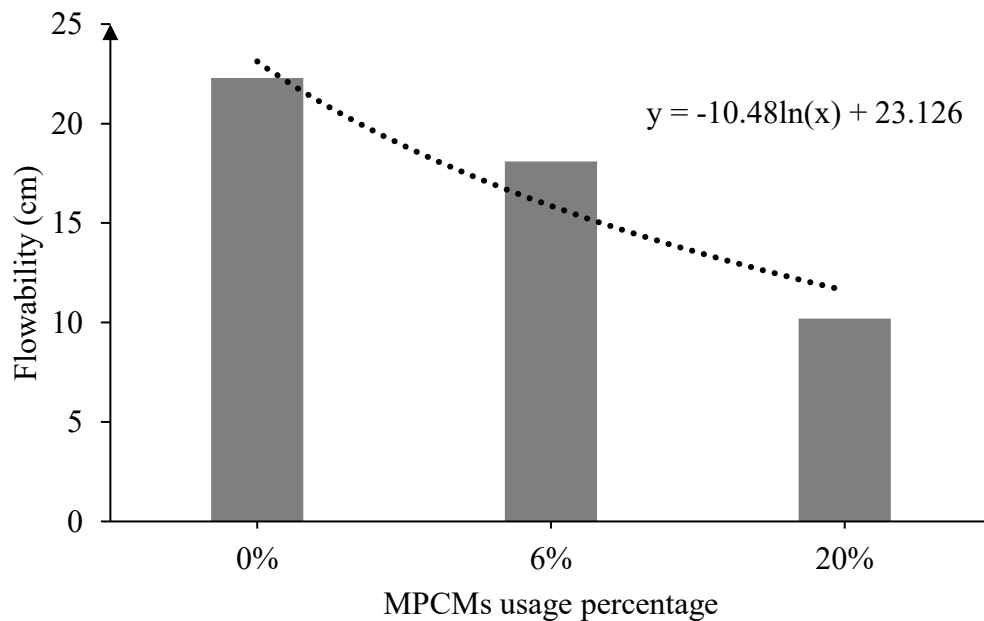


Figure 4.14 Flowability of AAMs mortars with/without the inclusion of MPCMs

Based on the thermal responses of the AAMs mortars with the inclusion of 6%, it was found that the AAMs mixture, due to higher chemical reactions and consequently higher density, presented

lower thermal fluctuation in the applied normal heat curing in comparison with the OPC mixture with the same MPCMs inclusion (**Figure 4.15**). Subjecting the AAMs mixtures to heat can greatly benefit microstructure evolutions in the early ages. This fact was observed through the mechanical strength comparisons between OPC and AAMs mixtures. Although, according to the findings, due to the use of NaOH in the synthesis of the used MPCMs' shell, the increase in the mechanical strength was not as high as anticipated.

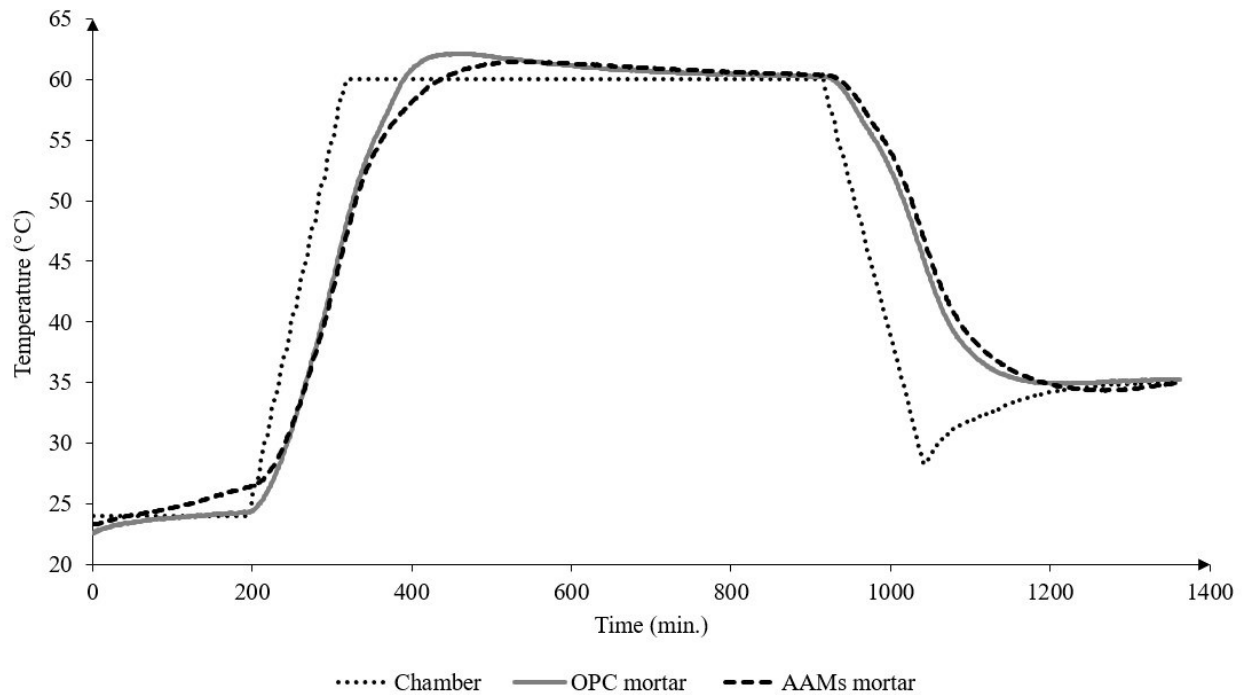


Figure 4.15 Thermal response of OPC and AAMs mortars containing 6% MPCM 57 in normal steam curing regime.

According to the information mentioned in the previous chapter, there is a high potential in the chemical reaction between the used MPCMs and the used activator that can cause the shell breakage of the MPCMs in the mixture. This fact may be the reason for a low increase in mechanical strength concerning curing time. Although this chemical reaction may affect the microstructure of the AAMs mortars, the AAMs mixtures presented a significantly higher mechanical performance than the OPC mixtures. AAM mortar containing 6% MPCMs57 showed

27% more compressive strength than OPC mortars with the same MPCMs inclusion at 28 days. An enormous reduction in the compressive strength was seen with the inclusion of 20% MPCMs in the mixtures (**Figure 4.16**).

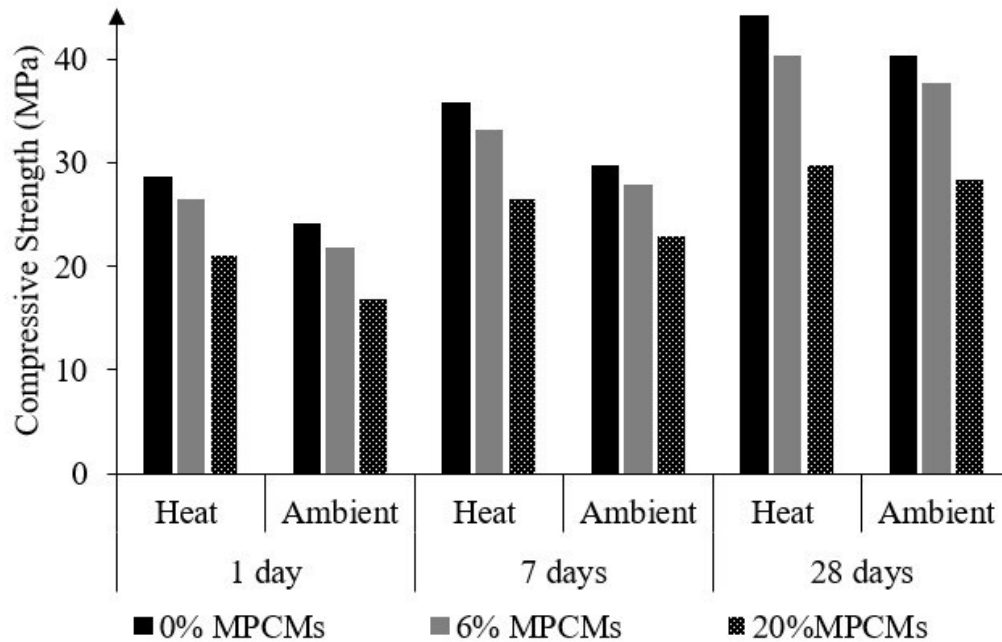


Figure 4.16 Compressive strength of AAMs mortars with different MCPMs inclusions in heat curing

4.5 Conclusion

This chapter evaluated the performance of OPC mortar specimens, including 0%, 6%, and 20% MPCMs with a melting point of 57°C during ambient and normal heat curing. The thermal responsiveness of the MPCMs was monitored through the applied curing regimes, and the mechanical strength of the specimens was analyzed concerning that. The flowability of the OPC specimens was reduced significantly with the inclusion of MPCMs. This was due to lowering water contact with the particles by adding MPCMs. A higher flowability with increased mixing time in

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the specimens containing MPCMs was seen. This increase was attributed to the release of paraffin due to high mixing tension between particles in the mixing period. A significant drop in the mechanical performance of the OPC mortar with the increase in the inclusion of MPCMs was seen. The available MPCMs in OPC mortars changed phase at $57 \pm 2^\circ\text{C}$. Great potential in saving energy was identified by analyzing the thermal response of OPC mortars containing MPCMs. Sawtooth curing was introduced concerning this matter to use the latent heat capacity of the MPCMs for subsidiary heat curing. Sawtooth presented identical mechanical strength compared to normal heat curing with the possibility of 30% energy saving.

Moreover, the possibility of including MPCMs with alkali-activated materials was examined. The exact opposite relation between the inclusion of MPCMs and flowability was also seen in AAMs. Although a 50% reduction in mechanical strength of the AAMs with the inclusion of 20% MCPMs was seen, they were structurally acceptable at the age of one day. The slight chance of a chemical reaction between the NaOH activator and the used MCPMs might be the reason for lowering the mechanical strength of the AAMs mixture. A significant improvement in mechanical strength over the OPC mixture with the inclusion of MCPMs was seen in the AAMs mixture. AAMs present slightly lower thermal fluctuation with the inclusion of 6% MPCMs compared to an OPC mixture containing the same inclusion.

MPCMs presented high potential in saving energy, possibly using their latent heat as the subsidiary heat curing. This effect can also be beneficial in lowering the thermal fluctuations in heat curing, reducing heat damage. Further study in identifying the performance of the mixture with the inclusion of MPCMs in subsidiary heat curing (sawtooth curing) is required. With the help of this kind of heat curing, tones of CO₂ can be saved yearly.

CHAPTER 5: CONCLUSION AND FUTURE WORK

Based on the conducted extensive experimental work, the following can be concluded:

- 1- MPCMs are one of the smart materials that can help modulate the thermal tolerance of the interior building temperature by easy inclusion with cementitious mixtures.
- 2- The chemical compatibility of the MPCMs is one of the challenges of these materials in inclusion with cementitious materials and zero-cement mixtures to avoid undesirable reactions. The high alkaline environments must be avoided in the inclusion of melamine based MPCMs with building materials due to the high chemical reactions that lead to extreme responses that disable partially/entirely their function.
- 3- MPCMs present excellent thermal stability in thermal fluctuations in the long term. Heating rate and exposure period are the two critical factors in the thermal responsiveness of the MPCM. The efficiency of these materials can be reduced by using short exposure periods. The selection of heating regimes should be done with respect to their melting point.
- 4- The inclusion of MPCM in cementitious mixtures will highly affect the mechanical strength and flowability. Inclusion of more than 20% MPMCs with cementitious mixtures is not recommended in this respect.
- 5- There is a possibility of reducing energy usage of cementitious materials' heat-curing process by inclusion of MPCMs into the mixture. These materials can maintain heat for longer period in the heat curing process as introduced with Sawtooth method.

- 6- There is a possibility of producing cementitious products incorporated with MPCMs with sawtooth curing to save almost 30% of the energy used for heat curing process in compare with the normal heat curing. There would be no effect on the mechanical strength of the samples in this method.
- 7- Alkali-activated specimens with MPCM inclusion can present higher mechanical strength in compare with cementitious specimens. The type of the MPCMs' shell must be selected carefully with respect to the used environment.

Future works and suggestions

- Further studies on the energy analysis of MPCMs in the inclusion with cementitious materials can be done.
- A balance between MPCMs inclusion, energy reduction, and mechanical strength should be established with respect to the target of the project.
- The sawtooth curing must be economically reviewed and compare with normal heat curing with and without MPCMs usage.
- Other types of PCMs should be tested in different environments to understand their chemical stability.
- The durability of the cementitious and zero-cement mixtures with PCM inclusion in long term must be tested.
- The energy saving of the cementitious mixtures with different type of PCMs' inclusion should be assessed in the heat curing process.

