ERDC/CRREL TR-23-11

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

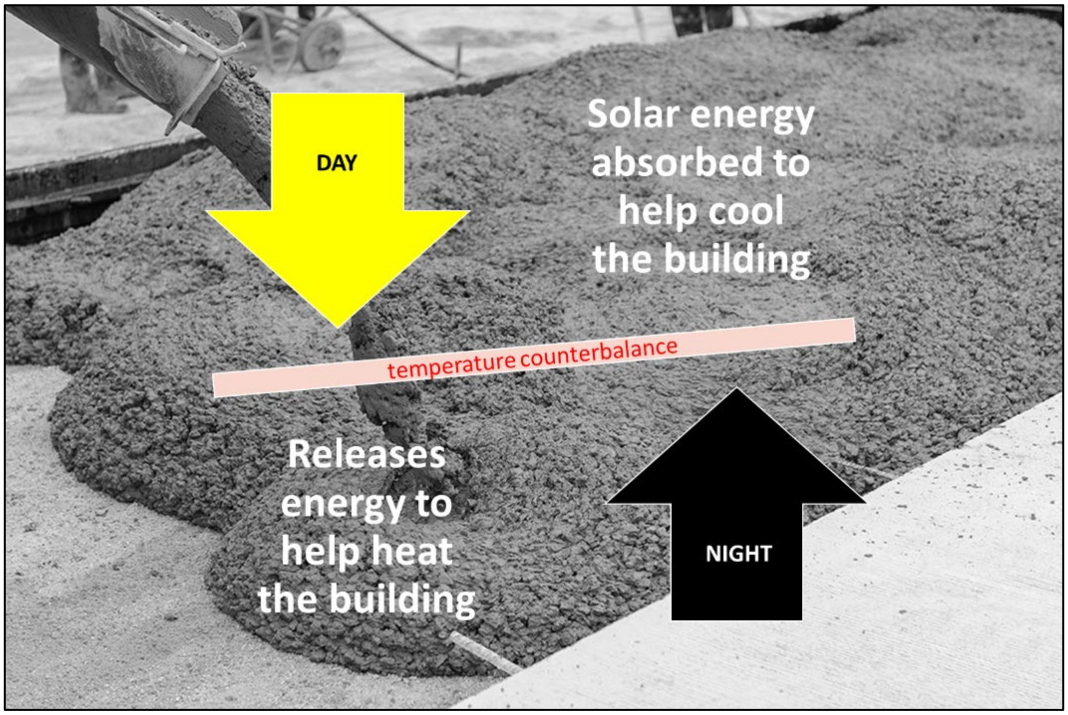
Congressional Program Increase–Cold Weather Energy Research

Enhancing Building Thermal Comfort

A Review of Phase Change Materials in Concrete

Melisa Nallar and Amelia A. Gelina

September 2023



Congressional Program Increase–Cold Weather
Energy Research

ERDC/CRREL TR-23-11
September 2023

Enhancing Building Thermal Comfort

A Review of Phase Change Materials in Concrete

Melisa Nallar and Amelia A. Gelina

US Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Prepared for Headquarters, US Army Corps of Engineers (USACE)
Washington, DC 20314-1000

Under Program Element 0633119A, Project Number B03

Abstract

The DoD accounts for over 1% of the country's total electricity consumption. However, DoD bases heavily rely on vulnerable commercial power grids, susceptible to disruptions from outdated infrastructure, weather-related incidents, and direct attacks. To enhance energy efficiency and resilience, it is imperative to address energy demand in buildings, especially heating and cooling. This study focuses on phase change materials (PCMs) incorporated into concrete to enhance thermal control and reduce energy consumption. Though PCMs have shown promise in heat transfer and energy storage applications, their integration into concrete faces challenges. Concerns include potential reduction in compressive strength, impacts on workability and setting time, effects on density and porosity, durability, and higher cost than traditional concrete. This report examines current obstacles hindering the use of PCMs in concrete and proposes opportunities for extensive research and application. By selecting appropriate PCMs and additives, comparable strength to control samples can be achieved. Moreover, specific techniques for incorporating PCMs into concrete demonstrate greater effectiveness. Embracing PCMs in concrete can significantly contribute to energy-efficient and resilient DoD installations.

Contents

Preface

This study was conducted for Headquarters, US Army Corps of Engineers (USACE), under Program Element 0633119A, Project Number BO3.

The work was performed by the Engineering Resources Branch of the Research and Engineering Division, US Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Melisa Nallar was branch chief; and Dr. John W. Weatherly was acting division chief. The acting deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

Phase change materials (PCMs) are materials that can absorb or release large amounts of energy in the form of heat during phase transitions, such as melting or solidification, without significantly changing their temperature. When incorporated into concrete, PCMs can help regulate the temperature of the concrete, reducing the energy needed to heat or cool buildings and potentially extending the lifespan of the concrete (Memon et al. 2015). PCMs can also be used to prevent thermal cracking which is caused by an excessive temperature difference between the concrete and its surroundings which can extend the concrete's lifespan.

