Journal of
Composites Science

Review

A Review of Recent Improvements, Developments, Effects, and Challenges on Using Phase-Change Materials in Concrete for Thermal Energy Storage and Release

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Citation: Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Bernardo, L.F.A.; Eleiwi, M.A.; Mahood, H.B.; Hashim, A. A Review of Recent Improvements, Developments, Effects, and Challenges on Using Phase-Change Materials in Concrete for Thermal Energy Storage and Release. *J. Compos. Sci.* **2023**, *7*, 352. https://doi.org/10.3390/jcs7090352

Academic Editors: Francesco Tornabene and Thanasis Triantafillou

Received: 28 June 2023
Revised: 28 July 2023
Accepted: 22 August 2023
Published: 25 August 2023

Abstract: Most concrete employs organic phase change materials (PCMs), although there are different types available for more specialised use. Organic PCMs are the material of choice for concrete due to their greater heat of fusion and lower cost in comparison to other PCMs. Phase transition materials are an example of latent heat storage materials (LHSMs) that may store or release thermal energy at certain temperatures. A phase transition occurs when a solid material changes from a solid state to a liquid state and back again when heat is added or removed. It is common knowledge that adding anything to concrete, including PCMs, will affect its performance. The goal of this review is to detail the ways in which PCMs affect certain concrete features. This overview also looks into the current challenges connected with employing PCMs in concrete. The review demonstrates a number of important findings along with the possible benefits that may pave the way for more research and broader applications of PCMs in construction. More importantly, it has been elucidated that the optimum PCM integrated percentage of 40% has doubled the quantity of thermal energy stored and released in concrete. Compared to conventional concrete, the macro-encapsulated PCMs showed thermal dependability, chemical compatibility, and thermal stability due to delaying temperature peaks. Furthermore, the maximum indoor temperature decreases by 1.85 °C and 3.76 °C in the test room due to the addition of 15% and 30% PCM composite, respectively. Last but not least, incorporating microencapsulated PCM has shown a positive effect on preventing freeze-thaw damage to concrete roads.

Keywords: thermal energy storage; phase change materials; concrete; building; review

1. Introduction

When a phase transition occurs (such as from solid to liquid or liquid to gas), phase change materials (PCMs) have the ability to absorb and release significant amounts of thermal energy. These substances are crucial for a number of applications, such as heat management, temperature control, and energy storage. The following elaborates on a few common examples of phase transition materials and their thermal behaviour, stability, physical, and chemical characteristics in relation to their applications [1–3].

First, paraffin wax (organic) has a well-defined melting point and strong thermal stability, which makes the phase shift process predictable and reproducible. It is generally stable across a broad temperature range and during numerous cycles of melting and solidification. Depending on its composition, paraffin wax commonly melts between 46 °C and 68 °C at relatively low temperatures [4]. Due to its non-toxic and non-reactive chemical properties, it can be used for a variety of purposes, including thermal energy storage, food packaging, and building insulation. The use of paraffin wax as a thermal interface medium in electronics and in passive thermal control systems for buildings is quite popular.

Second, salt hydrates (inorganic) are solid substances that have high latent heat values and acute melting points, which in turn results in effective energy storage and release during phase transitions. They are typically stable when kept in a closed container, although they can deteriorate when exposed to air moisture. Salt hydrates have hygroscopic properties, which means they are prone to absorbing moisture [5]. Water absorption must be avoided because it can impair their effectiveness. In applications for air cooling and solar thermal energy storage, salt hydrates are preferred.

Third, eutectic mixtures are made up of two or more organic compounds that have a certain composition that enables them to melt and solidify at consistent temperatures, resulting in a clearly defined phase shift. Eutectic mixes often display high cycle lives and are stable. These materials come in a variety of shapes, including slabs, powders, and pellets, and their melting points can be adjusted to meet the needs of certain applications [6]. Eutectic PCMs are typically non-toxic and non-corrosive, which makes them appropriate for thermal energy storage in electronics and structures such as portable cooling units and temperature-controlled packaging.

Fourth, metallic PCMs (inorganic) frequently exhibit strong thermal conductivity, allowing for quick heat transfer throughout phase change operations. These materials have great thermal stability and can endure repeated cycles of melting and solidification without suffering serious damage [7]. To best suit certain applications, metallic PCMs might take the form of pure metals or metal alloys with specialised melting points. Although they can differ depending on the particular metal or alloy used, chemical qualities are typically stable and non-toxic. Aerospace applications and high-power electronics cooling frequently use metallic PCMs.