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APPENDICES

APPENDIX A

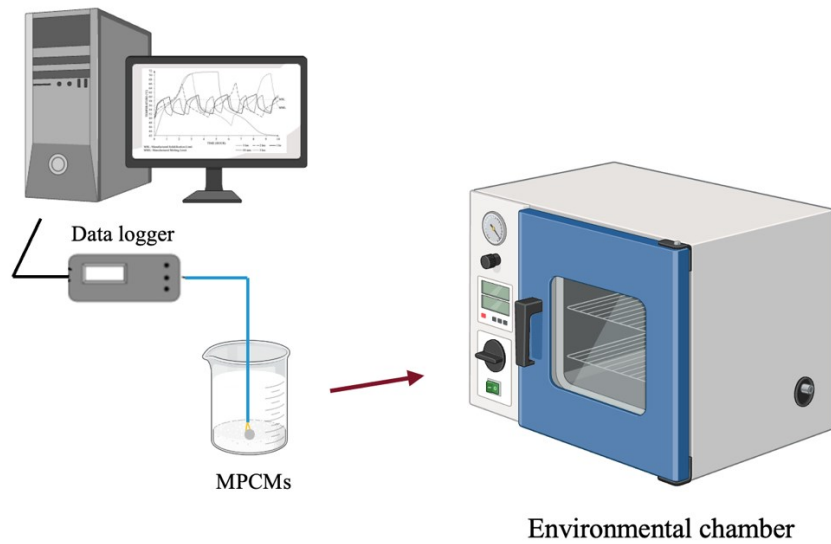


Figure A. 1 Schematic of thermal response specimen setup

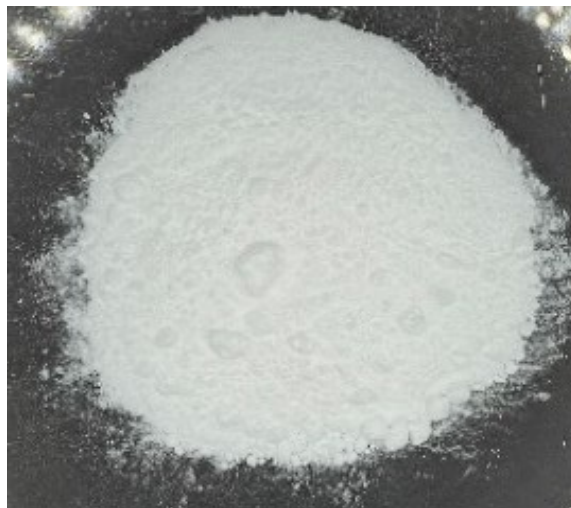


Figure A. 2 The used MPCMs 57 powder form

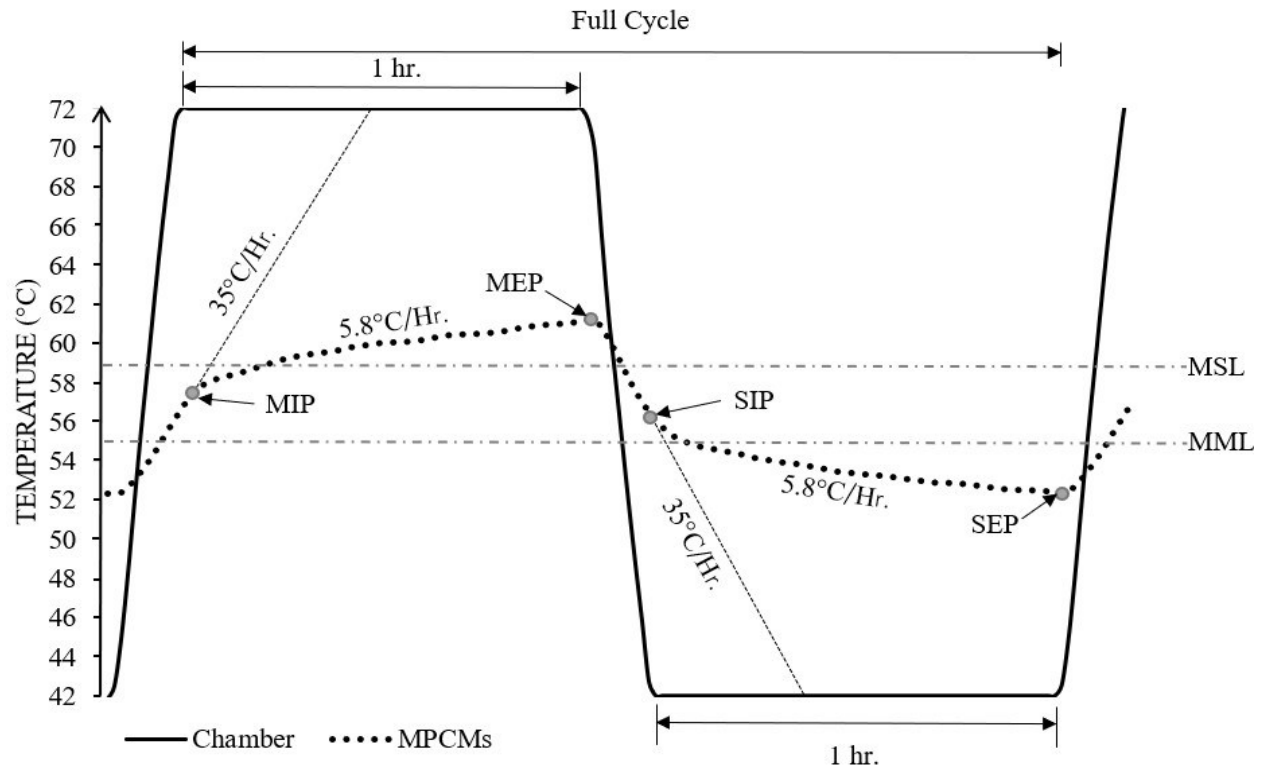


Figure A. 3 Thermal response of MPCMs in T1 - 1 hr.

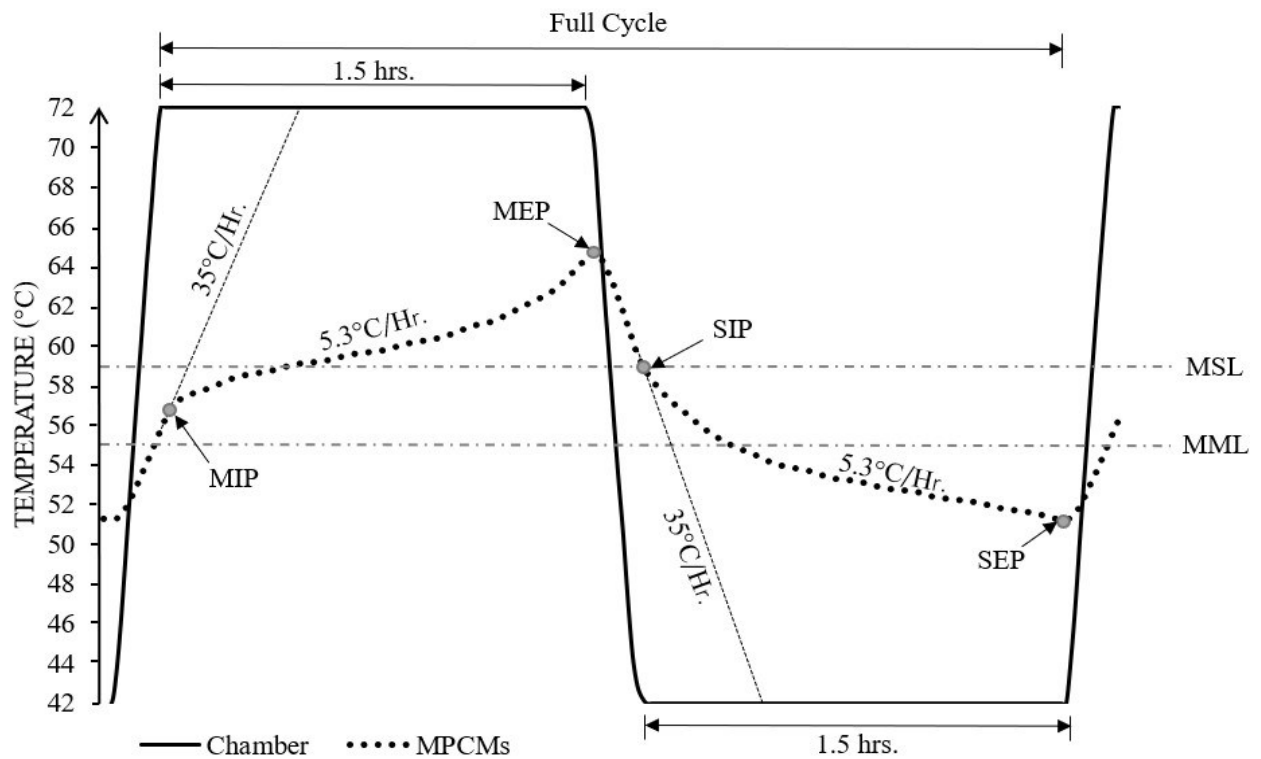


Figure A. 4 Thermal response of MPCMs in T1 - 1.5 hrs.

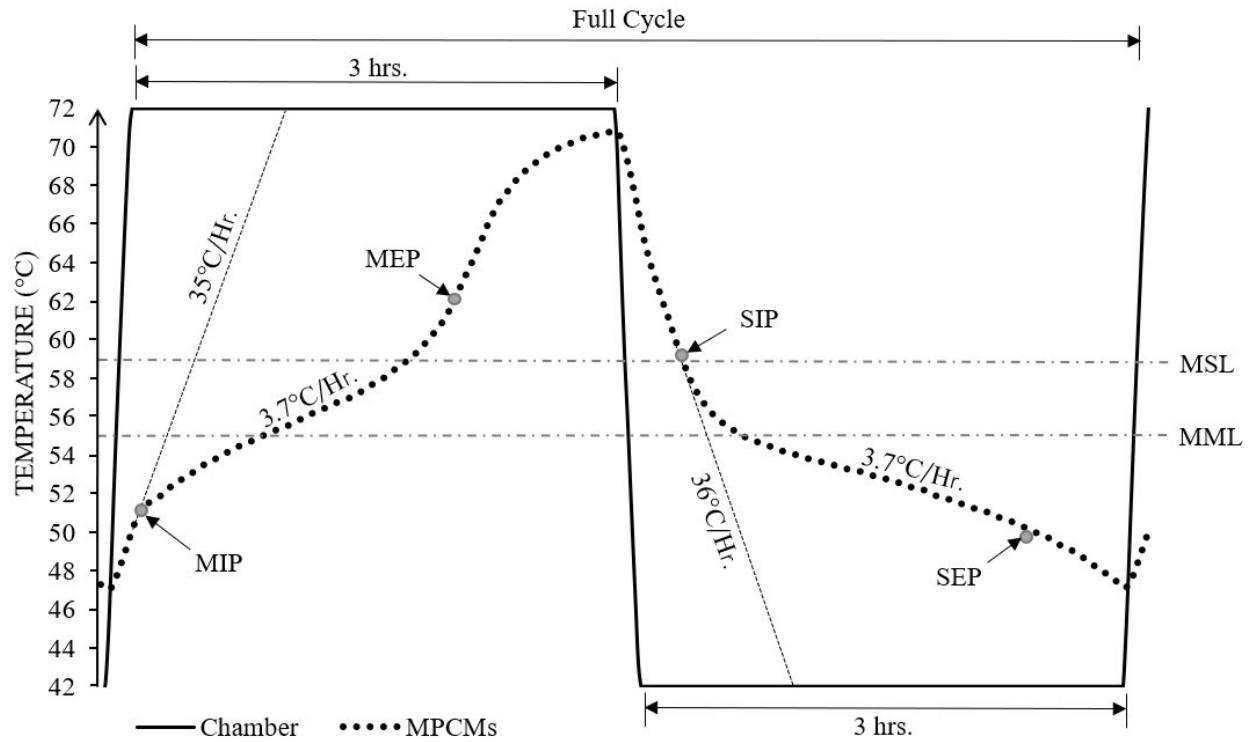


Figure A. 5 Thermal response of MPCMs in T1 - 3 hrs.

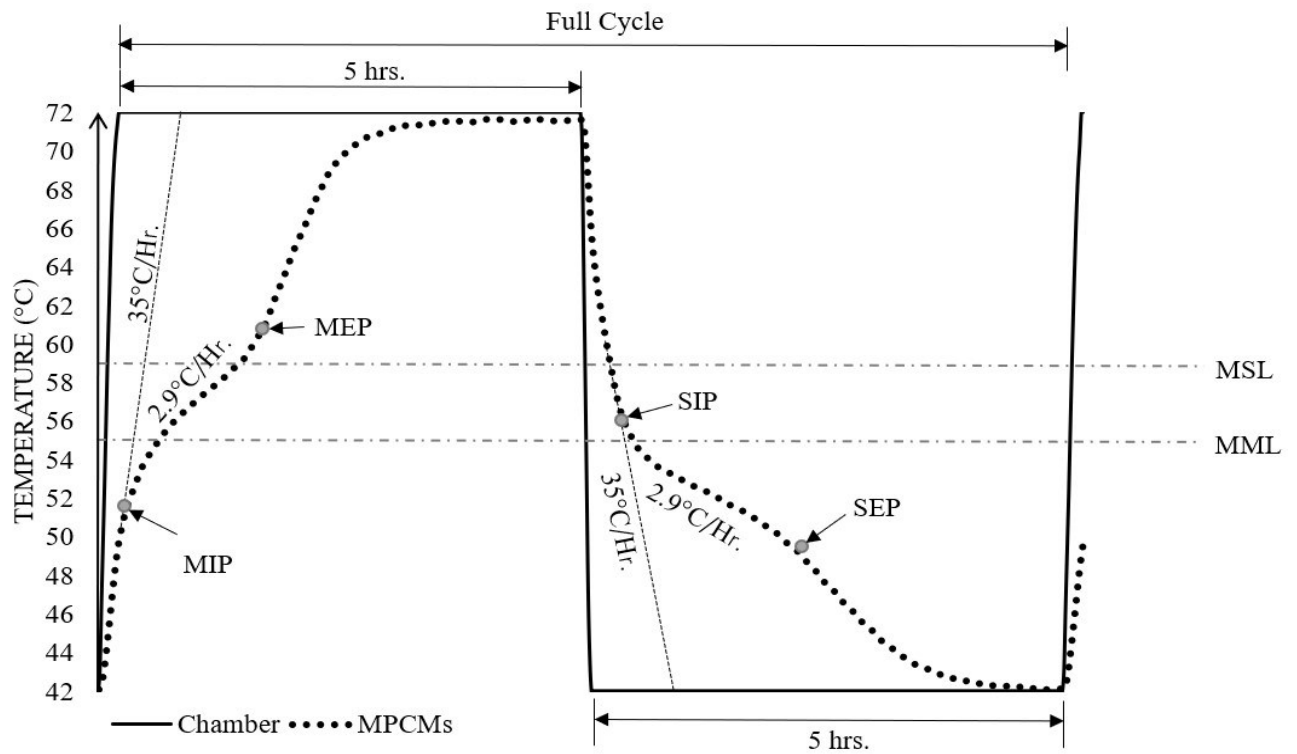


Figure A. 6 Thermal response of MPCMs in T1 - 5 hrs.

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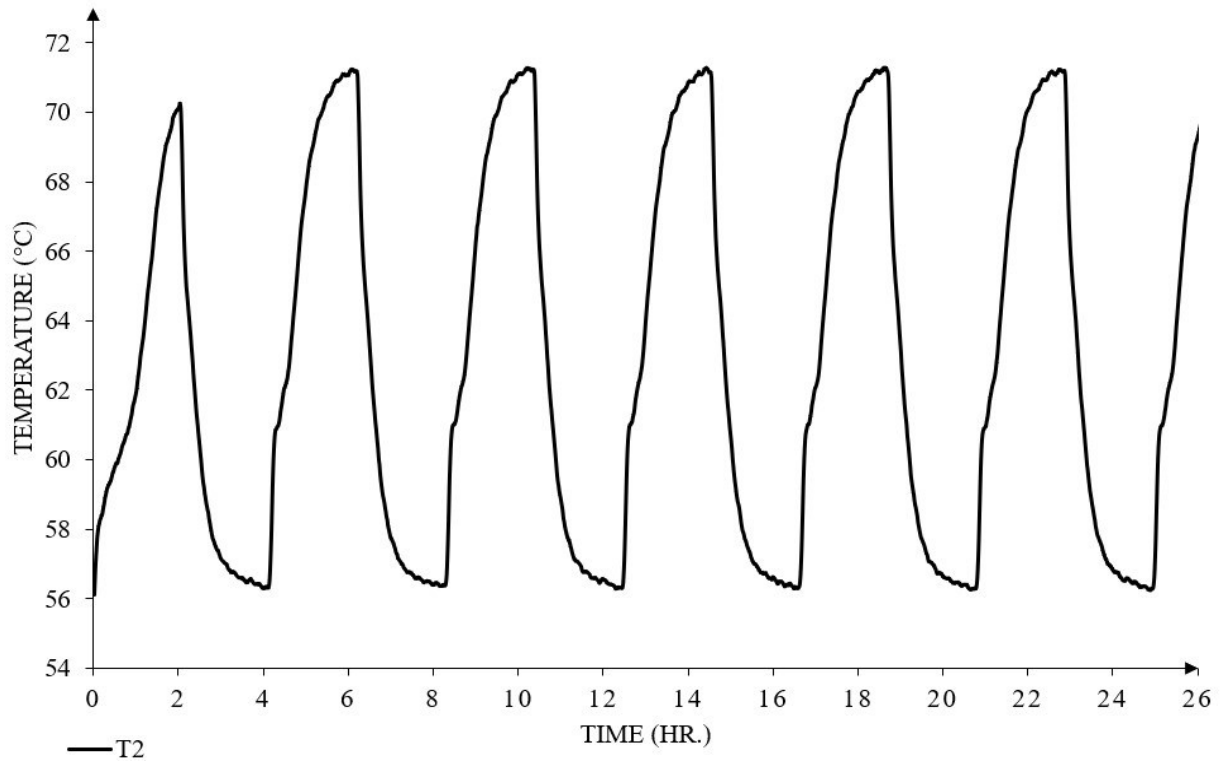


Figure A. 7 Thermal response of MPCMs in T2 (55-72 °C - cycles of 2 hrs.)