The use of PCMs in concrete is highly relevant to both Army and DoD research and Civil Works missions. In military operations, integrating PCMs into building materials offers the potential to minimize energy consumption in structures and enhance their durability in extreme environments. This application proves particularly advantageous for military bases situated in regions with severe temperatures or limited energy resources. Moreover, within the Civil Works context, incorporating PCMs into concrete presents an opportunity to reduce energy consumption and associated greenhouse gas emissions in buildings—an essential objective for the US Army Corps of Engineers (USACE) and other infrastructure development organizations. Furthermore, the utilization of PCMs in concrete can bolster building resilience against extreme weather events, an increasingly crucial aspect considering the ongoing climate change challenges we face.

The building and construction sector is responsible for a significant portion of energy consumption and greenhouse gas emissions worldwide (Das et al. 2021). Therefore, the development of sustainable and energy-efficient buildings is crucial to reduce the environmental impact of the sector. PCMs can be incorporated into concrete to enhance its thermal properties and reduce energy consumption in buildings. However, the use of PCMs in concrete is still relatively new and requires further investigation to understand the effects on the mechanical and thermal properties of concrete.

In our report, we explore the potential of using PCMs in concrete, both with and without additives, to enhance the energy efficiency and sustainability of buildings. Various additives can be incorporated into PCM-infused concrete to achieve specific objectives.

Additives and their intended purposes are in the following:

- Microencapsulated PCM additives—These additives consist of microcapsules containing PCMs dispersed within the concrete matrix. The purpose of microencapsulation is to protect the PCM from direct contact with moisture and other external factors, ensuring its stability and longevity. These additives enhance the thermal performance of concrete by enabling efficient thermal energy storage and release.
- Fibrous reinforcements—Adding fibrous reinforcements such as cellulose fibers or carbon fibers to PCM-infused concrete can improve its mechanical properties. These reinforcements enhance the concrete's strength, ductility, and resistance to cracking, ensuring the structural integrity of the building.
- Air entraining agents—Air entraining agents are commonly used additives in concrete to create tiny air bubbles within the mixture. When combined with PCM additives, these agents help improve the workability and pumpability of the concrete, making it easier to handle during construction. Additionally, the air bubbles contribute to increased freeze-thaw resistance, reducing the potential for damage in regions with colder climates.
- Superplasticizers—Superplasticizers are chemical additives that enhance the flowability and workability of concrete while reducing water content. By incorporating superplasticizers into PCM-infused concrete, it becomes easier to achieve a uniform distribution of PCM particles throughout the mixture. This, in turn, enhances the thermal performance and energy storage capacity of the concrete.
- Pozzolanic materials—Pozzolanic materials, such as fly ash or silica fume, can be used as additives in PCM-infused concrete. These materials react with calcium hydroxide produced during the hydration process, resulting in additional hydration products. Pozzolanic additives contribute to improved concrete strength, durability, and reduced carbon footprint, as they often contain industrial by-products that would otherwise go to waste.

By utilizing these various additives in PCM-infused concrete, we can optimize its thermal properties, mechanical strength, workability, and overall sustainability. This approach offers tremendous potential to enhance the energy efficiency and resilience of buildings, paving the way for more sustainable construction practices in the future.

1.2 Objectives

The incorporation of PCMs in building materials has garnered worldwide research interest due to concerns over climate change and high energy consumption. Although PCMs have superior thermal performance because of their ability to store thermal energy, they can negatively impact the properties of the concrete such as compressive strength, workability, setting time, density, and durability. Moreover, suitable PCMs for concrete are not readily available in the market, and they are extremely expensive. Therefore, the objective of this research is to examine PCMs and their applications in concrete to understand the challenges and opportunities.

1.3 Approach

This report provides a guidance of PCMs and their characteristics, including their properties, types, and applications. The study also examines the various methods for incorporating PCMs into concrete and their effects on concrete properties. Additionally, the report discusses the potential applications of PCM-concrete in military and civilian contexts, as well as the challenges and future directions for research in this field.

In the report, we review the existing literature on PCMs in concrete, including their benefits, challenges, and the effects of incorporating PCMs on the properties of concrete. Furthermore, we discuss the potential of using PCMs in concrete with or without additives to enhance the energy efficiency and sustainability of buildings.