Nowadays, the rising energy needs of buildings and the severity of global warming are significant problems. To address these issues, thermal energy storage (TES) building materials are being prepared by incorporating phase change materials (PCMs) into construction materials [8–11]. The ability of PCMs to collect and release thermal energy suggests that they might be used to mitigate the effects of temperature fluctuations on building performance. Thus, PCMs will serve to simultaneously provide thermal comfort and reduce energy consumption in buildings [12–19].

While, in theory, every substance may be called a PCM, not all of them are practical for everyday construction. In fact, PCMs necessitate guaranteeing a minimum of three rudimentary needs to be efficiently incorporated into the components of construction (such as structures and incorporated energy regimes): (1) an elevated melting enthalpy, (2) a suitable temperature of phase change, and (3) a limited volume variation through the phase change. Further features, like safety and heat conductivity, and many methodical as well as economic issues, such as manufacture cost and usage mode, have to be taken into account while selecting the correct PCM [20–25].

Over the last decade, there has been a significant surge in academic interest in PCMs as a result of the widespread availability of products at affordable prices and potential areas of utilisation in building applications [26]. Walls, ceilings, roofs, and windows are all examples of building components or structural members that can integrate PCMs [27–29].

To develop lighter architectural structures, PCM integration often reduces the mass density of the final materials. The usage of latent heat storage materials like PCMs was extensively researched by the technical community due to their significant perspective in relation to the enhanced heat of melting [30–34].

Cement, gypsum, concrete, brick, etc. are all viable options for the construction of interior walls. Many efforts have been undertaken in recent years to develop materials for construction that are capable of storing as well as releasing thermal energy. Although a large-scale study failed to demonstrate efficiency, Stoll et al. [35] claimed that passive thermal treatments using PCMs may significantly lower the risk of bridge freezing. Drissi et al. [36] looked at how microcapsules' decay affected their thermo-physical characteristics. This may happen, for instance, as a result of mechanical stress experienced during the mixing of PCM and concrete. The experiments revealed that the damaged PCMs lost roughly 12% of their fusion heat and 28% of their specific heat capacity. The heat conductivity of porous construction materials like wood [37] and concrete [38] has been the subject of modelling efforts as well, with the goal of developing fractal-based models to make predictions.

Bentz and Turpin [39] conducted a numerical analysis of the thermal reactions of bridge decks at twelve different sites using the CONTEMP computer model and found that the latent heat released by PCM might lower the yearly frequency of freeze-thaw cycles by roughly 30%. According to the research by Sakulich and Bentz [40], incorporating PCMs onto bridge decks might be an effective technique for elongating their useful life. Freeze-thaw management (FCM) using paraffin oil and methyl laurate was studied by Farnam et al. [41]. Using a differential scanning calorimeter (DSC), they compared the efficiency of two PCM impregnation techniques, namely, lightweight aggregate filling and tube filling. Sharshir et al. [42] directed a comprehensive analysis of the most current research on the TES using phase change materials in construction applications. Furthermore, the PCMs for sustainable and energy-efficient construction were the subject of a comprehensive study by Wang et al. [43].

Ling and Poon [44] provided an overview of PCMs, how to include them, and how they affect concrete's characteristics both while it is fresh and after it is hardened. The PCMs' thermal performance in concrete was also discussed, as were their stability and any issues encountered while incorporating them into the material.

From the above, it can be stated that research has not yet been conducted to examine all the important factors involved in utilising PCMs in the concrete industry, such as the categorization of these materials as organic, inorganic, and others. Furthermore, the associated challenges of utilising PCMs in the concrete industry have not yet been critically appraised. Thus, this review comes to discuss in detail the improvements made in PCMs to tackle their challenges and boost thermal energy storage and release in the concrete industry. The intention is to identify some key issues that need further research and draw some important conclusions based on the current body of literature. In-depth discussions of several PCM types and technical, research, and development approaches related to PCMs are provided. The findings of the current review may serve as a roadmap for future studies since they will help researchers better recognise the best techniques that still need to be investigated regarding the use of PCMs in concrete for thermal energy storage and release.