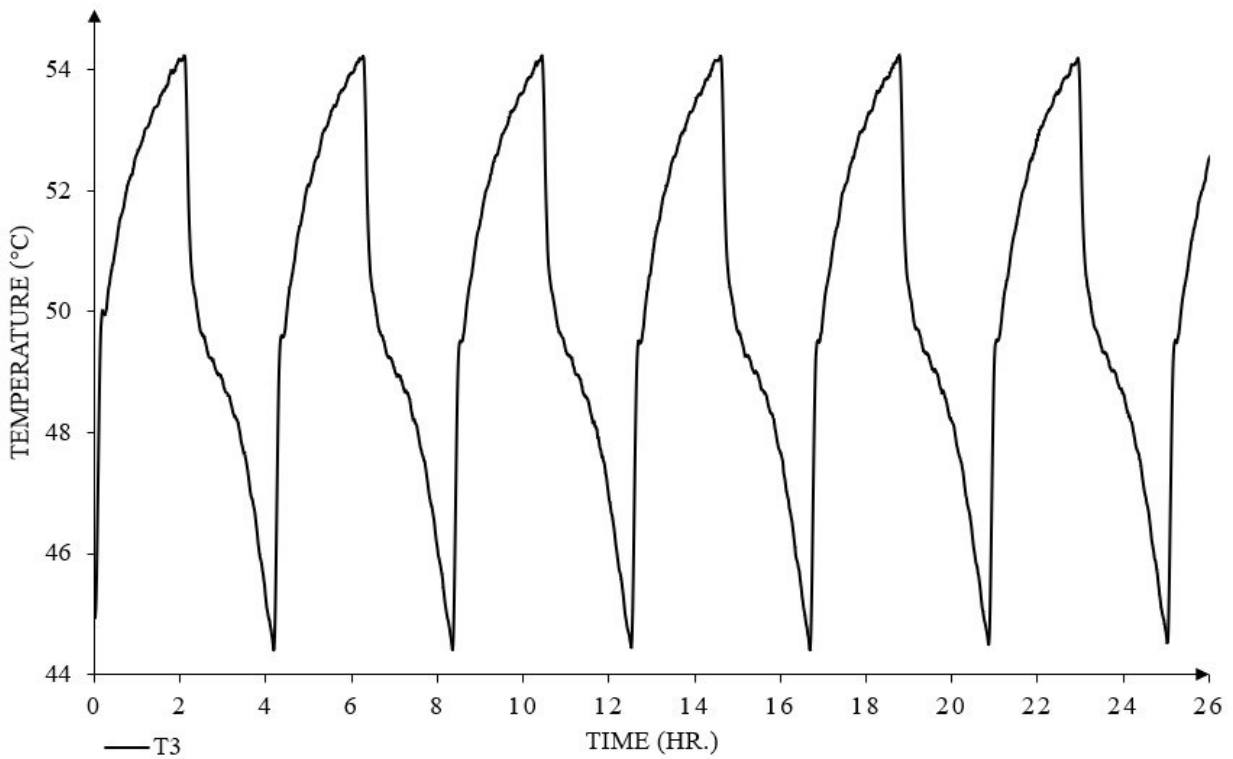


Figure A. 8 Thermal response of MPCMs in T3 (59-42 °C - cycles of 2 hrs.)

APPENDIX A

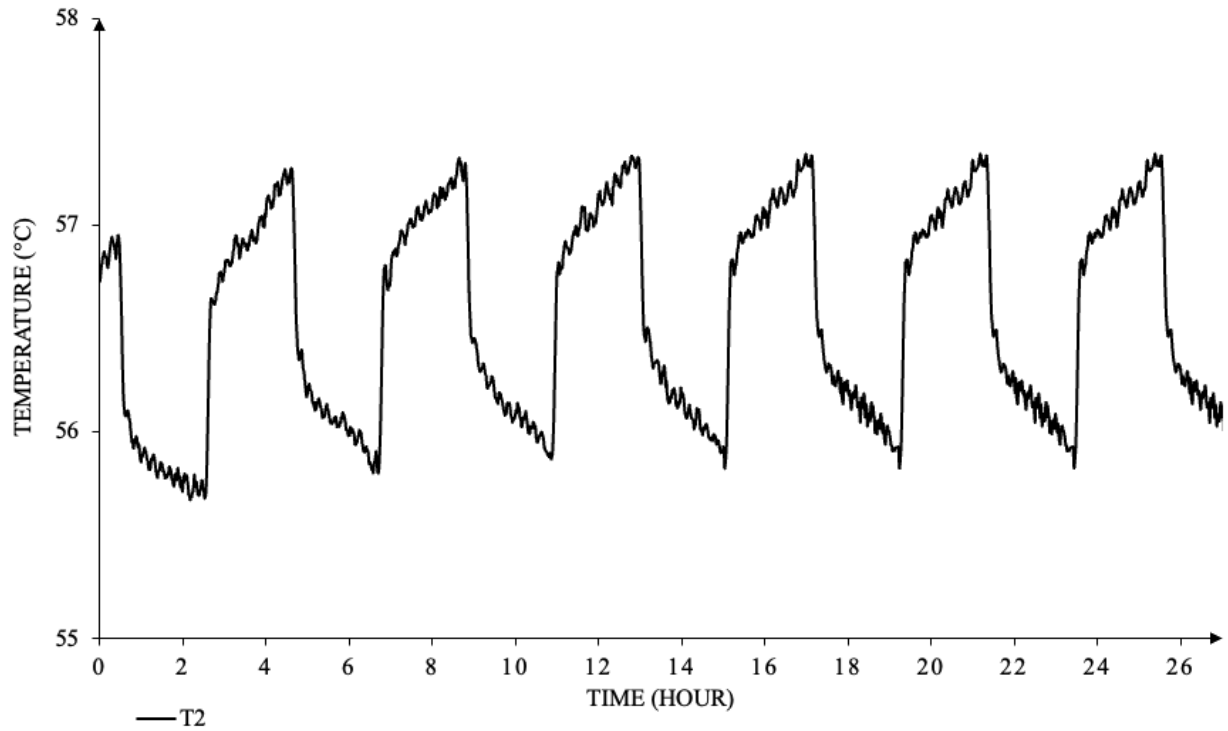


Figure A. 9 Thermal response of MPCMs in T4 (55-59 °C - cycles of 2 hrs.)

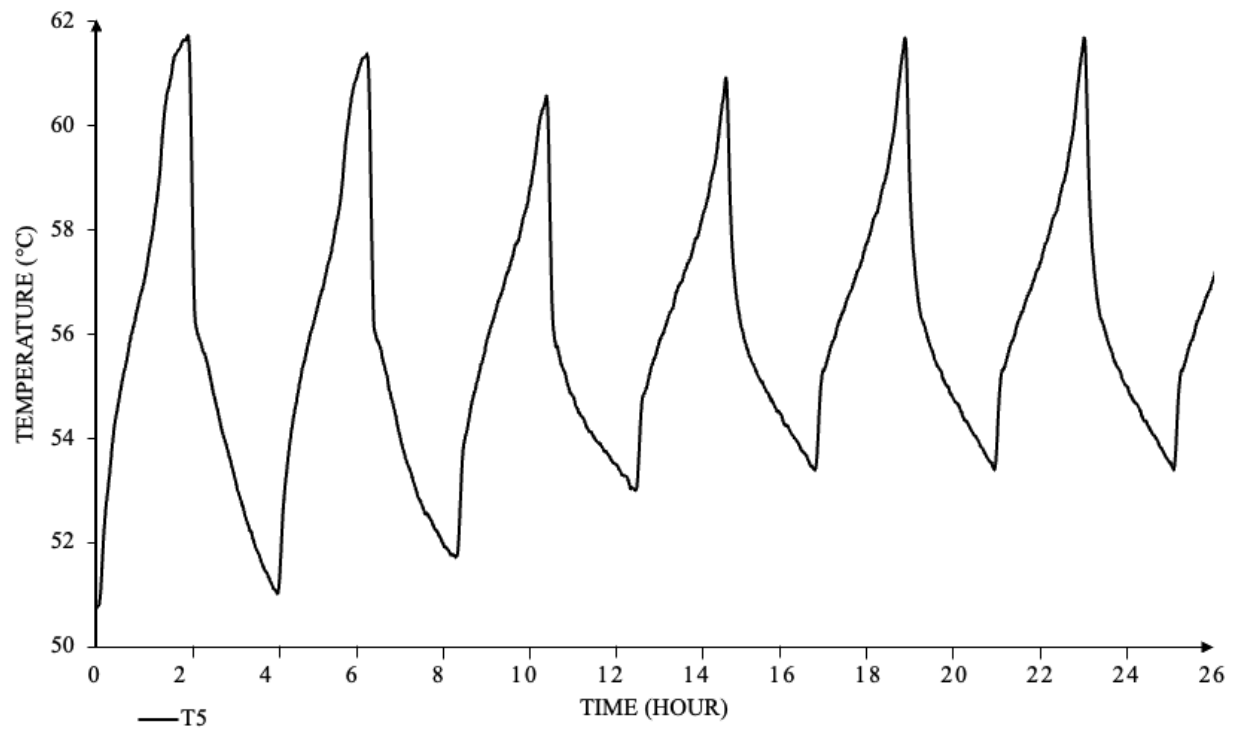


Figure A. 10 Thermal response of MPCMs in T5 (50-64 °C - cycles of 2 hrs.)

APPENDIX A

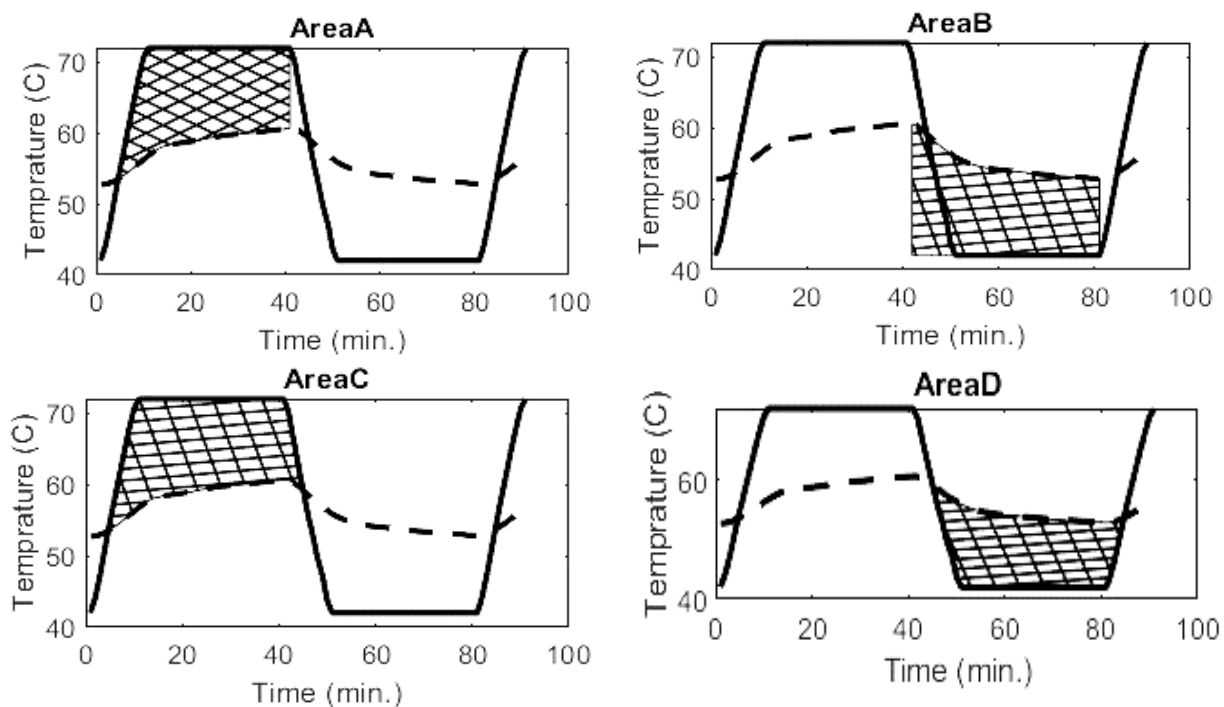


Figure A. 11 Energy evaluation of MPCMs in one cycle of T1- 30 min

Table A.1 The area of each section analyzed with MATLAB software.

Area A	$4.4121200000000000e^{+02}$
Area B	$5.1533999999999997e^{+02}$
Area C	$4.5967999999999999e^{+02}$
Area D	$4.2030299999999999e^{+02}$