2 Phase Change Materials (PCMs)

2.1 Properties, Applications, and Importance in Energy Efficiency and Sustainability

2.1.1 Properties of PCMs

PCMs have several properties that make them attractive for thermal energy storage applications. They typically have high specific heat capacities, which means they can store more thermal energy per unit volume or mass than traditional thermal storage materials. They also have melting and solidification temperatures that can be tailored to specific applications, making them suitable for a wide range of thermal energy storage applications. Researchers and professionals have explored various materials and approaches in applications where PCMs are desired (Tyagi et al. 2021; Zhu et al. 2009; Soares et al. 2013). The following are some examples of materials that have been investigated and their results:

- Microencapsulated PCMs—Microencapsulation involves enclosing PCM within microscopic capsules to protect them and facilitate their incorporation into other materials. Researchers have used materials such as polymers (e.g., polyurethane, and poly[melamine-formaldehyde]) and inorganic shells (e.g., silica) to create microcapsules (Wang et al. 2018; Maiti et al. 2023). Studies have shown that incorporating microencapsulated PCMs into building materials, such as concrete or gypsum boards, can enhance the thermal storage capacity and regulate indoor temperature fluctuations effectively.
- Organic PCMs—Organic PCMs, such as paraffins or fatty acids, have been widely investigated for their potential in thermal energy storage applications. They offer high energy storage densities and are capable of transitioning between solid and liquid states within a specific temperature range. Researchers have incorporated organic PCMs into building materials like concrete, wallboards, and plaster, and observed significant improvements in thermal performance and indoor temperature regulation (Karaipekli et al. 2016; Ling et al. 2013). Organic PCMs have a lower thermal conductivity and have a relatively larger fusion range.

- Inorganic PCMs—Inorganic PCMs, such as salt hydrates, have also been studied for their thermal energy storage capabilities. Salt hydrates have high latent heat storage capacities and can store or release thermal energy through the process of hydration or dehydration. Researchers have explored the incorporation of inorganic PCMs into various building materials, including concrete and gypsum boards (Hawes et al. 1993). Results have demonstrated improved thermal regulation, reduced energy consumption, and increased thermal comfort in buildings. However inorganic PCMs can be corrosive to metals and can experience supercooling.
- PCM-impregnated fibers and fabrics—Another approach involves impregnating fibers or fabrics with PCM. Researchers have used materials like polyethylene or polyester fibers to incorporate PCMs and develop PCM-enhanced textiles (Sundarajan et al. 2017; Sarier et al. 2012). These textiles can be used in building components like insulation or curtains to regulate indoor temperatures. Studies have shown that PCM-impregnated fibers and fabrics can effectively absorb and release thermal energy, improving the energy efficiency and thermal comfort of buildings.
- PCM-Enhanced coatings and paints—PCM-enhanced coatings or paints have been explored as a way to incorporate PCMs into existing building surfaces. These coatings contain microencapsulated PCMs dispersed in a paint or coating matrix. By applying these coatings to walls or roofs, the PCM-enhanced surfaces can contribute to improved thermal performance, reducing temperature fluctuations and energy consumption in buildings.

Overall, these studies and applications demonstrate the potential of incorporating various materials, such as microencapsulated PCMs, organic PCMs, inorganic PCMs, PCM-impregnated fibers and fabrics, and PCM-enhanced coatings and paints, in different building components. The results have shown enhanced thermal energy storage, improved temperature regulation, and increased energy efficiency, contributing to the development of more sustainable and comfortable built environments.

2.1.2 Applications of PCMs

PCMs have many potential applications, including building materials, textiles in clothing, solar thermal energy storage, and electronic cooling. PCMs have been integrated into textiles to create PCM-enhanced clothing, particularly for applications such as outdoor sportswear or protective clothing (Sarier et al. 2012). These textiles incorporate PCM-impregnated fibers or fabrics that can absorb and release heat, regulating body temperature and providing enhanced comfort. In solar thermal energy storage, PCMs can be used to store thermal energy collected from solar panels during the day and release it at night, reducing reliance on fossil fuels. In electronic cooling, PCMs can be used to absorb and dissipate heat generated by electronic devices, improving their efficiency and lifespan.

Some of specific successful implementations of PCMs for building applications are shown below.

- The BioPCM system—BioPCM is a commercially available PCM product that has been successfully implemented in buildings for thermal energy storage. It consists of a biodegradable and nontoxic PCM encapsulated in HDPE containers. The containers are installed within building materials such as walls, floors, or ceilings to regulate indoor temperature. The BioPCM system has been used in residential and commercial buildings, resulting in reduced energy consumption, improved thermal comfort, and decreased peak load demands.
- Thermal Energy Storage (TES)–PCM System in Concrete Elements—Researchers have incorporated microencapsulated PCMs into concrete elements, such as walls or floors, to enhance thermal storage capacity (Zhou et al. 2012; Navarro et al. 2016; Tyagi et al. 2011). These PCM-infused concrete elements are successfully implemented in both residential and commercial buildings. The PCM-infused concrete helps in reducing energy consumption by storing excess heat during the day and releasing it during cooler periods, improving indoor temperature regulation and reducing the need for mechanical cooling or heating.
- PCM-Enhanced coatings for roofs—PCM-enhanced coatings or paints have been applied to building roofs to mitigate temperature fluctuations and reduce cooling loads. These coatings contain microencapsulated PCMs dispersed in a paint or coating matrix that can absorb and release heat. Successful implementations of PCM-enhanced coatings on roofs have shown reduced cooling energy requirements and improved indoor comfort in buildings located in hot climates.