2. Conceptual Challenges of Utilising PCMs in the Concrete Industry

In order for the use of PCMs in the concrete industry to be effective and have optimum efficiency, a number of related difficulties must be resolved. The following are a few of the most pressing obstacles [45–48]:

- It is essential to guarantee PCM compatibility with various concrete mix types. Some PCMs may interact with certain admixtures or additives used in the manufacture of concrete, changing its mechanical properties or posing compatibility problems.
- Over time, some PCMs may experience phase change cycling, which could result in performance loss, leakage, or deterioration. For construction to be sustainable and long-lasting, PCM stability inside the concrete matrix must be guaranteed.

- During phase transitions, some PCMs can experience volume changes, which could cause micro-cracking in the concrete matrix. To prevent damaging impacts on the concrete's structural integrity, these volume variations must be controlled.
- Due to the super-cooling phenomenon, PCMs can experience a lack of solidification, which reduces their ability to store latent heat and causes an insufficient phase change cycle. As a result, ineffective phase change features of PCMs are anticipated.
- The inside environment of concrete is quite alkaline by nature, and in some circumstances, this high alkali causes the PCMs to degrade. For application in concrete, high-alkali PCMs such as polyethylene glycol ought to be excluded.
- When PCM is incorporated into concrete via the immersion method or the direct mixing method, PCM leakage from the concrete may result. During the mechanical mixing of these techniques with other concrete ingredients, some of the PCM that has been encapsulated may be broken. In order to achieve an efficient phase change of the PCMs while keeping the maximum strength of the concrete, extensive analysis must be performed to choose the appropriate way of PCM inclusion into the concrete.
- The rate of heat absorption and release during the phase transition operation is reduced considering PCM's poor thermal conductivity. Particularly when the temperature varies quickly, low thermal conductivity PCM is useless for energy storage. Thus, it is crucial to ensure efficient heat transmission during phase change transitions to increase the capacity for energy storage and release.
- In contrast to conventional concrete materials, PCMs that are acceptable for concrete are not always inexpensive or easily obtainable on the market.
- Buildings that use PCM-enhanced concrete might need to comply with specific regulations and requirements. It is crucial to create standards and guidelines concerning PCM applications because they can promote business acceptance and regulatory acceptability. However, the absence of long-term data on how PCMs affect the longevity of concrete has deterred stakeholders from approving their use.

For PCM-enhanced concrete to be successfully implemented and widely used in the building sector, it will be essential to cope with these challenges through ongoing research, better materials, advanced encapsulation methodologies, design optimisation methods, and the creation of appropriate standards.

3. Studies on Using Organic PCM in Concrete for Thermal Energy Storage

There are two main categories of organic PCMs: paraffin and non-paraffin. Paraffin works well as a passive cooling and energy storage PCM. In contrast, organic PCM's poor thermal conductivity results in a slower rate of heat release/storage capacity. In the next section, a detailed discussion of the relevant related research will be presented. The list of references [49–66] presents the research that is relevant to this review.

For structural-thermal multifunctional applications in high-energy-efficiency building envelopes, D'Alessandro et al. (2018) [49] reported the results of multiphysics thermo-mechanical research into novel concretes that include paraffin-based PCM. In the new composite preparation, shown in Figure 1, both traditional Microencapsulated Phase Change Materials (MPCMs) and the more innovative, ground-breaking Macroencapsulated PCMs with an 18 °C phase transition temperature were utilised. The results corroborated PCM's thermal advantages and showed that incorporating PCM into concrete has decreased mass density by almost twice PCM's weight. While adding PCM generally reduces the average compressive strength, it has less effect on the coefficient of variation, which is a good sign for the structural dependability of the material. Figure 2 shows that the coefficients of variation (or the standard deviation intervals) of the compressive strengths were reduced, and the characteristic compressive strength was even increased if MPCMs and Macroencapsulated PCMs were incorporated with 1% of the total weight.