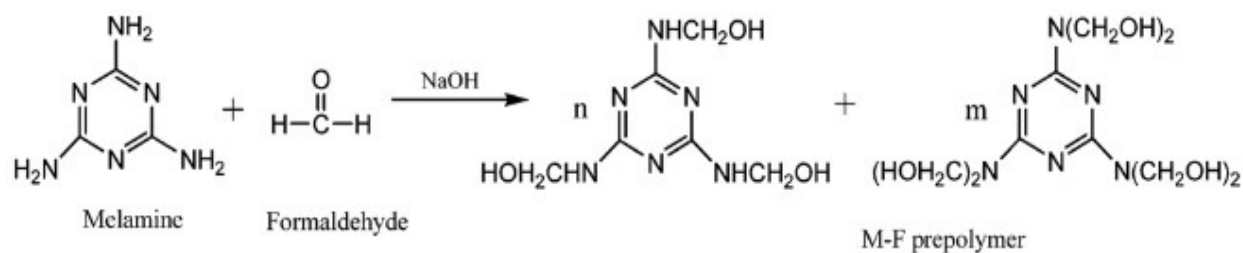


Figure A. 12 Synthesis of Melamine based shell of the used MPCMs

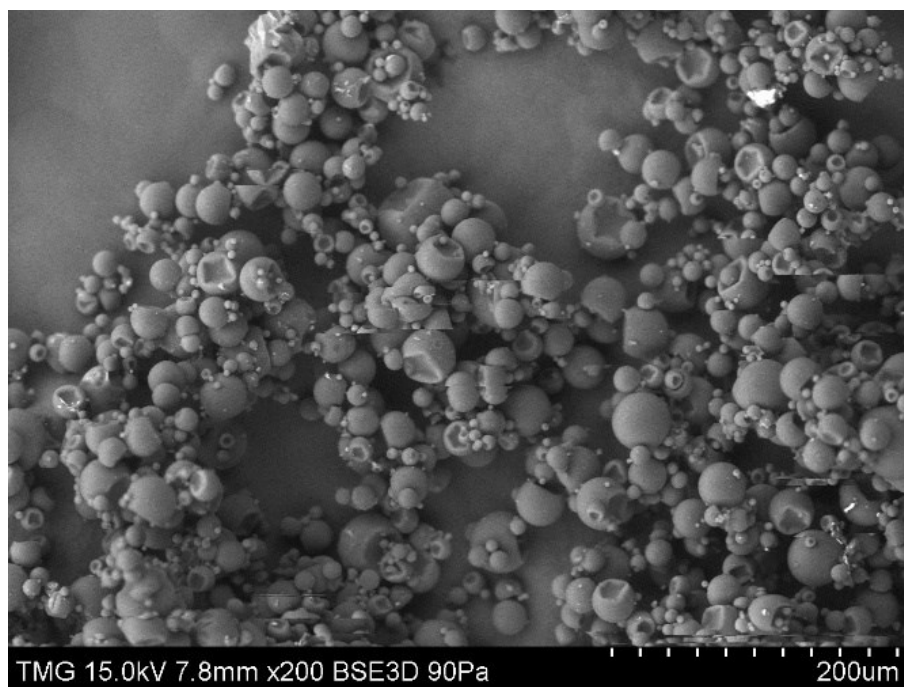


Figure A. 13 The reaction of MPCMs in water at 80°C temperature at 200 μm

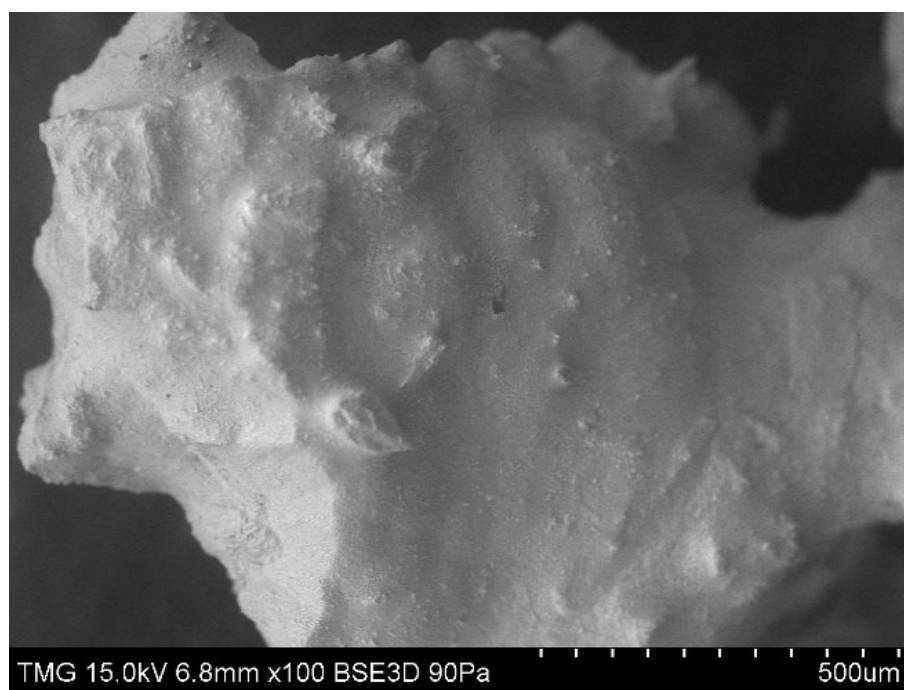


Figure A. 14 The NaOH in water at 80°C temperature at 500 μm

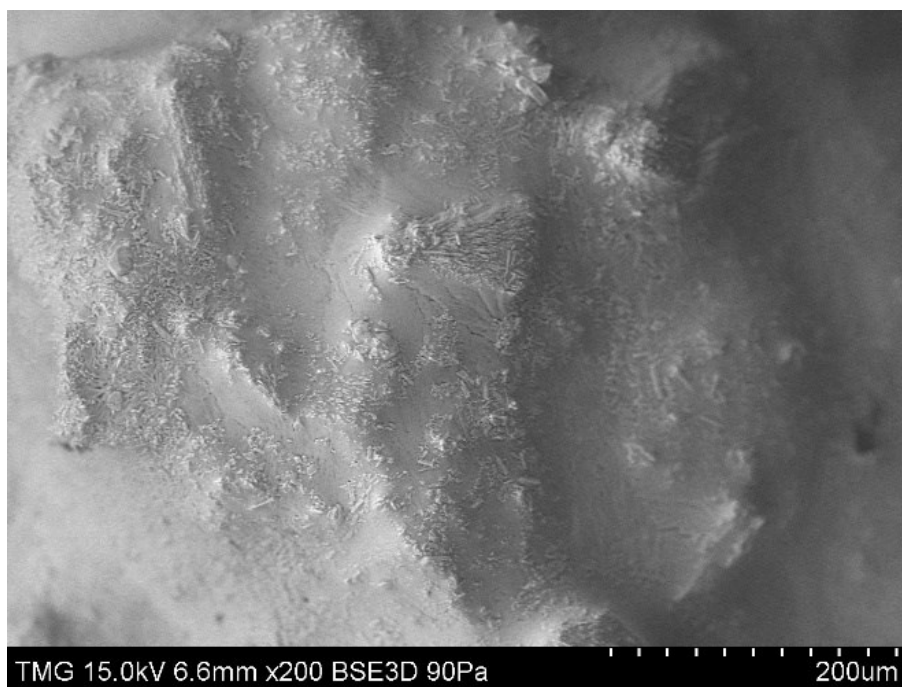


Figure A. 15 The NaOH in water at 80°C temperature at 200 μm

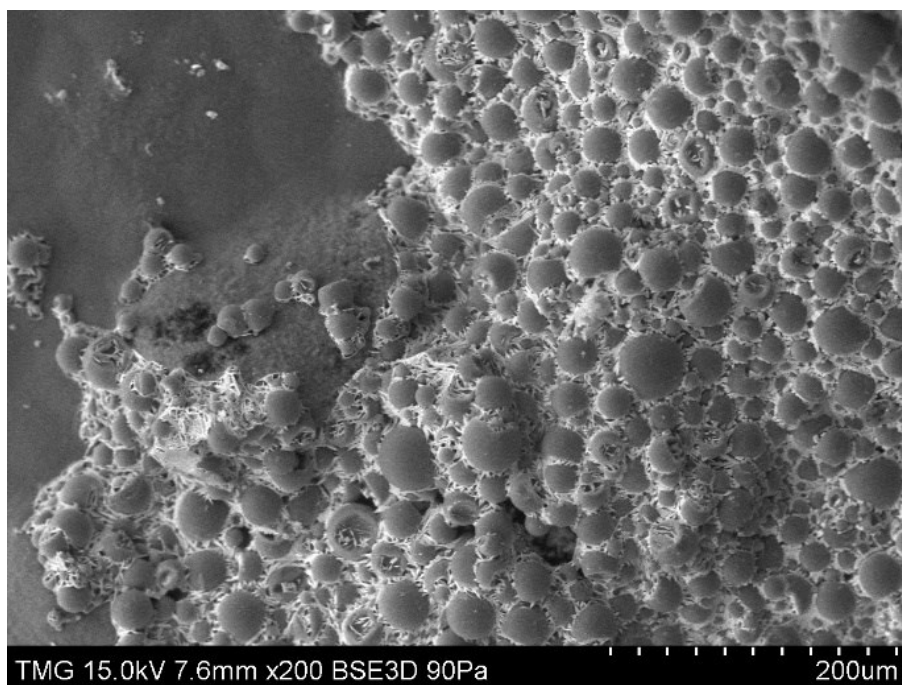


Figure A. 16 The reaction of MPCMs in 6m NaOH at ambient temperature at 200 μm

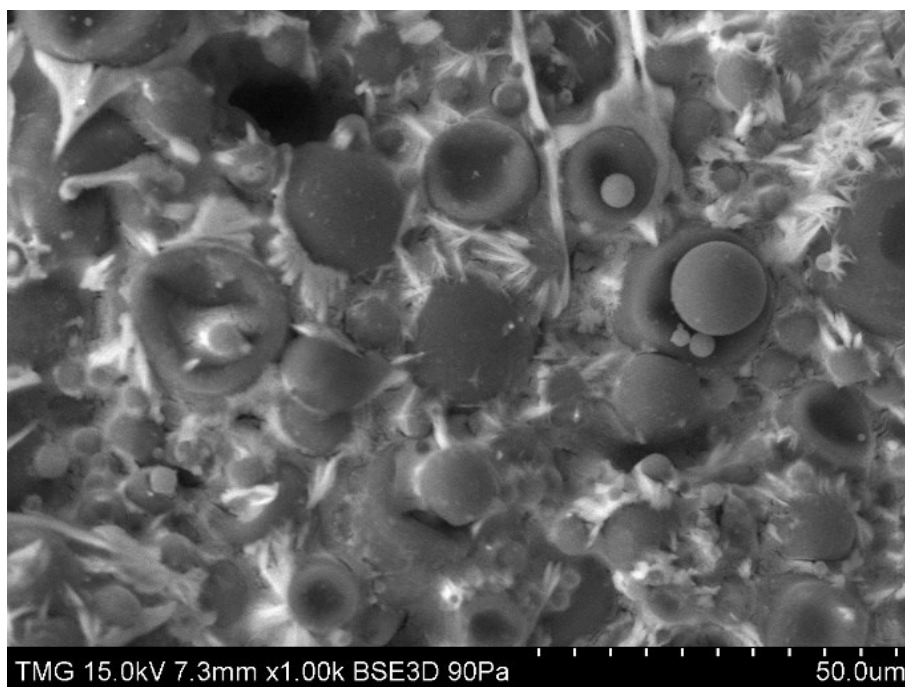


Figure A. 17 The reaction of MPCMs in 6m NaOH at ambient temperature at 50 μm

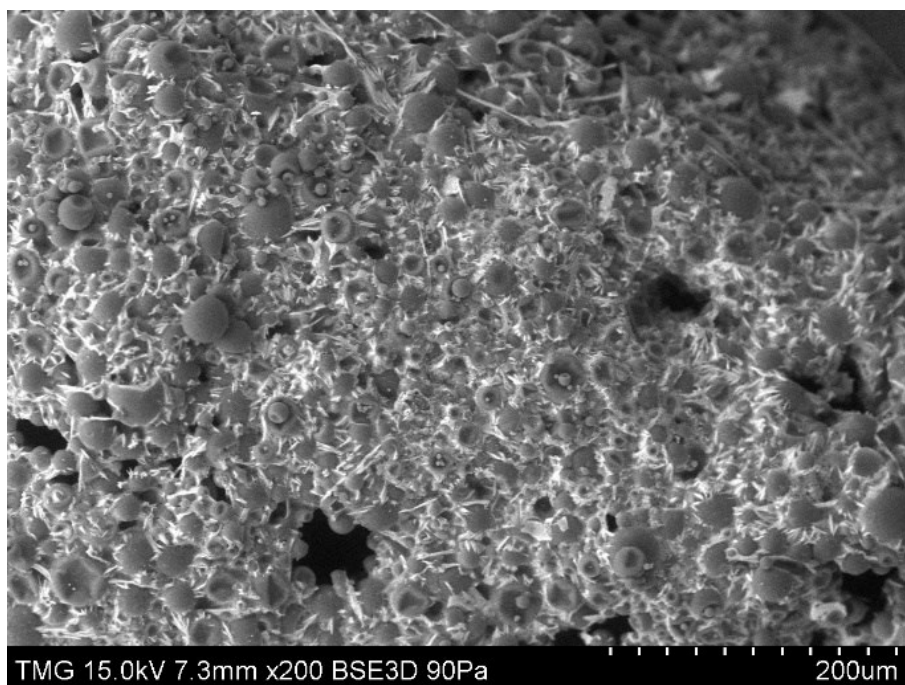


Figure A. 18 The reaction of MPCMs in 12m NaOH at ambient temperature at 200 μm

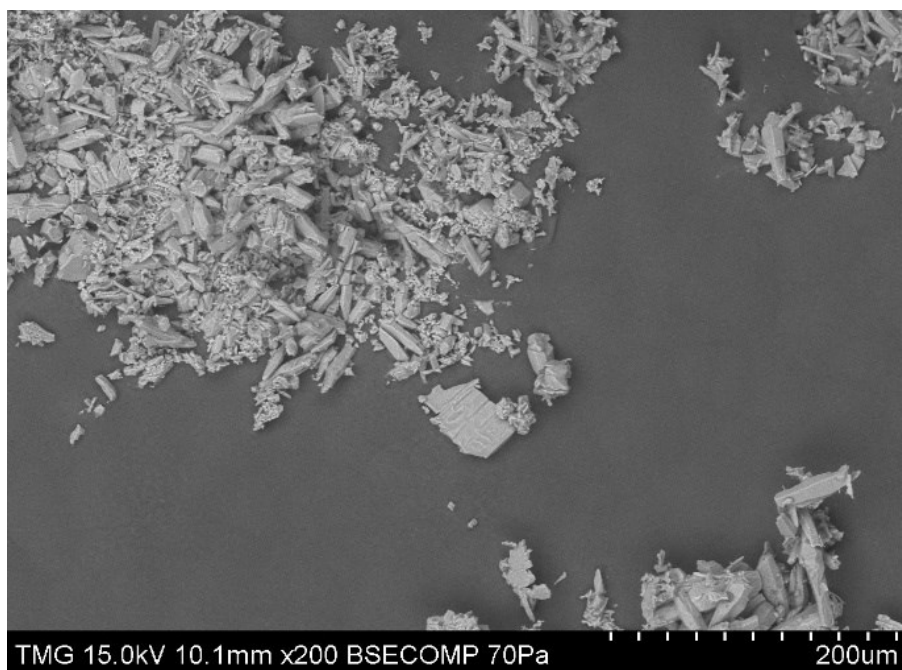


Figure A. 19 The reaction of MPCMs in 6m NaOH at 60°C temperature at 200 μm

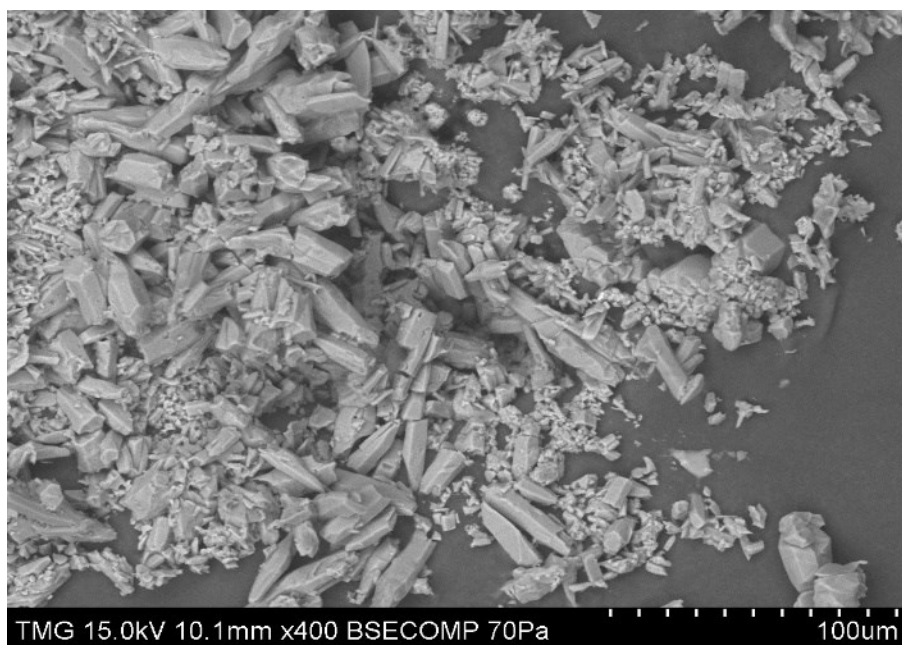


Figure A. 20 The reaction of MPCMs in 6m NaOH at 60°C temperature at 100 μm

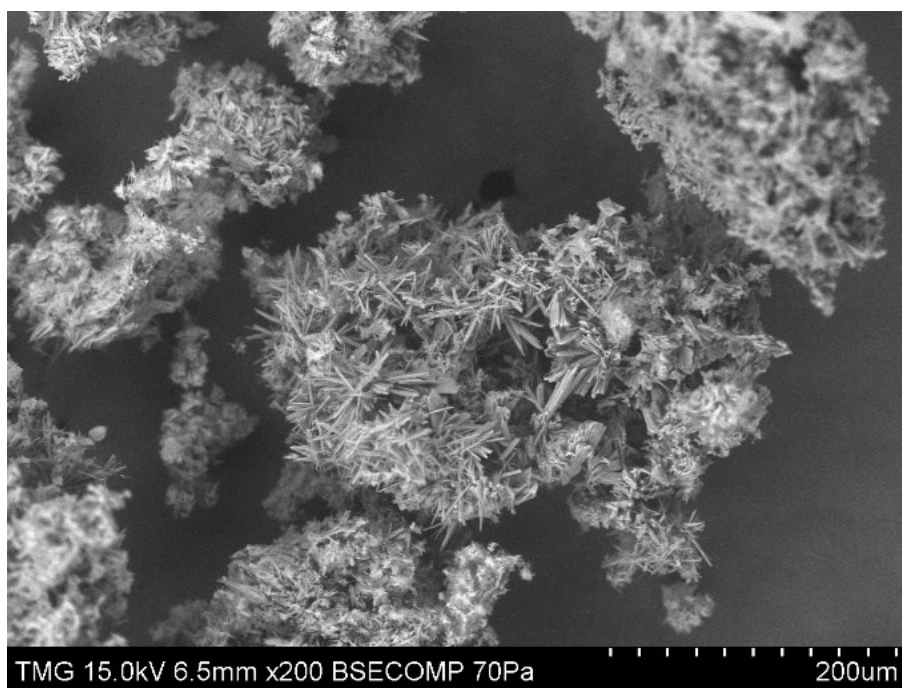


Figure A. 21 The reaction of MPCMs in 12m NaOH at 80°C temperature

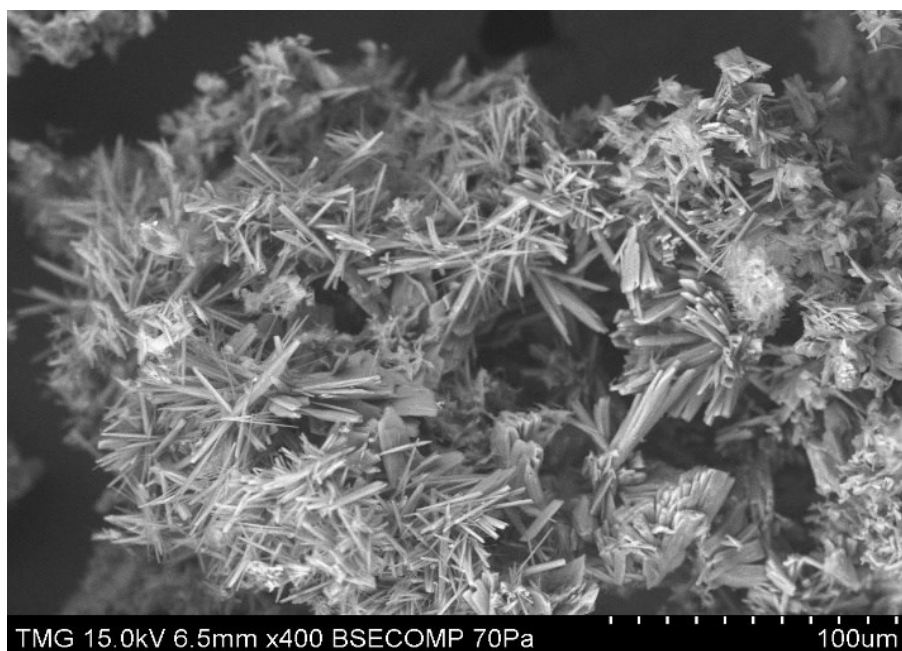


Figure A. 22 The reaction of MPCMs in 12m NaOH at 80°C temperature

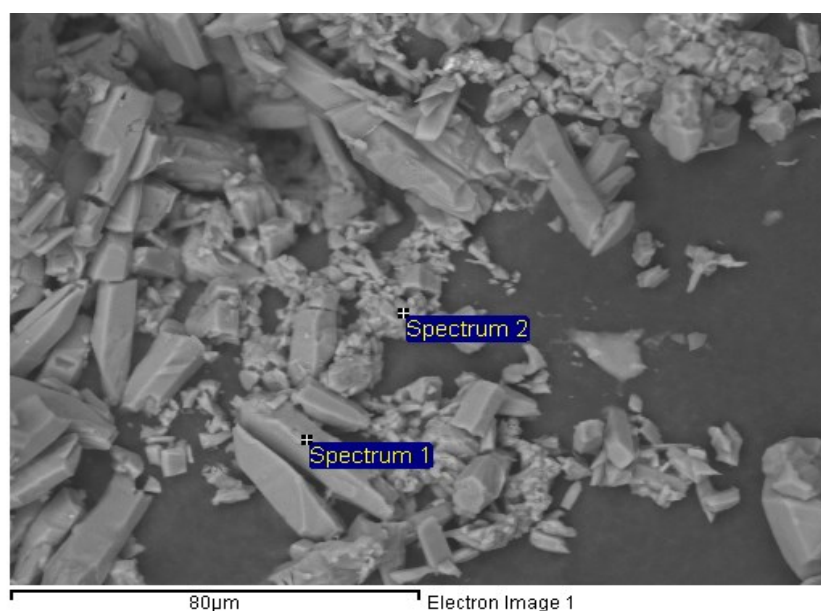


Figure A. 23 SEM photo of S3

Table A.2 Chemical composition of S3 in EDX analysis

Spectrum	In stats.	C	O	Na	Total
Spectrum 1	Yes	62.40	31.35	6.25	100.00
Spectrum 2	Yes	62.35	31.02	6.63	100.00
Mean		62.38	31.18	6.44	100.00
Std. deviation		0.03	0.23	0.27	
Max.		62.40	31.35	6.63	
Min.		62.35	31.02	6.25	

APPENDIX B

In the first stage of this research, OPC mortars' thermal response and mechanical performance were compared using different molds. This experiment was conducted to select the mold that performs better in thermal response and mechanical performance of mortars in the heat curing process. According to the results, to their thermal