- PCM-Enhanced insulation materials—PCMs are also integrated into insulation materials to improve their thermal performance. PCM-enhanced insulation products are designed to store excess heat during the day and release it during cooler periods, reducing temperature fluctuations and lowering energy consumption. Successful implementations of PCM-enhanced insulation have demonstrated improved energy efficiency and reduced heating and cooling loads in buildings.

2.1.3 Importance in Energy Efficiency and Sustainability

The use of PCMs is important for energy efficiency and sustainability because it can help reduce energy consumption and reliance on fossil fuels. By storing thermal energy during periods of low demand and releasing it during periods of high demand, PCMs can help reduce the need for heating and cooling systems to operate at peak capacity, reducing energy consumption and associated greenhouse gas emissions. Additionally, the use of PCMs in building insulation and electronic cooling can help reduce energy consumption and improve the efficiency and lifespan of devices. As technology continues to advance and new PCMs are developed, their potential applications will continue to expand, contributing to a more sustainable future. The following are a few key findings from existing research:

- Building energy consumption—Studies have shown that incorporating PCMs into building materials, such as walls, roofs, or floors, can effectively reduce the energy consumption for heating and cooling (Song et al. 2018; Kuznik et al. 2008). PCMs act as a thermal energy storage medium, absorbing and releasing heat to regulate indoor temperatures. This helps to minimize the need for mechanical heating and cooling systems, leading to energy savings ranging from 10% to 40% in different climatic conditions.
- Peak load reduction—PCM integration can also contribute to peak load reduction in buildings (Halford et al. 2007; Lee et al. 2016). By storing excess heat during the day and releasing it during peak demand periods, PCM-enhanced building components can help to flatten the electricity demand curve. This reduces the strain on the electrical grid and enables more efficient energy utilization.

- Greenhouse gas emissions—The reduced energy consumption achieved through PCM integration has a direct impact on greenhouse gas emissions (Amoatey et al. 2022; Anisur et al. 2013). Several studies have quantified the emissions reduction potential of PCM-enhanced buildings. The exact reduction varies depending on factors such as building type, climate, and PCM configuration. However, research suggests that PCM integration can lead to emissions reductions of up to 30% compared to conventional buildings.
- Life-cycle assessment (LCA)—LCA studies have been conducted to evaluate the overall environmental impact of PCM integration (Kylili et al. 2016; Cabeza et al. 2014). LCAs consider the entire life cycle of PCM-enhanced buildings, including raw material extraction, manufacturing, construction, use phase, and end-of-life. These studies have found that despite the additional energy and emissions associated with PCM production and integration, the overall environmental benefits in terms of energy savings and reduced operational emissions outweigh the impacts of PCM implementation.

It is worth noting that the specific findings may vary depending on factors such as the type of PCM, its concentration, the climate, the building design, and the local energy mix. However, most studies indicate that PCM integration has the potential to significantly reduce energy consumption and emissions, contributing to more sustainable and energy-efficient buildings.

2.2 Usage of PCMs in Concrete

There are various ways to incorporate PCMs in concrete, such as adding them to the mix or embedding them in prefabricated panels. Different types of PCMs can be used depending on the desired thermal behavior and application. For example, paraffin-based PCMs are often used for low-temperature applications, while salt hydrates are preferred for high-temperature applications.

The potential applications of PCMs in concrete are vast. They can be used in various building components, such as walls, roofs, and floors, to improve thermal performance and energy efficiency. Additionally, PCMs can be used in both new construction and retrofit projects, making them a versatile and adaptable solution for sustainable building design. As research and development in this field continues, there is potential for further advancements in the use of PCMs in concrete and other building materials.

2.3 Incorporating PCMs into Concrete and the Effects on the Thermal Properties and Performance of the Resulting Composite Material

One approach for incorporating PCMs into concrete is to mix the PCM with the concrete mixture directly. In this method, the PCM particles are dispersed throughout the concrete matrix. As the temperature rises, the PCM melts and absorbs heat, and as the temperature drops, the PCM solidifies and releases heat. However, the incorporation of PCM directly into the concrete mix may result in poor dispersion of the PCM particles, leading to non-uniform thermal performance of the material.

A second approach is to use prefabricated PCM modules or capsules that are embedded in the concrete. In this method, the PCM is encapsulated in a container or a tube, which is then placed in the concrete during casting. This approach allows for better control over the location and distribution of the PCM, but it may increase the complexity and cost of the construction process.