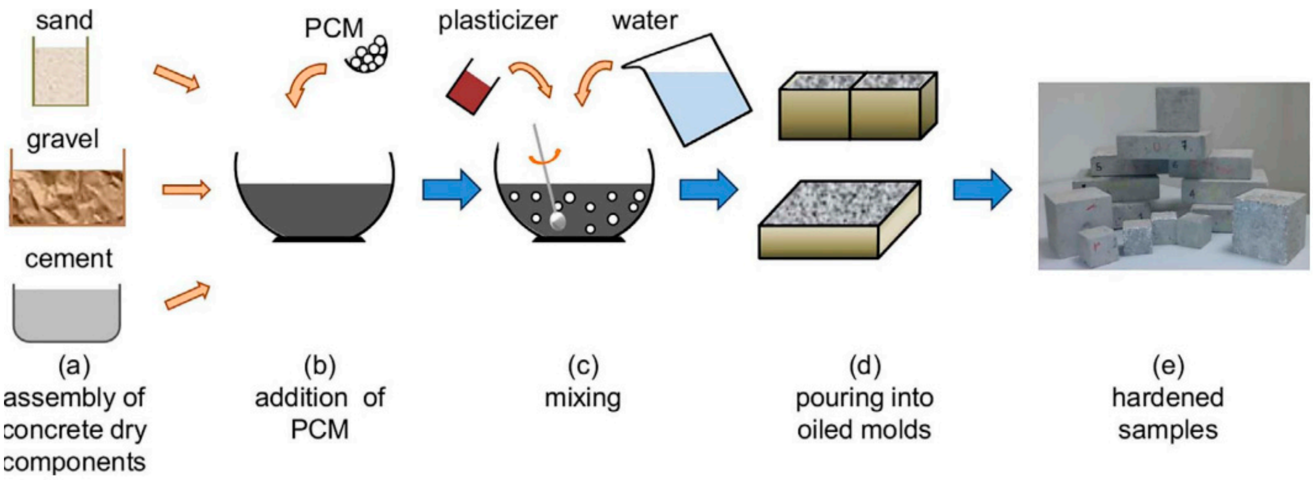


Figure 1. MPCMs and Macroencapsulated PCMs in concrete sample preparation [49].

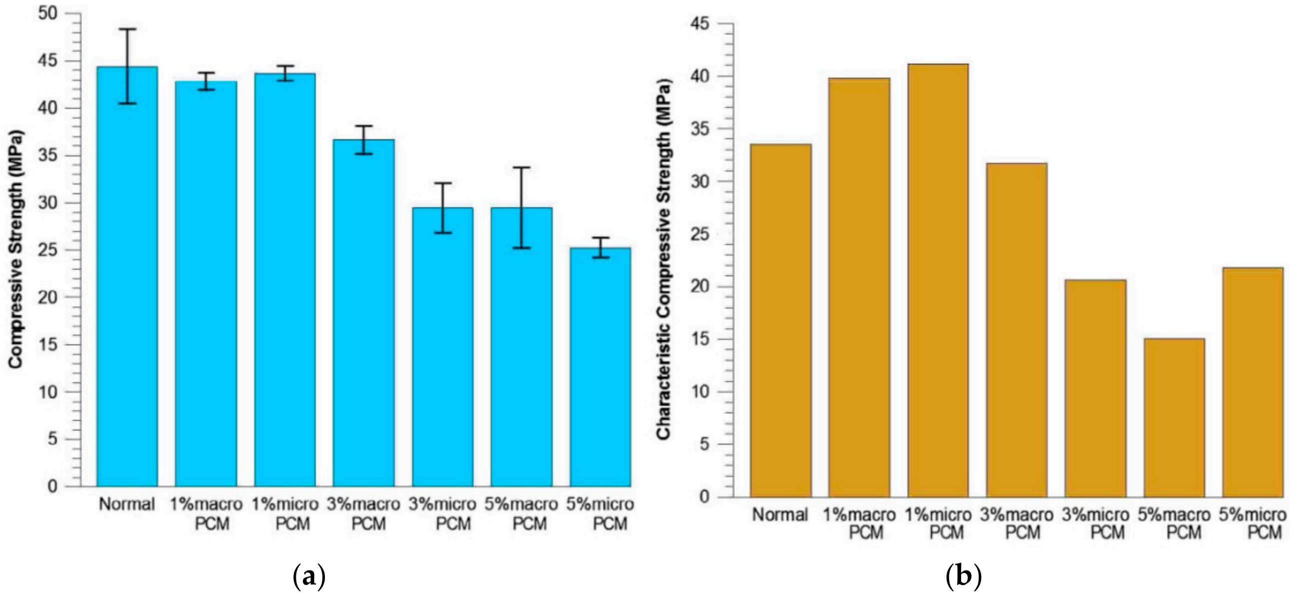


Figure 2. (**a**) The average compressive strength with the standard deviation intervals; and (**b**) The characteristic compressive strength of studied concretes without PCM, with MPCMs, as well as Macroencapsulated PCMs [49].