capacity, metal cubes tend to absorb and release heat faster than plastic molds. This phenomenon can be seen in **Figure B.1**. Plastic molds act as heat isolators for mortars, so they maintain heat longer than metal molds. This effect can be beneficial for the specimens for internal curing, and lower heat variation can help to reduce the heat damage of the specimens through the heat curing process. Based on the one-day compressive strength test results after this process, specimens cured in plastic molds presented a slightly higher mechanical strength. This difference can be due to the more extended internal heat curing of the plastic molds because of their heat isolation behavior. It was indicated that there is no difference in using these molds in the ambient condition regarding mechanical performance. Both specimens presented the same results in ambient curing (**Figure B.2**).

Moreover, it was identified that as the size of the specimens in heat curing increases, the internal heat curing capacity increases. These findings were obtained by evaluating the OPC mortars with different sizes, including 50 mm cubic, 100 mm, and 150 mm diameter cylinders. Considering the differences in thermal responses and mechanical strength, 50 mm plastic cubic molds were selected for the rest of the experiments.

APPENDIX B

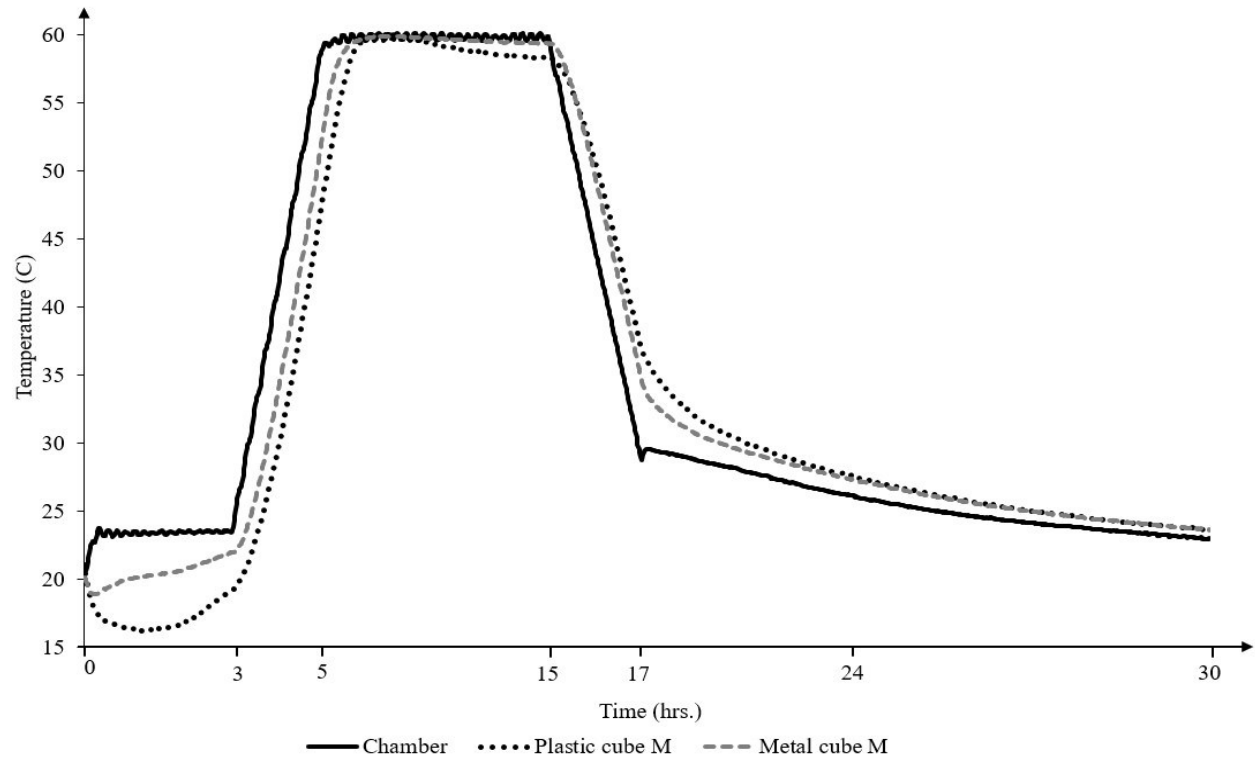


Figure B. 1 Thermal response of OPC mortars cast into plastic and metal molds during heat curing.

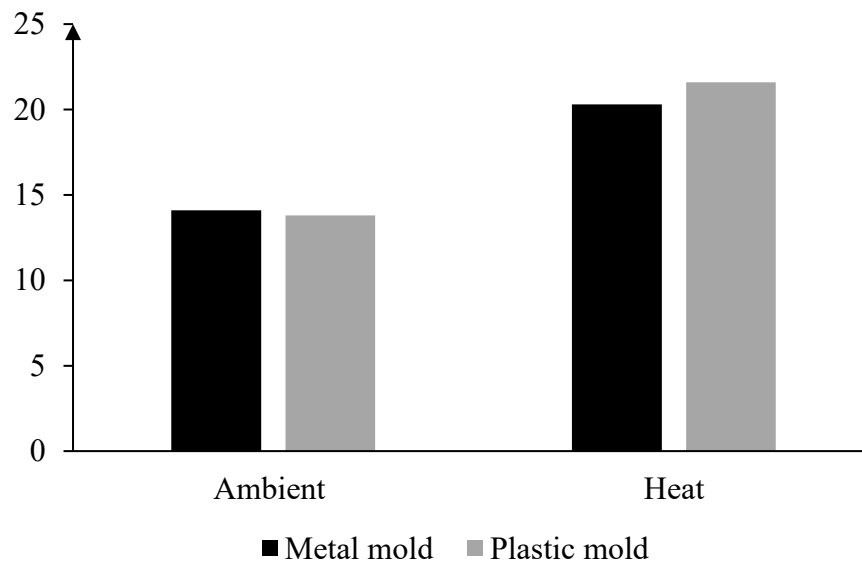


Figure B. 2 Mechanical strength of OPC mortars at the age of one day with different mold

APPENDIX B

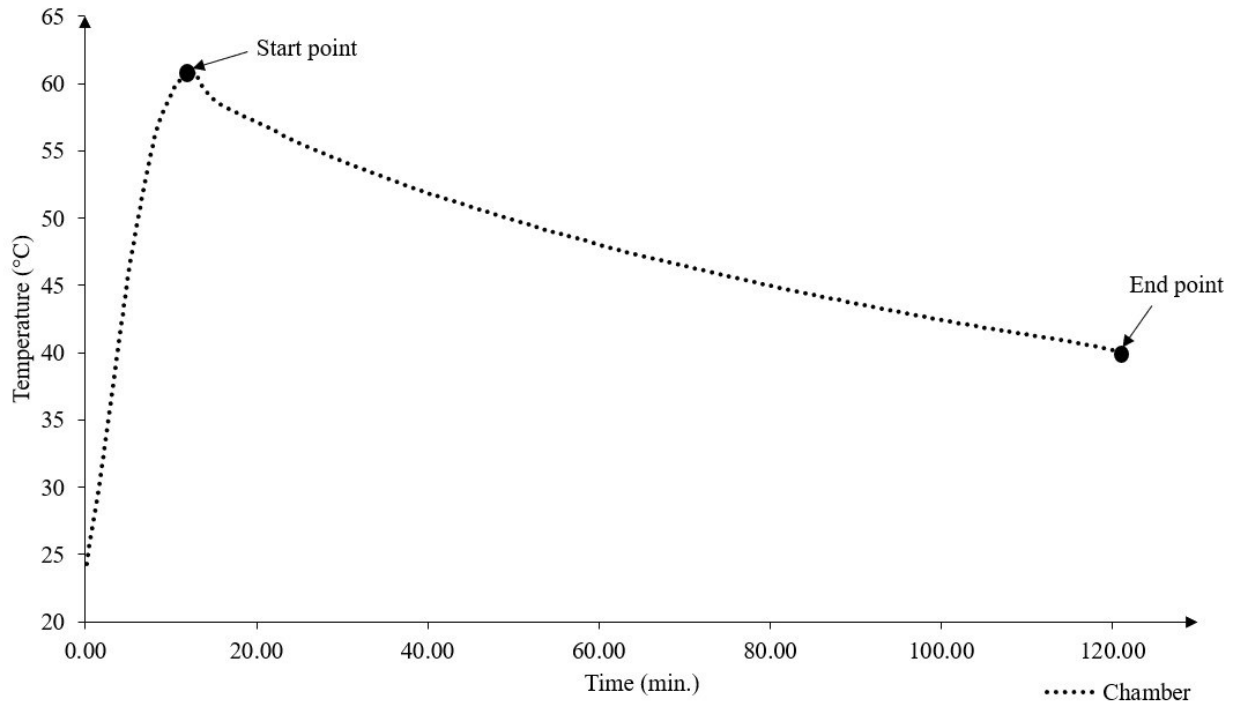


Figure B. 3 The thermal response of a closed environmental chamber when turned off at 60 °C, 110 min. It takes to reduce temp. from 60°C to 40°C.

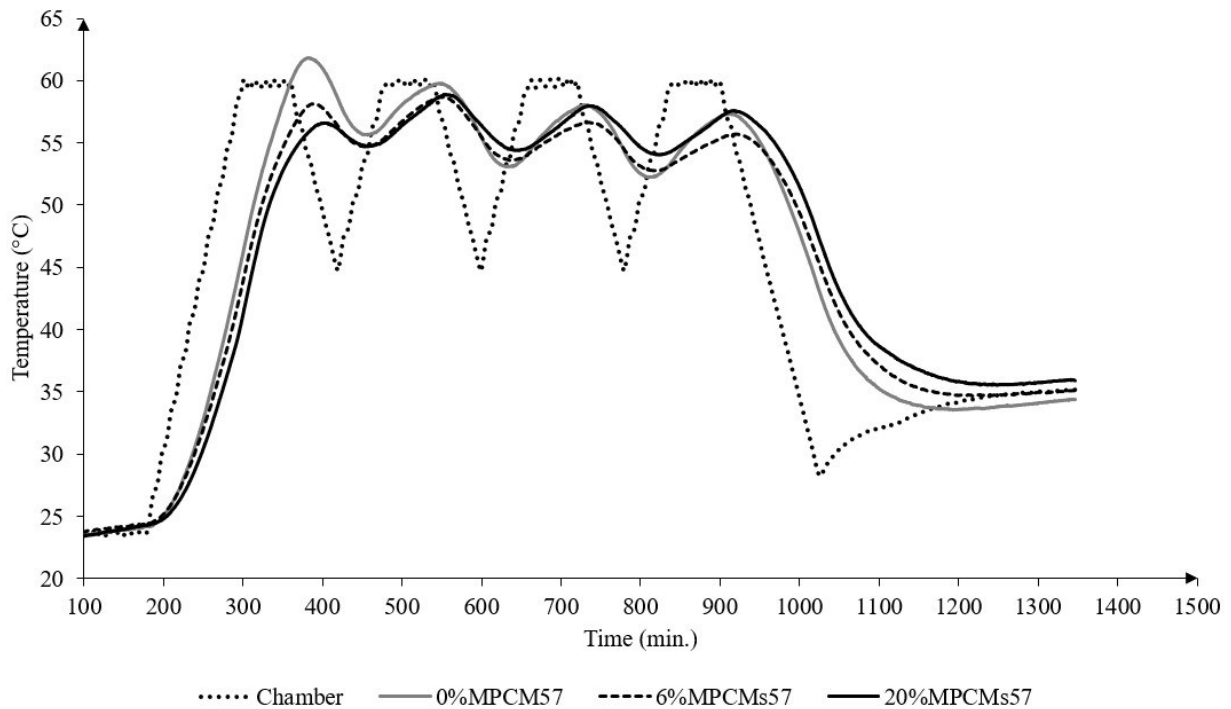


Figure B. 4 Comparing the thermal response of OPC mortars containing 0%, 6%, and 20% MPCMs 57 in Sawtooth I.