A third approach is to use PCM-containing admixtures, which are added to the concrete mix to enhance its thermal performance. These admixtures typically contain microencapsulated PCMs that are mixed with the concrete. This method offers better control over the dispersion of PCM particles, and it can also improve the workability of the concrete mixture. However, the effectiveness of the admixture may depend on the type and amount of PCM used, as well as the curing conditions of the concrete.

The incorporation of PCMs into concrete has several benefits, including increased thermal mass, reduced temperature fluctuations, and improved energy efficiency. However, the effectiveness of the PCM in concrete depends on several factors, including the type and amount of PCM used, the method of incorporation, and the environmental conditions. Therefore, the selection of the appropriate PCM and incorporation method is critical to achieving optimal thermal performance in concrete.

2.4 Challenges of PCMs in Concrete

While PCMs offer thermal benefits, their incorporation into concrete can introduce challenges in other aspects.

The addition of PCMs to concrete can lead to a reduction in compressive strength. PCMs may hinder the cement hydration process, affecting the formation of cementitious crystals and resulting in lower strength development. The extent of strength reduction depends on factors such as PCM type, content, and distribution within the concrete matrix.

PCMs can influence the workability and setting time of concrete. The presence of PCMs may increase the viscosity of the concrete mixture, making it less workable and more difficult to handle during construction. Furthermore, PCMs can extend the setting time, as they can interfere with the hydration process and delay the formation of hardened cement paste.

PCMs often have lower densities compared to typical concrete components. Incorporating PCMs into concrete can reduce the overall density of the composite material, potentially affecting its mechanical properties and weight-bearing capacity. Additionally, the introduction of PCMs may alter the pore structure of concrete, potentially impacting its durability and resistance to freeze-thaw cycles or chemical attacks.

The long-term durability of concrete can be affected by the presence of PCMs. The interaction between PCMs and the concrete matrix may influence moisture transport properties, pore structure, and chemical reactions. This can result in potential challenges related to freeze-thaw resistance, alkali-silica reaction, or other forms of degradation. To overcome the stability challenge, researchers and manufacturers are exploring several potential solutions, including developing stable PCMs, encapsulation of PCMs, and using additives such as nanoparticles, to enhance the stability of PCMs and improve their performance in concrete.

The use of PCMs in concrete can also present several challenges related to cost, which must be addressed to ensure their effective and widespread use. The cost of PCMs is generally higher than that of conventional building materials. This is because PCMs are often made of high-quality materials that are designed to withstand high temperatures and repeated phase transitions. Additionally, the cost of manufacturing PCMs is high due to the complex process involved in their production. One potential solution to reduce the cost of PCMs is to develop low-cost alternatives that are still effective in storing and releasing thermal energy. A few examples of cheaper materials that were investigated are salt mixtures, eutectic mixtures, and waste or by-product materials.

Salt mixtures, such as sodium sulfate and potassium sulfate or sodium nitrate and potassium nitrate, were studied as low-cost alternatives to organic PCMs. These salt mixtures undergo phase transitions at specific temperatures, enabling thermal energy storage. While salt mixtures have lower energy storage densities compared to some high-cost PCMs, they can still offer viable performance at a lower price point, particularly in applications with moderate temperature ranges.

Eutectic mixtures are combinations of materials that have a lower melting point compared to their individual components. For example, mixtures of fatty acids or alcohols can form eutectic compositions that exhibit phase change behavior. These eutectic mixtures can provide cost advantages over high-cost organic PCMs while still offering significant thermal energy storage capacities. Eutectic mixtures tend to have a low thermal conductivity and are prone to leakage during phase changes.

Researchers have also explored the use of waste or by-product materials as cost-effective thermal energy storage media (Gutierrez et al. 2016). Examples include using waste cooking oil, waste palm oil, or waste vegetable oils. These materials can be treated or modified to serve as phase change materials, providing a more economical option for thermal energy storage applications.

The production of PCMs may involve energy-intensive processes, chemical synthesis, and the extraction of raw materials. These activities can result in emissions of greenhouse gases and other pollutants, consumption of resources, and potential environmental impacts associated with material extraction.

However, it is worth noting that the environmental benefits of PCMs can still outweigh their production impacts when considering their application in energy-efficient buildings. The reduction in energy consumption achieved through PCM integration can lead to significant long-term energy savings and reduced greenhouse gas emissions during the operational phase of buildings. Life cycle assessment studies, which consider the environmental impacts across all life cycle stages, have generally shown that the benefits of PCM integration outweigh the production impacts.

2.5 Potential solutions

Potential reduction in compressive strength is to

- optimize PCM selection and concentration to minimize the negative impact on compressive strength,
- choose PCMs with suitable melting points and latent heat capacities that align with the desired thermal performance without compromising the strength of the concrete, and
- explore the use of microencapsulation techniques to protect PCMs and maintain concrete strength.