To fabricate environmentally friendly concrete with an elevated capability of TES, Cao et al. (2018) [50] produced Geo-polymer Concrete (GPC) including Microencapsulated Phase Change Materials (MPCMs). GPC's microstructure and thermal characteristics were studied using many MPCM types to determine the impact of hygroscopicity, latent heat, and microcapsule size. The capacity of the GPC to store energy was observed to increase as MPCM concentration and latent heat did. An energy balance and heat capacity approach were built from the model's basis using the technique of Implicit Finite Differences. A novel equation was effectively used to fit the specific heat capacity of GPC, including MPCM, as a function of temperature, which allowed for the improvement of the model. The thermal performance of the GPC was measured experimentally to validate the computational model. With more MPCM and thicker concrete walls, it takes less energy to keep a room at a comfortable 23 °C. Using a wall of concrete with MPCM (5.2 wt.%) and 75 mm thickness led to a decrease in electricity consumption of about 35%.

To use the GPC as a TES concrete for passive structure uses, Cao et al. (2018) [51] incorporated MPCM into the GPC. The microstructure, thermal characteristics, and compressive strength of GPC made with three different MPCMs were investigated to look at the influence of the MPCM shell's hygroscopic nature, the dimension of the MPCM, and the ratio of PCM core to polymer shell. Improved interface bonding between the matrix of the GPC and the microcapsules led to an increase in the GPC's energy storage capability. The excellent MPCM dispersion in the matrix of GPC was also observed when a polymer shell's hygroscopic nature was combined with an elevated ratio of core to shell and a small dimension of MPCM. GPC with a PS-(DVB/RT27) core (Paraffin Rubitherm®RT27 core with a Polystyrene cross-linked shell with the divinylbenzene) and a PMMA/PCM26 shell (Paraffin mix core with a shell of cross-linked polymethyl methacrylate) can reduce the consumption of power to maintain the indoor temperature (23 °C) to about 18.5 °C. In addition, as can be seen in Figure 3, for GPC with an MF/PCM24 core (paraffin mixture core), the compressive strength can be reduced if MPCM is incorporated into the GPC because it causes a higher number of air pockets.