APPENDIX C

EVALUATING MECHANICAL AND INSULATION PROPERTIES OF BIO-BASED CEMENT-BONDED PARTICLEBOARD PANELS

Abstract

One of the outstanding issues of the 21st century lies in waste management. A massive portion of the produced waste in the world is related to agricultural waste. Cementitious materials are one of the best solutions for incorporating waste materials, especially agro waste. Utilizing these materials may lead improving the insulation properties of cementitious building envelopes. On the other hand, cement is one of the world's greatest actors in CO₂ emissions, which needs to be aligned with the global cement and concrete association (GCCA) environmental goals by 2050. In this respect, this study examined cement-bonded particleboards with high percentages of Jerusalem artichoke stalks as the agro-waste inclusion in terms of mechanical and insulating properties. Cement was replaced with silica fume by ten percent to not only support environmental purposes but improve the mechanical strength of the product. A novel method to reduce the water absorption of the used agro-wastes during the mixing was implemented. The particleboards were evaluated at the age of 28-day by ultra-pulse velocity, density, water absorption, thickness swelling, flexural strength, sound transmission loss, thermal conductivity, fire resistivity, and scanning electron microscope. According to the results, due to the high content of available air inside the stalks structure, significant insulating effectiveness was seen in the products' evaluations. A direct correlation between the inclusion rate of agro-waste and the insulating properties of the

particleboards was seen. This study can enlighten the in-situ engineers to understand the excellent value of utilizing agro-waste materials to construct eco-friendlier buildings envelopes and reduce the waste management issues.

C.1 Introduction

Energy consumption worldwide has significantly increased in the past two decades (Wang et al., 2016). The heating process for industrial and domestic purposes generates 40% of global emissions. Half of this globally produced heat is used for space and tap water heating in the built environment (Dodoo et al., 2014; Jakob et al., 2020). According to the intergovernmental panel on climate change (IPCC), buildings handled 19% of energy-related emissions in 2010. Approximately 80% of this energy is produced with natural resources (Teo et al., 2010).

Contrary to the efforts made in this respect, calculations present that to achieve Net Zero Emissions by 2050, building consumption per square meter in 2030 must be declined by 45% compared to 2020 (Ohene et al., 2022; Harish et al., 2016). One of the best practices that can be improved to achieve this goal is to rectify the building's interiors. A closed system, such as a house, would theoretically be the best option for reducing energy consumption because it maintains its temperature by not reacting with the outside world (Balaji et al., 2022; M. C. Bozchalui et al., 2012). However, insulating materials help engineers improve the energy efficiency of building envelopes; they are very costly. In this respect, researchers are studying the behavior of waste materials to reduce the related cost. Agricultural waste is one of the promising recent waste materials that can supply high-insulating performances (Aprianti et al., 2015; Shah et al., 2021).

Agricultural wastes are the byproduct of the manufacturing and processing raw agricultural products like fruits, vegetables, and crops (Capanoglu et al., 2022). Due to the cellulosic structure

APPENDIX C

and chemical compositions, many can be mixed with cementitious materials. These agro-waste materials play the role of supplementary cementitious materials and serve as alternative aggregates in construction (Kawasaki et al., 2020; Ganesan et al., 2007). One of the agro-wastes found widely in northern countries is Jerusalem artichoke stalks that, because of their porous structure, can be the perfect candidate for the inclusion of cementitious materials for insulating purposes.

Jerusalem artichoke waste disposal is one of the leading worldwide issues in agricultural sections (Johansson et al., 2015; Szufa et al., 2020). The difficulty and cost of their recycling process made researchers look for alternative solutions to reduce their environmental impacts (Maier et al., 2021). Due to their high resistance to pests, frost, and drought, and on the other hand, having cellulose structure, they are excellent insulating materials that can be incorporated with cementitious mixtures (M. R. Cabral et al., 2018; M. Cabral et al., 2016).

Aims and objectives

One of the methods for including a vast amount of these materials in cementitious mixtures is the production of cement-bonded particle boards. Very few articles have studied the insulating properties of these materials in cementitious mixtures. Therefore, there has been a vast emphasis on maximizing the amount of agro-waste usage in producing cement-bonded particle boards acting as insulating components in buildings. Specimens with different binder-to-agro-waste ratios varying from 1:3 to 1:0.5 by weight were compared in mechanical and insulation properties. In addition, to reduce the carbon footprint of the final product, a part of the cement was replaced with silica fume in all mixtures. These properties were checked with sound transmission loss, thermal conductivity, fire resistivity, ultra-pulse velocity, water absorption, density, thickness swelling, and flexural strength. This research can guide engineers to expand their knowledge on utilizing agro-waste with cementitious materials for cleaner production.

C.2 Materials and methods

C.2.1 Materials and mix design

Jerusalem artichoke stalks in dimensions between 3 to 15 mm with initial moisture of less than 5% and density of 0.099 g/cm^3 were used in this study (**Figure C.1**). Naturally, these materials absorb water more than three times their weight in short period which was considered in mixture design (Taş et al., 2020; Nunes et al., 2021). General Use (GU) cement with ten percent cement replacement with silica fume (SF) was utilized in the mixture design.



Figure C. 1 The used agro-waste in this study

The chemical composition and physical properties of the used cement and silica fume can be found in **Table C.1**. The mixture designs used in this study are presented in **Table C.2**. To reduce the amount of agro-waste water absorption, they were put into water to reach the saturation level for 24 hrs. The tap water was used for the mixture design and pre-wetting of the agro-waste. Also, silica fume (SF) was added at a rate of 10% replacement of cement to improve the product's bond mechanical properties, abrasion resistance, and degree of sustainability. An accelerator was used to compensate for the delay caused by the agro-waste materials.

Table 0.1 Chemical and physical properties of the used binder materials

Item		Cement	SF
SiO ₂	(%)	19.8	90.21
Al ₂ O ₃	(%)	4.90	0.12
CaO	(%)	62.30	0.15
Fe ₂ O ₃	(%)	2.30	0.30
SO ₃	(%)	3.70	0.73
Na ₂ O	(%)	0.34	0.46
MgO	(%)	2.80	0.01
C ₃ S	(%)	57.00	-
C ₂ S	(%)	14.00	-
C ₃ A	(%)	9.00	-
C ₄ AF	(%)	7.00	-
Loss of ignition	(%)	1.90	-
Specific gravity	-	3.15	2.22
Surface area	(m ² /kg)	360	20.000

Table 0.2 Mixture design of the cement-bonded particleboards (by weight)

Sample ID	Cement (g)	SF (%)	Agro-waste (g)	Water to Cement ratio	Additional water (g)	Accelerator % cement
M1	100	10	33.3	0.25	0	0.5
M2	100	10	50.0	0.25	0	0.5
M3	100	10	66.6	0.25	5	0.5
M4	100	10	100	0.25	8	0.5
M5	100	10	200	0.25	10	0.5

C.2.2 Specimens' preparation

The pre-wetted agro-waste was compressed with a manual hydraulic jack to reduce its initial volume and emit the extra water. The manually compressed agro-wastes were mixed with cement for two minutes in a mixer, according to standard (ASTM C192, 2015). The accelerator was mixed with water and appropriately sprayed into the mixture to obtain a homogenous mixture (**Figure C.3**). A 150 × 150 × 7.5 mm square mold with a fixable heavyweight cap size as the expelative

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part for supporting the pressure on the sample was used to produce the samples (**Figure C.2**). The mold was oiled and covered with plastic sheets on the top and bottom sides to reduce the cohesion between the mold and mixture. After the cast, the mold cap was tightened, and the mold was transferred into a hydraulic jack for compaction to obtain a 10 mm thickness sample. The sample, along with its mold, was put into the steam curing chamber with a maximum temperature of 60°C and relative humidity of 95% for 24 hrs. concerning ASTM C192 and ISO 8335 (ISO 8335, 1987; Zeyad et al., 2022). The specimens were kept in an environment with 95 ± 1 % relative humidity at room temperature with 24 ± 1 °C for 28 days. The final product shape and dimensions can be seen in **Figures C.4** and **C.5**.



Figure C. 2 The mixture of cement and agro-waste materials



Figure C. 3 The designed mold for producing cement-bonded particleboard.



Figure C. 4 The final product quality and dimension after 24hrs. of steam curing



Figure C. 5 The product's thickness after 24hrs. of steam curing

C.2.3 Test methods

C.2.3.1 Unit weight

The specimens' density was determined on three replicant beams in $150 \times 75 \times 10$ mm considering the standard (ASTM C642, 2022). The density was taken in two conditions of after the demolding and after 28 days of curing. For the second condition, the specimens were dried out in the oven at 110°C for 72 hrs., and their weight and volume were recorded. The density was calculated using **Equation C.2** as follows.

$$\textbf{Equation C.2} \quad \text{Density} = \frac{\text{Weight (g)}}{\text{Volume (cm}^3\text{)}}$$

C.2.3.2 Ultra-Pulse Velocity (UPV)

The ultra-pulse velocity of the specimens was monitored on three replicant specimens of $150 \times 150 \times 10$ mm according to standard (ASTM C597, 2023) at the age of 28-day. This test was used

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to compare different mixtures on integrity and quality in this study to confirm the relationship between quality, density, and insulating properties.

C.2.3.3 Water absorption

Water absorption was done at 28 days on three replicant specimens in $150 \times 75 \times 10$ mm dried out in an oven at 110°C for 72hrs considering the standard (ASTM C1585, 2020). The samples were put into 3 ± 0.5 mm water, and their weight change was checked at 1, 15, 30, 45 minutes, 1, 4, 24hrs until no changes were recorded. The water absorption was recorded daily after the initial 24hrs, and the samples were covered with plastic sheets to prevent water evaporation (Borg et al., 2016; Sant et al., 2006).

C.2.3.4 Thickness swelling

The thickness of the specimen was measured and recorded after 28 days of curing on specimens in $150 \times 75 \times 10$ mm dried out in an oven at 110°C for 72hrs. After the initial thickness measurement, the specimens were soaked in water for 24hrs. and their thickness was recorded. The percentage difference in thickness was obtained as the formula below concerning the standard (ASTM D1037, 2020; Odeyemi et al., 2020; Sotannde et al., 2012). The related formula is shown in **Equation C.3**.

Equation C.3 *Thickness swelling (%)* = $\frac{T_f - T_i}{T_i} \times 100$

where T_i = initial thickness, and T_f = final thickness. This experiment was also carried out in one week concerning the water absorption results. Three replicant specimens were utilized to have an average result.

C.2.3.5 Mechanical properties: three-point flexural strength

The mechanical behavior of cement-bonded particleboards is commonly evaluated in bending mode. Flexural tests are easy to conduct and allow the determination of the core shear properties, as well as the in-plane mechanical response of the face sheets. In the three-point configuration, the test combines bending and shear deformations on the samples (Régál et al., 2017; Haach et al., 2011). A static three-point flexural test was conducted on the universal testing machine equipped with a load cell of 10 kN considering CBPB standard (ISO 8335, 1987). According to ISO 8335, the particleboards should have at least 9 N/mm² bending strength in dry conditions. The test was performed on beam-shaped samples 150 × 75 × 10 mm by setting the flexural speed to 0.5 mm/min, a pre-load of 20 N, and a support spacing of 30 mm. The bending strain was recorded with a displacement transducer in contact with the samples. The mechanical results are the average of at least three replicates.

C.2.3.6 Acoustic insulation

Sound Transmission Loss (STL) was carried out according to standards (ASTM E336, 2023; ASTM E90, 2017) on specimens with 100 mm and 300 mm diameters to cover all frequencies from 100 to 5500 Hz in terms of efficiency of the particleboards in sound insulation and noise canceling properties (Chalangaran et al., 2021; Cole, 2019; Oliazadeh et al., 2018). The acoustic insulation performance was evaluated experimentally utilizing a custom-made impedance tube, following the test configuration illustrated in **Figure C.6**.

The measurement apparatus consists of a sound-insulated plastic duct where the test sample is placed in the middle. At the same time, a loudspeaker generates sine wave acoustic signals at one end of the tube. At the other end of the duct, a polyurethane foam absorbent termination was applied to minimize unwanted acoustic reflections in the tube during the test. Two condenser

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microphones, located before and after the sample, made it possible to measure the sound attenuation level (D) provided by the test material at a specific dB in the receiving part of the tube (downstream of the sample).



Figure C. 6 Sound insulation test setup

An audio interface and a computer with software were used for signal processing and data acquisition. D-values were recorded at six frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Once computed, the D-values for each investigated frequency were, and the sound reduction index (SRI) was determined as the arithmetic average of D in the low-medium frequency band (125^{500} Hz) and high-frequency band (1000^{4000} Hz). SRI is a clear indicator of the noise barrier properties of a material, measuring the effectiveness of building elements, such as walls and floors, in restricting the passage of sound through the element (Hwang et al., 2015; Litvin et al., 1980; Chalangan et al., 2019).

C.2.3.7 Fire resistivity

Three replicant specimens of $150 \times 150 \times 10$ mm were used to simulate the fire test response and relative fire characteristics of particleboard panels when the source of fire is inside. This experiment was based on the guidance of the standard (ASTM E119, 2022). A gas burner was used as the source of flame uniform gas pressure. The changes on the surface, displacement of the portions, and weight difference before and after the fire were evaluated. This test does not cover all factors related to the fire risk assessment of the materials under actual fire conditions (Papadopoulos, 2008; Manica et al., 2020; Bilow et al., 2008; Seleem, Rashad et al., 2011).

C.2.3.8 Thermal insulation

The heat transfer rate of the specimens in $150 \times 150 \times 10$ mm was monitored utilizing a chamber with a heat barrier set up for cold and hot sections simulation (Su et al., 2015; Shin et al., 2002; Bondareva et al., 2022). A heat regime was designed to simulate the heat and cold cycle to simulate different temperature variation scenarios between 27°C and 17°C degrees concerning Montreal's daily weather tolerance (Weather Spark, 2023). The specimen's heat transfer rate was monitored with thermocouples attached to a data logger (**Figure C.7**). The temperature of the specimens was recorded every minute. Thermocouples a, b, and c are respectively related to monitoring the temperature inside the chamber, inner side of CBPB, and outer side of CBPB. The variation in the sample surface's temperature was monitored using a high-resolution camera forward-looking infrared (FLIR) in every 10 minutes.

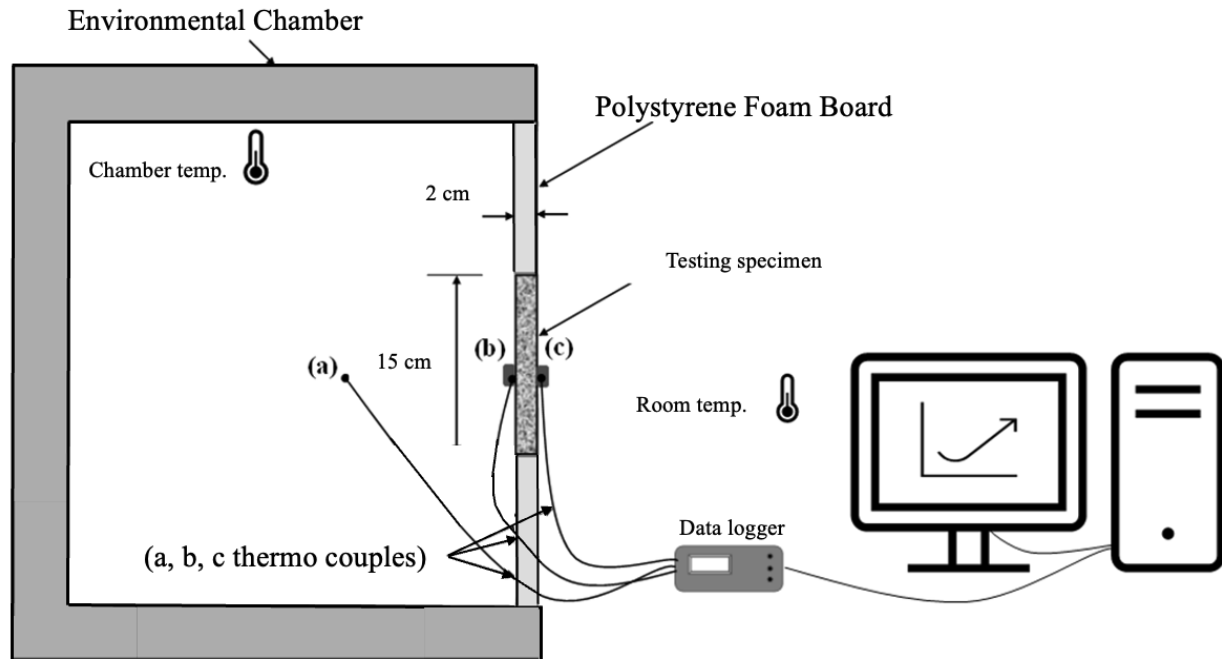


Figure C. 7 Schematic of the heat transfer rate of the produced CBPB

C.3 Results

C.3.1 Unit weight

According to the data gathered from the unit weight results of the specimens after 28 days, a correlation between the decrease in the cement: agro-waste ratio and the density of the specimens was seen. The specimens' density decreased as the cement: agro-waste ratio decreased. **Figure C.8** presents the density of the products of each mixture design. The density of the M1 was 57% reduced in M5, considering the 6 times reduction of the cement utilization in this mixture. This fact is attributed to agro-waste's lower specific gravity than cement (0.6 g/cm^3 to 3.15 g/cm^3). According to the visual observations of the used Jerusalem artichoke stalks, using these materials with cementitious materials could induce voids and entrap air into the product due to the high

cellulosic structure of these materials. The mixtures of M1 to M4, according to the standard (ASTM D1554, 2023), were considered as high-density particleboards ($+800 \text{ kg/m}^3$).