Impacts on workability and setting time will

- utilize superplasticizers or other workability-enhancing admixtures to improve the flow and workability of PCM-infused concrete,
- optimize the dosage and timing of admixture incorporation to achieve the desired balance between workability and PCM integration, and
- adjust concrete mix proportions to compensate for any delays in setting time caused by the presence of PCMs.

Effects on density and porosity can

- incorporate suitable additives or reinforcements to mitigate the impact of PCMs on density and porosity (e.g., the addition of fibers or pozzolanic materials can help maintain or improve the density and strength of the concrete) and
- optimize the mix design to achieve the desired density and minimize any potential increase in porosity caused by PCM integration.

Considerations of long-term durability include

- conducting thorough research and testing to evaluate the long-term durability of PCM-infused concrete,
- exploring the use of additives that enhance durability properties, such as corrosion inhibitors or mineral admixtures like silica fume, and

- optimizing the curing conditions and quality control measures during construction to ensure the long-term performance and durability of the concrete.

Higher cost compared to traditional concrete materials include

- developing cost-effective PCM formulations by exploring alternative PCM types, such as eutectic mixtures or salt hydrates, that offer comparable thermal performance at a lower cost,
- investigating the use of waste or by-product materials as PCM sources to reduce material costs, and
- continually improving production processes and scale up manufacturing to achieve economies of scale and reduce costs.

Limited availability and compatibility with concrete production processes include

- collaborating with PCM manufacturers to expand the availability of PCM options suitable for concrete applications,
- developing partnerships between PCM manufacturers and concrete producers to ensure compatibility and streamline integration processes, and
- investing in research and development efforts to optimize PCM formulations specifically for concrete applications, addressing compatibility challenges.

3 Conclusions and Recommendations

3.1 Conclusions

By optimizing PCM selection, utilizing appropriate additives, considering long-term durability, addressing cost concerns, and enhancing availability and compatibility, PCM-infused concrete can be effectively implemented while maintaining or even improving its overall performance. Studies have reported a reduction in compressive strength ranging from 5% to 30% when incorporating PCMs into concrete, depending on factors such as PCM type, content, and distribution within the matrix. The presence of PCMs can lead to a decrease in workability, with a slump loss of approximately 10% to 30% reported in some cases. Setting time can be extended by 1 to 4 hours because of the interference of PCMs with the cement hydration process. The addition of PCMs can result in a slight reduction in concrete density, typically ranging from 1% to 5%. PCMs may increase the porosity of concrete, resulting in an increase of 1% to 8% compared to conventional concrete. PCM-infused concrete may exhibit some degradation due to factors such as increased permeability and potential chemical interactions with the PCM. The extent of the impact on long-term durability varies based on the specific PCM used, but it can affect properties such as freeze-thaw resistance and resistance to chemical attack. PCMs are generally more expensive than conventional concrete materials on a per-unit basis. The cost of PCMs can range from $5 to $50 per kilogram, depending on factors such as PCM type, purity, and production scale. While there is a growing range of PCMs available on the market, the selection of suitable PCMs specifically designed for concrete applications is still relatively limited. Compatibility issues may arise during the manufacturing and integration of PCMs into concrete, requiring adjustments to mixing procedures or the use of specialized techniques.

It is important to note that the specific quantitative impacts can vary based on the PCM type, concentration, and specific application context. Mitigation strategies, such as optimizing PCM selection, using additives, and employing specific manufacturing techniques, can help minimize these challenges and maximize the benefits of PCM-infused concrete.

3.2 Recommendations

Our recommendations are to include testing PCMs in concrete construction applications based on function, cost, and constructability for the efficacy of PCMs in concrete mixtures, and effect the of PCMs on other concrete properties.

Bibliography

Amoatey, Patrick, Khalifa Al-Jabri, and Saleh Al-Saadi. 2022. “Influence of Phase Change Materials on Thermal Comfort, Greenhouse Gas Emissions, and Potential Indoor Air Quality Issues Across Different Climatic Regions: A Critical Review.” *International Journal of Energy Research* 46 (15): 22386–22420. https://doi.org/10.1002/er.8734.

Anisur, M. R., M. H. Mahfuz, M. A. Kibria, Rahman Saidur, I. H. S. C. Metselaar, and T. M. I. Mahlia. 2013. “Curbing Global Warming with Phase Change Materials for Energy Storage.” *Renewable and Sustainable Energy Reviews* 18: 23–30. https://doi.org/10.1016/j.rser.2012.10.014.

Cabeza, L. F., A. Castell, and G. Pérez. 2014. “Life Cycle Assessment (LCA) of Phase Change Materials (PCMs) Used in Buildings.” In *Eco-Efficient Construction and Building Materials*, 287–310. Sawston, UK: Woodhead Publishing. https://doi.org/10.1533/9780857097729.2.287.