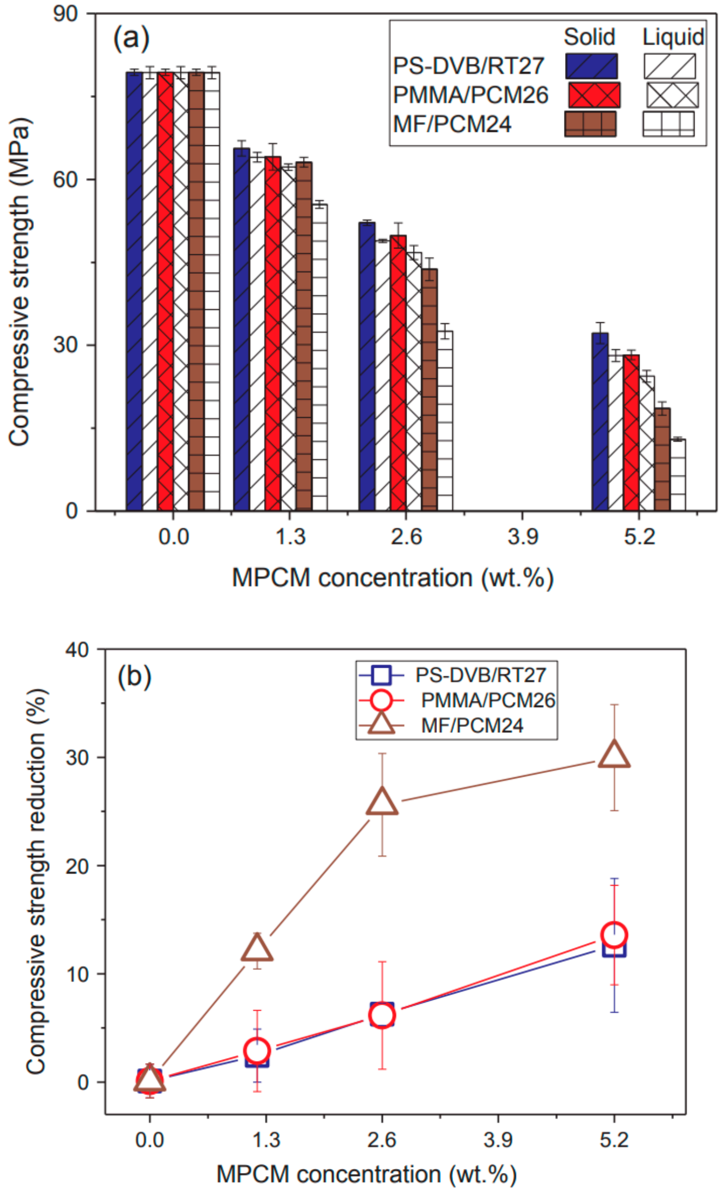
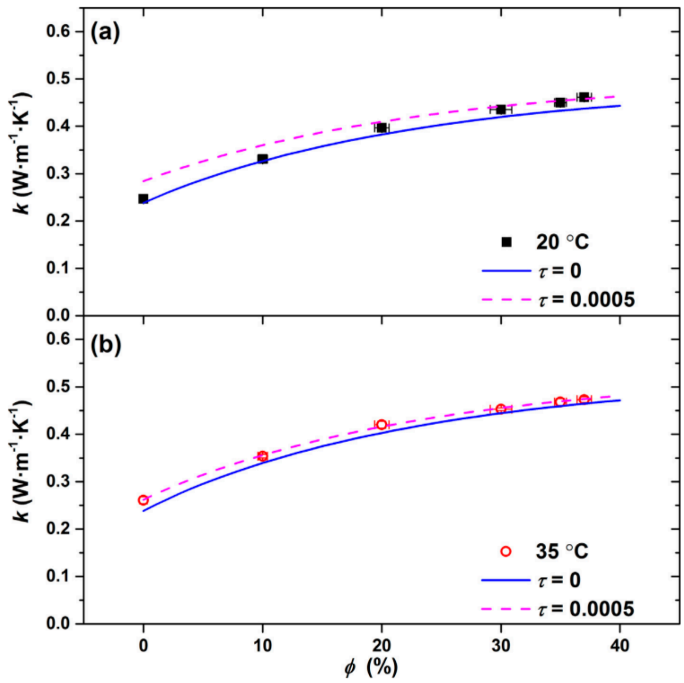


Figure 3. (**a**) Compressive strength of GPC-containing microcapsules below (20 °C) and above (40 °C) PCM's melting range; and (**b**) Compressive strength reduction between solid and liquid states of PCM [51].

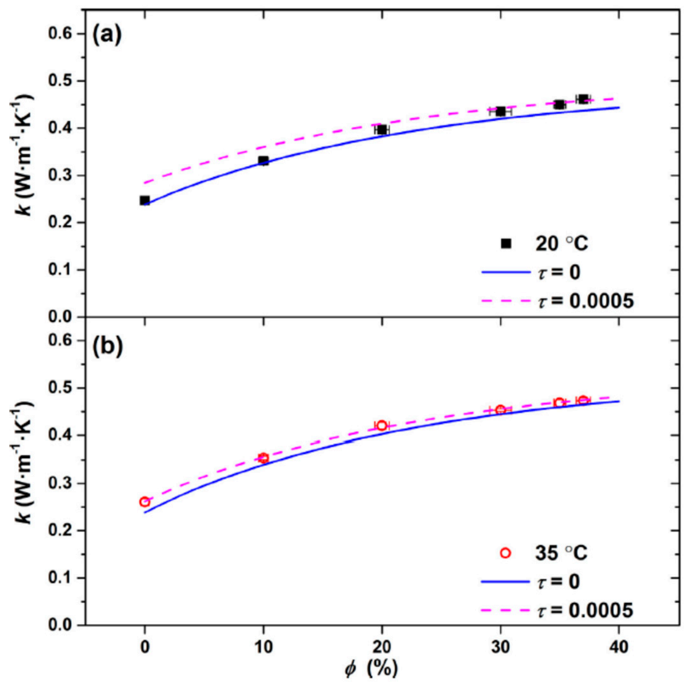
A novel cement composite including n-octadecane (OC)/diatomite shape-stabilised composite PCM was investigated for the first time by Qian and Li (2018) [52]. Due to its hierarchical porosity microstructure and appealing crystallisation character, diatomite coated with carbon nanoparticles and calcined at 800 °C for 3 h (DC) was regarded as the optimal supporting matrix. These suborbicular thermal storage media are uniformly distributed throughout the cement matrix, showing good compatibility and having no discernible impact on the mortar's apparent density or porosity. Furthermore, the cement mortar containing 30% OC/DC could still achieve flexural and compressive strengths of 3.5 MPa and 18.3 MPa, respectively. Notably, the cement's chemical, mechanical, and thermal dependability remained almost unchanged even after being exposed to a 400 melt-freeze cycle when more OC/DC was included in the mix. It has been discovered that the heat-storage cement mortar produced can lessen the fluctuations in interior temperature and has great potential for energy savings and thermal comfort in the built environment.