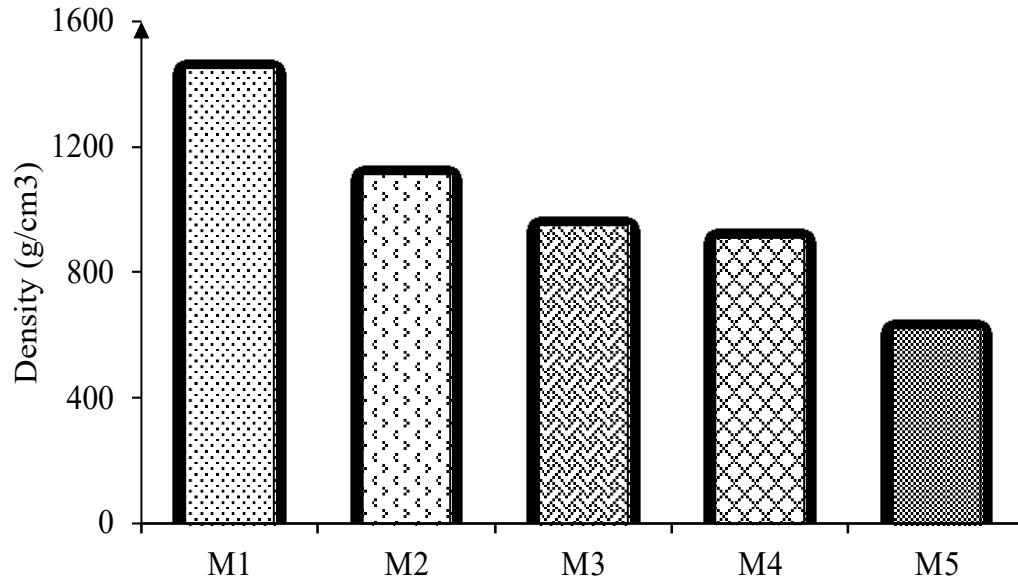


Figure C. 8 Unit weight of the CBPBs

C.3.2 Ultra-Pulse Velocity (UPV)

A significant drop in the UPV results was seen with respect to the density of the CBPBs. The UPV was reduced by 21% and 71% from M1 to M2 and M1 to M5, respectively (**Figure C.9**). M1 and M2 samples presented an excellent surface quality with lower pores than the rest. **Figure C.10** shows the correlation between UPV and the density of the CBPBs produced in this study. A sudden drop in the UPV using lower cement: agro-waste ratio than 1 was observed. This fact is attributed to the very low cement usage, resulting in low bonding between the agro-waste particles and, consequently, low UPV results. According to the visual observations, the M4 and M5 samples were brittle to handle due to the low cement content, with some physical defects.

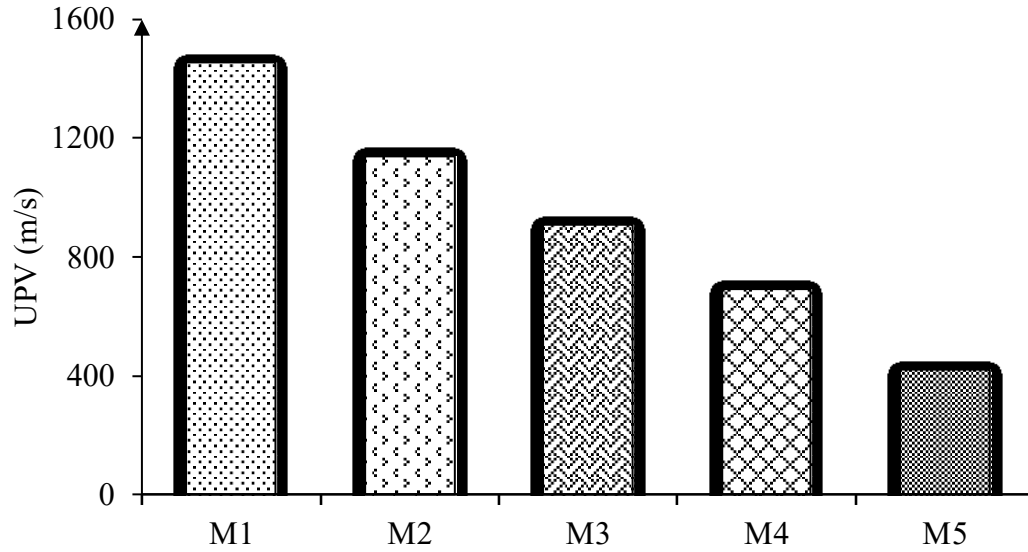


Figure C. 9 UPV results of the CBPBs

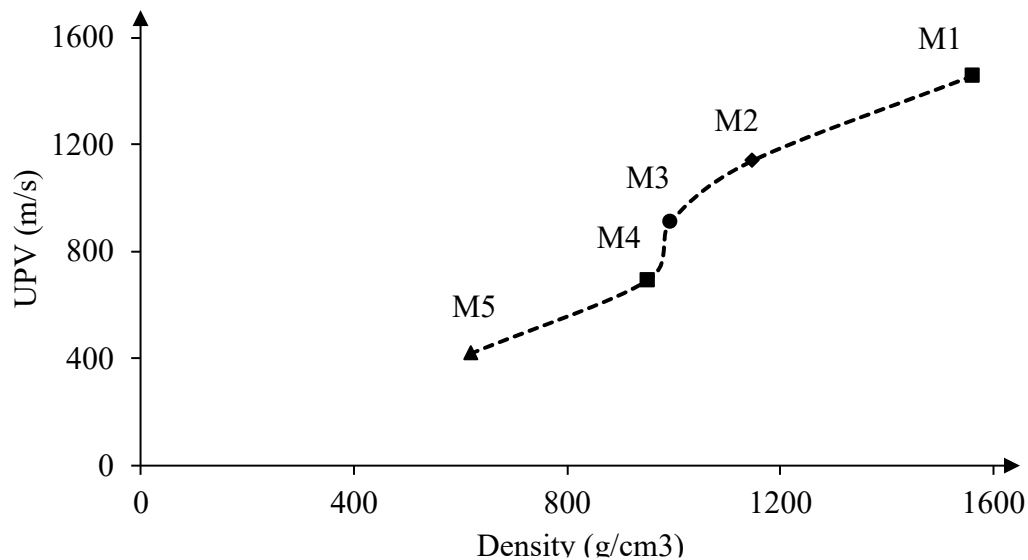


Figure C. 10 Comparison between UPV and density of the CBPBs

C.3.3 Water absorption

The Jerusalem artichoke stalks have a fibrous and cellulosic structure with high pores and voids, increasing their potential to maintain water in their tissue. This fact came to practice in water absorption evaluation on the CBPB of M1 to M5. **Figures C.11** and **C.12** shows the water absorption results. According to the outcomes, in one hour test, the specimens presented high water

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absorption. The amount was the highest in M5 specimens with high content of agro-waste. M5 absorbed water two times M1 in the first 60 minutes. The M1 became saturated in 5 days with 14 g water absorption. The M5 became steady in 7 days of water absorption with 30 g of absorbed water (+52% more than M1). There was a sudden mutation in water absorption in M4 and M5. This fact is due to the low cement content that made the product vulnerable to water accession to the sample. The total water absorption of the M1 to M5 was 9%, 17%, 21%, 33%, and 40% in 7 days. Considering the targeted purpose of the produced CBPB, which is interior facades, the thickness swelling of the specimens should be determined to have a complete evaluation in this respect.

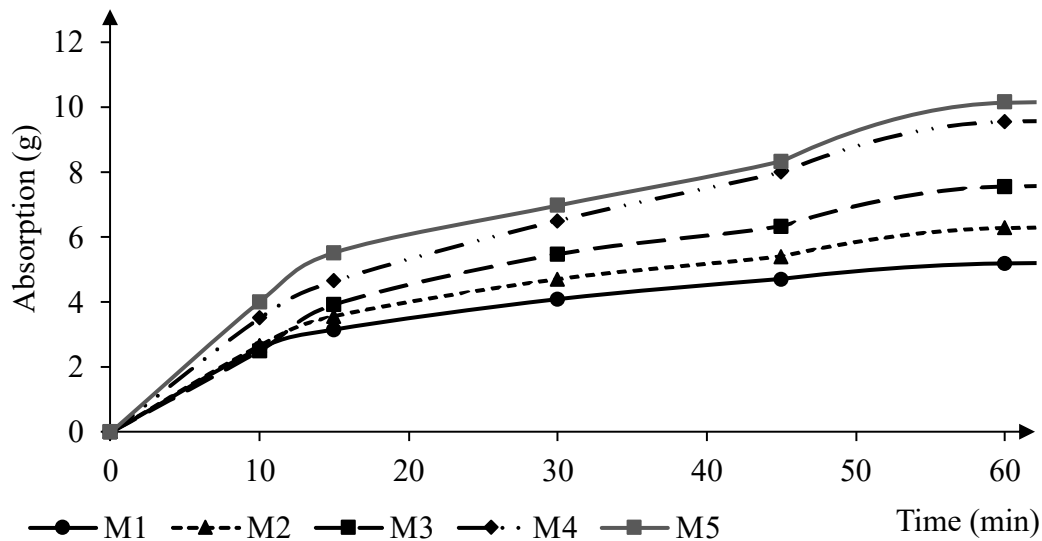


Figure C. 11 Water absorption of CBPB in one hour test

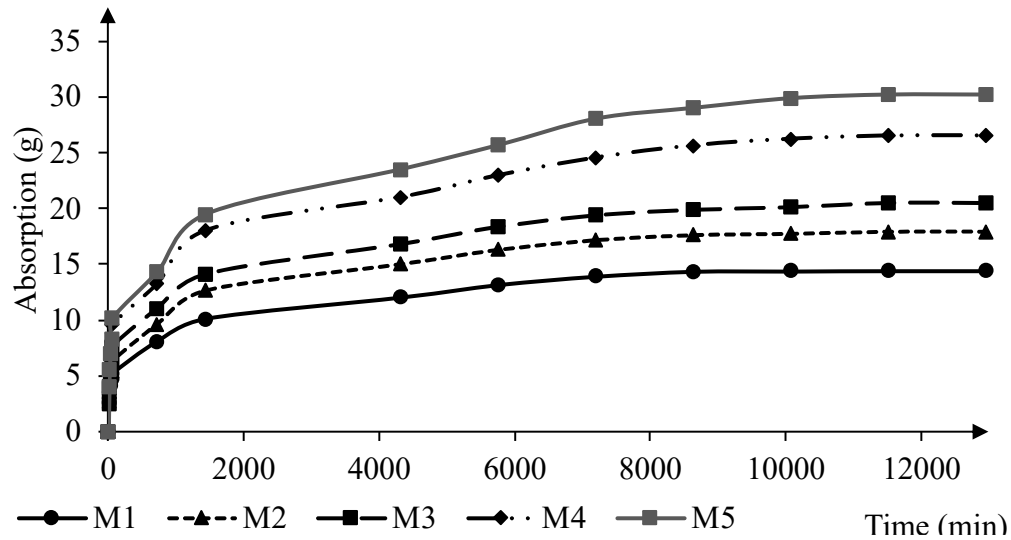


Figure C. 12 Water absorption of CBPB in one week test

C.3.4 Thickness swelling

According to the results, the M1 presented a thickness swelling as low as 3.0% considering its high cement content, which led to lower pores and voids. The M5 specimen presented 4.5 times more thickness swelling compared with M1. As mentioned earlier, the agro-waste's high fibrous and cellulosic structure made M5 absorb more water content. The vegetal structure of the Jerusalem artichoke used in this mixture expanded the product significantly. The results of the thickness swelling can be seen in **Figure C.13**.

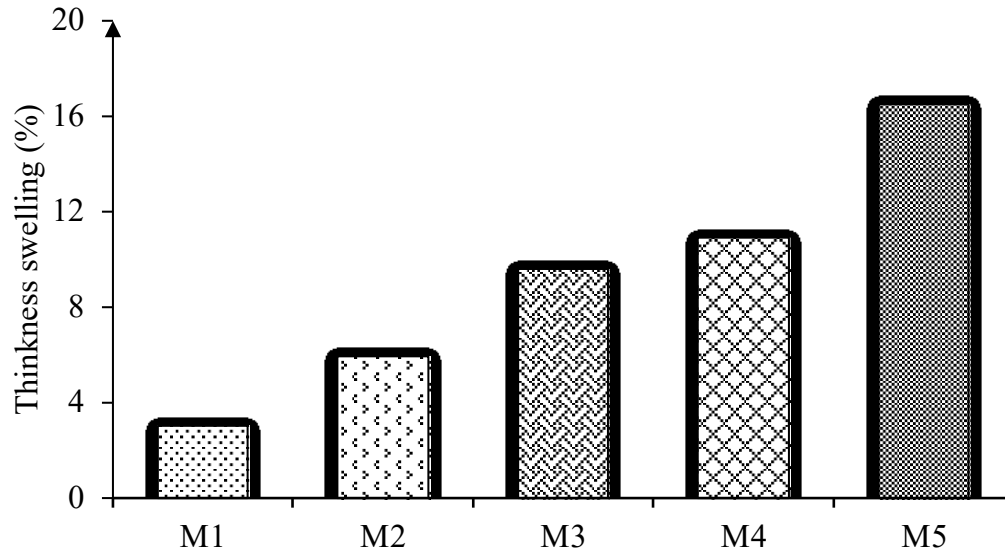


Figure C. 13 Thickness swelling of the CBPB.

C.3.5 Three-point flexural strength

The flexural strength results of the specimens can be observed in **Figure C.14**. The flexural strength of the specimens was correlated to the cement: agro-waste ratio and density. As this ratio increased, the flexural strength improved. The flexural strength of the CBPB is directly related to the density and UPV results. The M1 samples presented the highest flexural strength with 13 N/mm² which was reduced through the other mixtures, respectively. The M3 and M5 presented 32% and 40% reduction compared to M1. M4 and M5 presented similar results, which can be attributed to the high agro-waste entanglement resulting from high compaction in the mixture placing. The sharp strength drop from M1 to M5 has resulted in a considerable reduction of cement content and increasing agro-waste content. As an outcome, the low cement content in the mixtures caused a low bonding effect among the agro-waste particle. Utilization of these agro-wastes as the main material in the CBPB production increased the flexural strength significantly. This increase is particularly due to the high interaction between the Jerusalem stalks and cementitious materials. In the compaction stage, the cement and silica fume were injected inside the cellulosic structure of

the Jerusalem stalks and hydrated within these structures. This fact made a great bonding inside and outside the agro-waste and increased the friction between the particles.