Das, Subodh. 2021. “The Quest for Low Carbon Aluminum: Developing a Sustainability Index.” *Light Metal Age* 79 (1): 34–43. https://static1.squarespace.com/static/5fecb6479b54c51485875e10/t/605b73d83dfe27312d723ebc/1616606169112/LMA_FEB_2021_Quest+for+Low+Carbon+Aluminum-secure.pdf.

Gutierrez, Andrea, Laia Miró, Antoni Gil, Javier Rodríguez-Aseguinolaza, Camila Barreneche, Nicolas Calvet, Xavier Py, et al. 2016. “Advances in the Valorization of Waste and By-Product Materials as Thermal Energy Storage (TES) Materials.” *Renewable and Sustainable Energy Reviews* 59: 763–783. https://doi.org/10.1016/j.rser.2015.12.071.

Halford, Christopher K., and Robert F. Boehm. 2007. “Modeling of Phase Change Material Peak Load Shifting.” *Energy and Buildings* 39 (3): 298–305. https://doi.org/10.1016/j.enbuild.2006.07.005.

Hawes, D. W., D. Feldman, and Dorina Banu. 1993. “Latent Heat Storage in Building Materials.” *Energy and Buildings* 20 (1): 77–86. https://doi.org/10.1016/0378-7788(93)90040-2.

Karaipekli, Ali, and Ahmet Sarı. 2016. “Development and Thermal Performance of Pumice/Organic PCM/Gypsum Composite Plasters for Thermal Energy Storage in Buildings.” *Solar Energy Materials and Solar Cells* 149: 19–28. https://doi.org/10.1016/j.solmat.2015.12.034.

Kuznik, Frédéric, Joseph Virgone, and Jean Noel. 2008. “Optimization of a Phase Change Material Wallboard for Building Use.” *Applied Thermal Engineering* 28 (11-12): 1291–1298. https://doi.org/10.1016/j.applthermaleng.2007.10.012.

Kylili, Angeliki, and Paris A. Fokaides. 2016. “Life Cycle Assessment (LCA) of Phase Change Materials (PCMs) for Building Applications: A Review.” *Journal of Building Engineering*, 6: 133–143. https://doi.org/10.1016/j.jobe.2016.02.008.

Lee, Kyoung Ok, and Mario A. Medina. 2016. "Using Phase Change Materials for Residential Air Conditioning Peak Demand Reduction and Energy Conservation in Coastal and Transitional Climates in the State of California." *Energy and Buildings* 116: 69–77. https://doi.org/10.1016/j.enbuild.2015.12.012.

Ling, Tung-Chai, and Chi-Sun Poon. 2013. "Use of Phase Change Materials for Thermal Energy Storage in Concrete: An Overview." *Construction and Building Materials* 46: 55–62. https://doi.org/10.1016/j.conbuildmat.2013.04.031.

Maiti, Tushar Kanti, Prakhar Dixit, Amit Suhag, Sakchi Bhushan, Aparna Yadav, Namita Talapatra, and Sujay Prabhat Chattopadhyay. 2023. "Advancements of Organic and Inorganic Shell Materials for the Preparation of Microencapsulated Phase Change Materials for Thermal Energy Storage Applications." *RSC Sustainability* 4 (1): 665–697. http://dx.doi.org/10.1039/D2SU00116K.

Memon, Shazim Ali, H. Z. Cui, Hang Zhang, and Feng Xing. 2015. "Utilization of Macro Encapsulated Phase Change Materials for the Development of Thermal Energy Storage and Structural Lightweight Aggregate Concrete." *Applied Energy* 139: 43–55. https://doi.org/10.1016/j.apenergy.2014.11.022.

Minos, Scott. 2022. "Majorly Awesome Military Energy Savers - We Salute You!" *Energy Saver*, May 20, 2022. https://www.energy.gov/energysaver/articles/majorly-awesome-military-energy-savers-we-salute-you.

Navarro, Lidia, Alvaro De Gracia, Dervilla Niall, Albert Castell, Maria Browne, Sarah J. McCormack, Philip Griffiths, and Luisa F. Cabeza. 2016. "Thermal Energy Storage in Building Integrated Thermal Systems: A Review. Part 2. Integration as Passive System." *Renewable Energy*, 851334–1356. https://doi.org/10.1016/j.renene.2015.06.064.

Sarier, Nihal, and Emel Onder. 2012. "Organic Phase Change Materials and Their Textile Applications: An Overview." *Thermochimica Acta* 540: 7–60. https://doi.org/10.1016/j.tca.2012.04.013.

Soares, Nelson, José J. Costa, Adélio Rodrigues Gaspar, and Paulo Santos. 2013. "Review of Passive PCM Latent Heat Thermal Energy Storage Systems Towards Buildings' Energy Efficiency." *Energy and Buildings* 59: 82–103. http://dx.doi.org/10.1016/j.enbuild.2012.12.042.