Experimental research on the thermo-physical properties and heat storage characteristics of an organic PCM for waste heat recovery applications was introduced by Moldgy and Parameshwaran (2018) [53]. Based on experimental data, it can be stated that organic PCM has desirable properties for use in thermal management systems, including a low phase transition temperature of 60.8 °C, a high latent heat capacity of 164.28 kJ/kg, good thermal conductivity, and a high degree of thermal stability. The findings implied that the PCM's thermo-physical characteristics and heat storage potential significantly affect the rate at which energy is exchanged between the PCM and the surrounding fluid throughout the heating and cooling cycles. Heat transfer rates ranged widely from a few watts to over 1 kilowatt, depending on the operating circumstances. Thus, PCM has been deemed a potentially useful and energetic component in waste heat recovery systems.

Autoclave aerated concrete (AAC) and paraffin were combined by Tian et al. (2019) [54] to create innovative composite construction materials with enhanced heat storage capability. The composite specimens were made via the impregnation of 3 AACs with RT28 paraffin, with varying degrees of porosity. Both solid and liquid paraffin were used to determine the paraffin/AAC composites' active thermal conductivity at 20 °C and 35 °C. In addition, the active composites' thermal conductivity was calculated using a fractal model. Figure 4 depicts the correlation between the thermal conductivity and paraffin content, showing that the experimental data, as well as the predictions from the model, reveal that the thermal conductivity rises by increasing the level of paraffin, leading to a decrease in the pure AAC's thermal insulation capability. Additionally, the thermal diffusivity of the AACs, a measure of the composites' thermal storage ability, was derived from their volumetric heat capacities. Since fully impregnating the AAC samples with paraffin would reduce the performance of insulation and raise the paraffin seepage risk during melting, it was proposed that intermediate paraffin contents, around two-thirds of the level of saturation, are suitable for the whole specimens.



(**a**)



(**b**)

Figure 4. Variation of anticipated thermal conductivity as a function of paraffin content for AAC-600-based composite samples at (**a**) 20 °C and (**b**) 35 °C [54].

By analysing the fresh and hardened characteristics of multiple sets of mixes generated with variable cement and free water levels, Zéhil and Assaad (2019) [55] investigated the viability of using cross-linked polyethylene (XLPE) waste materials in concrete. Up to 8% of the cement mass was made up of shredded XLPE of variable sizes. The results of the tests revealed that the workability and air content of the concrete were not significantly changed by the addition of XLPE, but the unit weight was reduced because of the density difference between the aggregates and the XLPE shreds. Water permeability is another property where XLPE additions improve concrete performance. As XLPE content and particle size increase, concrete strength and shrinkage decrease somewhat. Reducing the water-to-cement ratio, however, may help make up for these drawbacks. The residual compressive strengths of XLPE-modified concrete mixes decrease due to the thermal breakdown of XLPE after exposure to heat.

To successfully encapsulate the aggregate holding phase transition components, Afgan et al. (2019) [56] developed a nano-refined epoxy paste employing optimal portions of the fume of nano-silica as well as the powder of graphite. By enhancing workability, decreasing consumption, and strengthening adherence to the formed interfacial bond, the improved recipe provided postponements in the setting to 3–3.5 h and a 15-fold decrease in the coated layer thickness. Thermal stability, chemical compatibility, and thermal dependability were all observed in the macro-encapsulated phase transition materials. With a latent heat storage capacity of 12.6 J/g, the melting and freezing points were calculated to be 17.12 °C and 32.9 °C, respectively. With a compressive strength of over 15 MPa, the thermocrete developed through 100% integration of macro-encapsulated aggregates owed its potential energy savings to its lower internal temperature of 6.4 °C, to the resistance to elevated fluctuations in the temperature while keeping a limited range of 22–30.2 °C, and to the ability to shift loads of energy through the highest times of 15 min.