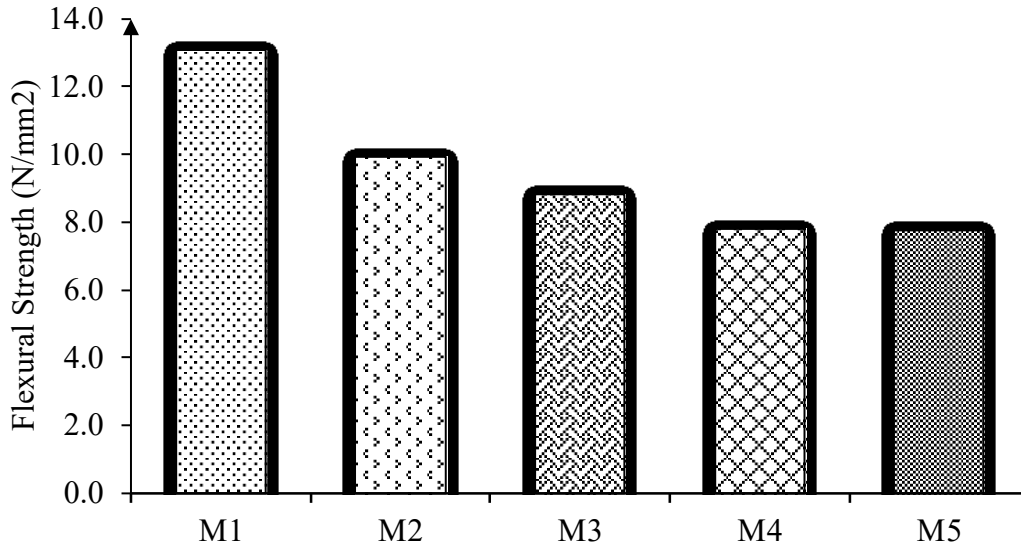


Figure C. 14 Flexural strength of the CBPB

C.3.6 Acoustic insulation

Figures C.15 - C.17 shows theoretical patterns of sound transmission loss of CBPB. Because of resonance, increasing TL with higher frequencies and with a specific dip at a coincidence frequency. A dip in sound transmission loss for M1 was seen, presenting a good noise barrier, even though the general TL values are less. Less agro-waste utilization presented better sound insulation in CBPB. Different sound-insulating responses of the tested specimens concerning the investigating frequency ranges were observed. Better acoustic insulation performance was captured at the high-frequency range. Overall, a slight improvement was seen while using agro-waste in the CBPB. Since the agro-waste used has a cellulosic structure, it can be beneficial in terms of sound insulation. But due to the very thin layer of CBPB made in this experiment, some defects, such as voids, caused some errors in this experiment.

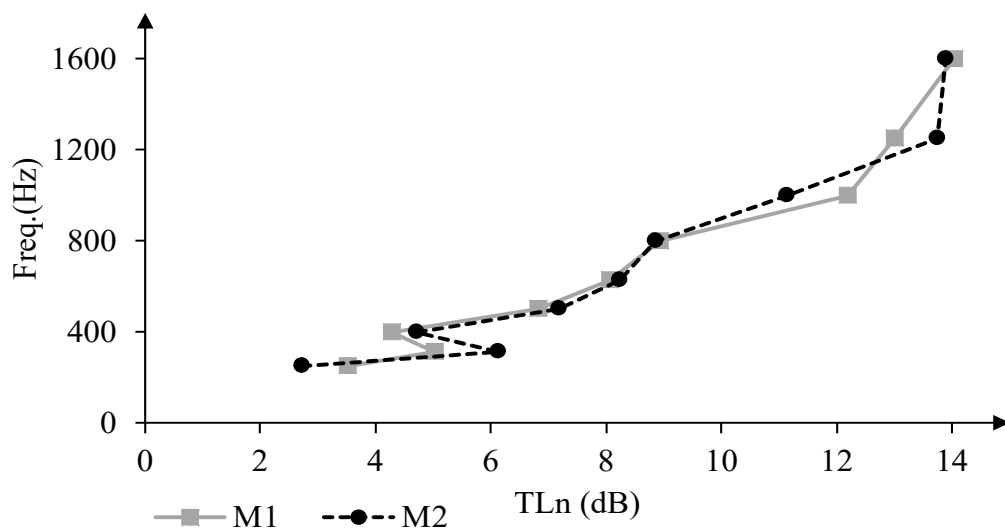


Figure C. 15 The sound transmission loss of CBPB

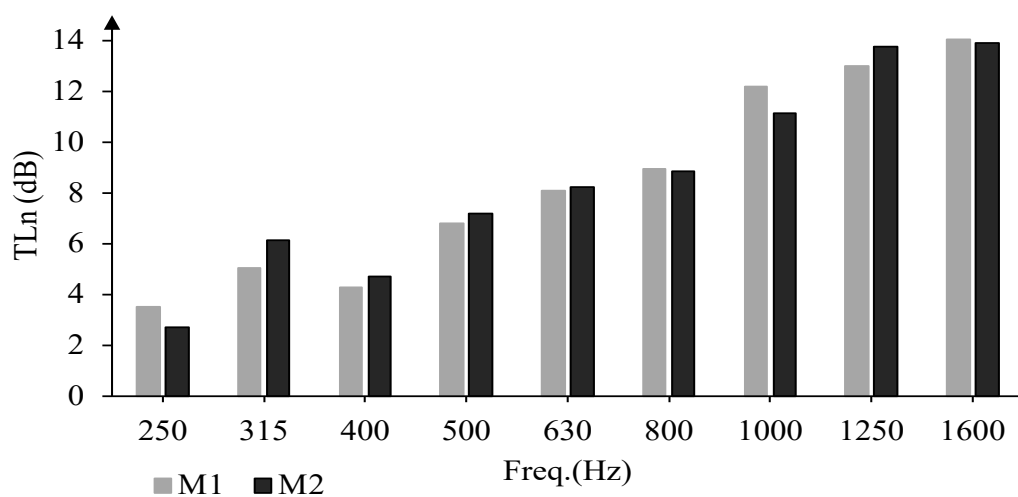


Figure C. 16 The sound transmission loss of CBPB

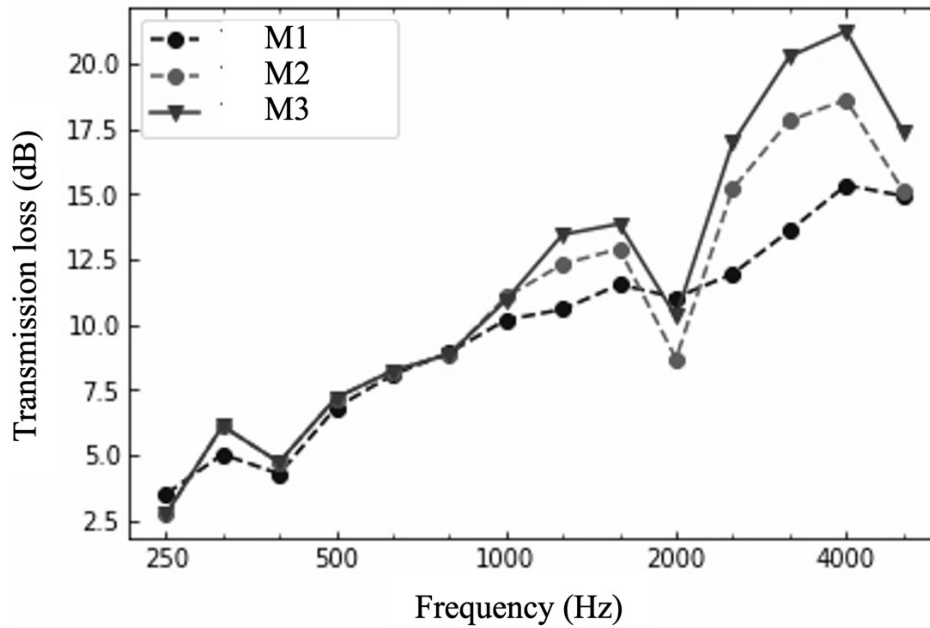


Figure C. 17 The sound transmission loss of CBPB

C.3.7 Fire resistance

In the fire resistance evaluation, the specimens presented a generally low value due to the vegetal structure of the used materials. M1 and M2 presented better performance than other mixtures in the direct content of the fire due to the low number of available agro-wastes covered with cementitious materials. **Figure C.18** presents the weight loss of the CBPB specimens in the direct fire test. In this respect, M1 presented 6% weight loss in 10 minutes of direct fire contact, which was 10 times less than M5 in the same experiment. M3 with the equal cement: agro-waste content ratio presented 18.69% weight loss in the fire resistance test. Based on the visual inspections of the specimens during the test, it was observed that the specimen's surface would burn fast as the agro-waste content increased. The irreversible physical change of the samples and the inflammability of the used agro-waste led to categorizing the CBPB in low fire resistance building envelopes. The product continues burning even long after the fire-ending test.

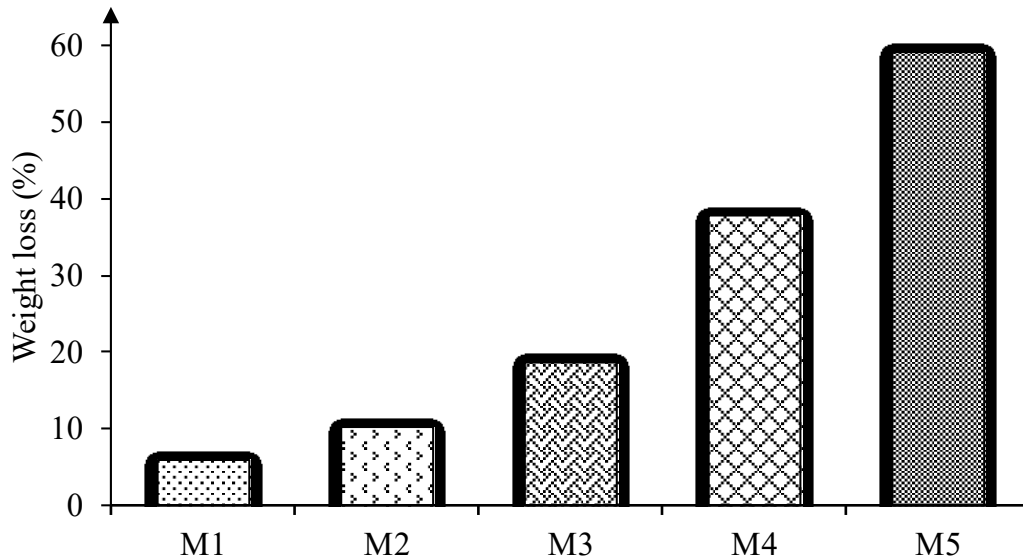


Figure C. 18 Weight loss percentage of CBPB samples in fire test

C.3.8 Thermal insulation

Based on the data gathered from the thermal response test, CBPB specimens showed great thermal insulation behavior. **Figure C.19** illustrates the thermal response of the CBPB specimens in the heat simulation as their insulating effect, which showed a significant temperature difference between the two environments. This difference refers to the temperature variation between the specimen's inner and outer side in the simulation with the environmental chamber. More temperature difference of the sample indicates the better thermal insulation properties. According to the outcome, M5, with the highest agro-waste content, presented the highest thermal insulation improvement. M5 could present four times better thermal performance than M1, although M1 had the highest cement content in terms of better particle binding. This fact can be related to the high number of voids and entrapped air inside the M5 sample due to the excellent cellulosic structure of agro-waste. The outcome of this experiment was contrary to the previous results, such as density, UPV, and flexural strength. The low cement: the agro-waste ratio was beneficial in thermal insulating terms.

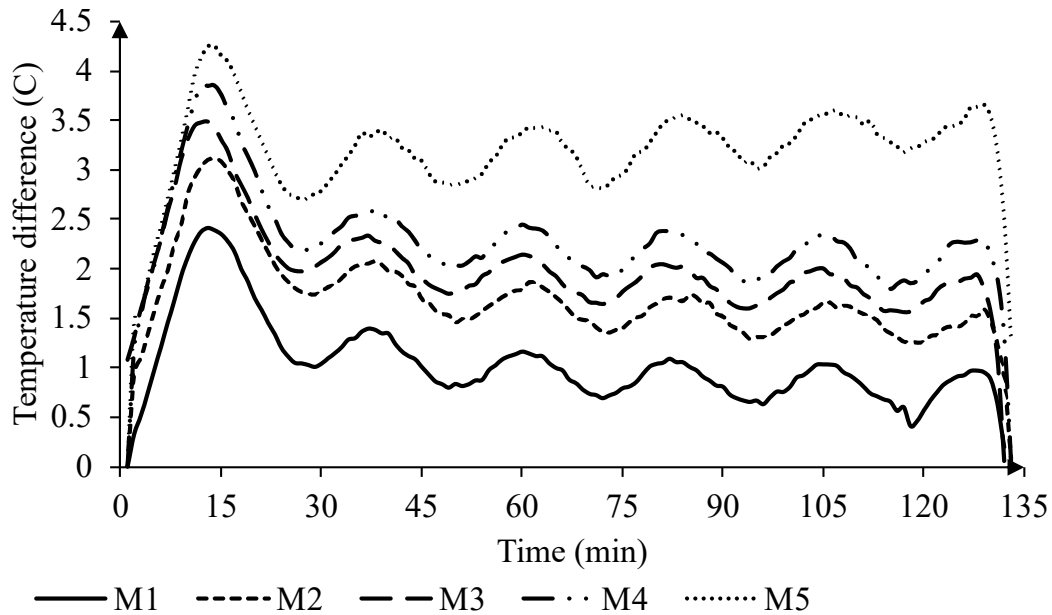


Figure C. 19 The thermal insulation of the CBPB shown as temperature difference of inner and outer surface of the panel in the thermal simulation

The thermal photo of the specimen during this experiment can be seen in **Figure C.20**. The temperature difference between the sample and the environment as the simulation of the outer building envelope and the ambient temperature can be seen in this figure. The temperature variations from low to high is indicated as colors from blue to red respectively. It should be mentioned that as the setup was partially contained aluminum tape to seal the surrounding of the panel, it reflected the heat of the hand during the test. The main target with the heat gun was the center part of the panel.



Figure C. 20 Thermal photo of the CBPB captured with FLIR camera

C.4 Conclusion

Utilizing agro-waste in cementitious materials is a unique method of reducing the related disposal issues and improving some of the properties of cementitious products. This project targeted to evaluate these properties on the cement-bonded particleboard panels and determine the pros and cons of plant waste called Jerusalem artichoke stalks, whose disposal has become a major problem these days. Some of the outcomes of these evaluations are as follows.

- The density of the products made with low cement: agro-waste was reduced significantly due to the lower specific gravity of the used agro-waste.

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- The UPV was reduced with the increase of the agro-waste content due to the increment in the number of voids and air entraps. A direct correlation between the UPV and density was seen.
- Considering the high amount of water absorption and thickness swelling of the mixtures with high content of the agro-waste, it is suggested to be used with a water protection insulator to prevent the expansion and subsidiary damages to the building envelopes.
- The inflammability of the agro-waste caused a major vulnerability to this product. Hence, using fire protection covers on these products is highly recommended. 6% weight loss in M1 was seen.
- The flexural strength of the samples was reduced with the increase of the inclusion of the agro-waste. This strength was maintained steady at the high agro-waste inclusion with mixtures. This fact was due to the high entanglement of the artichoke stalks in each other after the compaction in the casting stage. 60% flexural strength reduction in M5 compared with M1 was seen.
- The panels made in this study can be used in the internal walls to improve the insulation properties of the building. Their durability can be improved by using coatings to be able to expand their application.
- The CBPB presented high thermal insulation corresponding to the amount of agro-waste content use in the mixture. The increase in the agro-waste utilization can lead to an improvement in thermal insulation.
- The panels illustrated a slight improvement in the sound transmission loss. The sound insulation improved with the increase in agro-waste utilization.