Song, Mengjie, Fuxin Niu, Ning Mao, Yanxin Hu, and Shiming Deng. 2018. "Review on Building Energy Performance Improvement Using Phase Change Materials." *Energy and Buildings* 158: 776–793. https://doi.org/10.1016/j.enbuild.2017.10.066.

Sundararajan, Swati, Asit B. Samui, and Prashant S. Kulkarni. 2017. "Versatility of Polyethylene Glycol (PEG) in Designing Solid–Solid Phase Change Materials (PCMs) for Thermal Management and Their Application to Innovative Technologies." *Journal of Materials Chemistry* A5 (35): 18379–18396. https://doi.org/10.1039/C7TA04968D.

Tyagi, V. V., K. Chopra, B. Kalidasan, Aditya Chauhan, U. Stritih, Sanjeev Anand, A. K. Pandey, Ahmet Sarı, and Richa Kothari. 2021. “Phase Change Material Based Advance Solar Thermal Energy Storage Systems for Building Heating and Cooling Applications: A Prospective Research Approach.” *Sustainable Energy Technologies and Assessments*, 47. https://doi.org/10.1016/j.seta.2021.101318.

Tyagi, V. V., S. C. Kaushik, S. K. Tyagi, and T. Akiyama. 2011. “Development of Phase Change Materials Based Microencapsulated Technology for Buildings: A Review.” *Renewable and Sustainable Energy Reviews* 15 (2): 1373–1391. https://doi.org/10.1016/j.rser.2010.10.006.

Wang, Xianfeng, Chunhong Li, and Tao Zhao. 2018. “Fabrication and Characterization of Poly (Melamine-Formaldehyde)/Silicon Carbide Hybrid Microencapsulated Phase Change Materials with Enhanced Thermal Conductivity and Light-Heat Performance.” *Solar Energy Materials and Solar Cells* 183: 82–91. https://doi.org/10.1016/j.solmat.2018.03.019.

Zhou, Dan, Chang-Ying Zhao, and Yuan Tian. 2012. “Review on Thermal Energy Storage with Phase Change Materials (PCMs) in Building Applications.” *Applied Energy* 92: 593–605. https://doi.org/10.1016/j.apenergy.2011.08.025.

Zhu, Na, Zhenjun Ma, and Shengwei Wang. 2009. “Dynamic Characteristics and Energy Performance of Buildings Using Phase Change Materials: A Review.” *Energy Conversion and Management* 50 (12): 3169–3181. https://doi.org/10.1016/j.enconman.2009.08.019.

Abbreviations

LCA	Life-cycle assessment
PCM	Phase change material
TES	Thermal energy storage
USACE	US Army Corps of Engineers

REPORT DOCUMENTATION PAGE

1. REPORT DATE September 2023	**2. REPORT TYPE** Final	**3. DATES COVERED** **START DATE** FY22	**END DATE** FY23

4. TITLE AND SUBTITLE
Enhancing Building Thermal Comfort
A Review of Phase Change Materials in Concrete

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT** 0633119A
5d. PROJECT NUMBER BO3	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Melisa Nallar and Amelia A. Gelina

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) 72 Lyme Road Hanover, NH 03755-1290	**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/CRREL TR-23-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, US Army Corps of Engineers	**10. SPONSOR/MONITOR'S ACRONYM(S)** USACE	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The DoD accounts for over 1% of the country's total electricity consumption. However, DoD bases heavily rely on vulnerable commercial power grids, susceptible to disruptions from outdated infrastructure, weather-related incidents, and direct attacks. To enhance energy efficiency and resilience, it is imperative to address energy demand in buildings, especially heating and cooling. This study focuses on phase change materials (PCMs) incorporated into concrete to enhance thermal control and reduce energy consumption. Though PCMs have shown promise in heat transfer and energy storage applications, their integration into concrete faces challenges. Concerns include potential reduction in compressive strength, impacts on workability and setting time, effects on density and porosity, durability, and higher cost than traditional concrete. This report examines current obstacles hindering the use of PCMs in concrete and proposes opportunities for extensive research and application. By selecting appropriate PCMs and additives, comparable strength to control samples can be achieved. Moreover, specific techniques for incorporating PCMs into concrete demonstrate greater effectiveness. Embracing PCMs in concrete can significantly contribute to energy-efficient and resilient DoD installations.

15. SUBJECT TERMS
Building materials; Energy-efficient design; Energy resilience; Energy savings; Heating and cooling; PCM-Concrete; Phase change materials (PCMs); Thermal control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**C. THIS PAGE** Unclassified	SAR	25

19a. NAME OF RESPONSIBLE PERSON Melisa Nallar	**19b. TELEPHONE NUMBER (include area code)** (603) 646-4264

STANDARD FORM 298 (REV. 5/2020)
PREVIOUS EDITION IS OBSOLETE. *Prescribed by ANSI Std. Z39.18*