The thermal characteristics of paraffin-impregnated burned clay aggregate (PIA) concrete were investigated by Pongsopha et al. (2019) [57]. Incorporating paraffin as a PCM carrier into the burned clay aggregates required the application of heat and pressure. The concrete's compressive and flexural strengths, as well as the concrete panels' ability to insulate against heat loss, were evaluated. Tests showed that PIA in traditionally used burned clay aggregate concrete increased its strength and thermal insulation. It was also indicated that the time to peak temperature and peak temperature decrease were both higher for the PIA-treated panels than for the control panel.

The novel Geopolymer-Coated Expanded Clay-phase Change Material (GP-L-PCM) macrocapsules were supplemented to the GPC at 25%, 50%, and 75% volume ratios to create GP-L-PCM slabs, as detailed by Hassan et al. (2019) [58]. The production of LECA slabs required a similar quantity of Lightweight Expanded Clay Aggregates (LECA). A comparison was made between a reference GPC slab's thermal and structural performance and those of LECA and GP-L-PCM slabs. It was found that the maximum surface temperatures on the LECA and GP-L-PCM slabs are lower than those of the GPC slab, indicating a decreased heat transfer (a drop of 5.6 °C and 8.0 °C, respectively). When compared to GPC's U-value of 2 W/m^2 K, the U-values of GP-L-PCM and LECA are 0.9 W/m^2 K and 1.6 W/m^2 K, respectively, after a 75% capsule supplement of GP-L-PCM and LECA. The compressive strength of the LECA and GP-L-PCM slabs was significantly lower than that of the GPC in all cases.

The walls of GPC with MPCM were studied by Cao et al. (2019) [59] for their possible use in buildings subjected to a range of climates. Numerical studies using the finite differences technique and the energy balancing method were used to comprehensively examine the impact of climatic variables (solar radiation and temperature) and the design of MPCM (concentration and shell thickness) upon the construction's energy efficacy. The higher quantities of MPCM addition and denser walls of concrete were found to enhance the construction's energy efficacy. Moreover, the construction's energy efficacy is diminished if the ultimate solar radiation is increased when the external temperature is greater than the inside temperature.

The use of a phase change composite as an aggregate substitute to control the temperature of porous asphalt concrete was studied by Chen et al. (2020) [60]. After settling on the PEG, FT-IR spectroscopy and DSC were used to investigate its chemical and mass stability when exposed to a continuous high temperature, a high-temperature cyclic conditioning, and a low-temperature cyclic conditioning. The fine aggregate in porous asphalt concrete was replaced with a composite material made of SiO_2 as the shell and PEG as the phase transition material. Porous asphalt concrete may benefit from using a PEG/SiO_2 composite with a 70% PEG mass content, as has been found. The optimal replacement amount was found to be 1.4% of the total weight of aggregate, while the suitable particle size range for phase change composites was found to be between 0.6 and 1.18 mm.

Concrete's thermal energy storage capability employing paraffin wax, silicon carbide, and slag aggregate-based PCM was studied by Kim et al. (2020) [61]. The DSC curve demonstrated a phase transition and thermal energy storage in the PCM/SiC-based composite aggregate at 33–34 °C. The thermal heat storage ability of the PCM/SiC-based composite aggregate was shown by the internal temperature test, which revealed that the sample with PCM/SiC-based composite aggregate had a temperature that was about 2–10 °C higher. The surface temperature of the wall on both the inside and outside of the energy storage structure was found to be 42 °C. While the temperature inside the energy storage building was measured at 35 °C. The incorporation of PCM/SiC-based composite aggregate into the concrete led to a 3 °C reduction in both ambient and latent heat.

To create a form-stable composite PCM, Chin et al. (2020) [62] looked into the feasibility of using activated carbon made from oil palm kernel shell (OPKS) as the supporting material for paraffin. There was a mass retention of 31% for paraffin by the activated carbon that was manufactured. Paraffin-OPKS-activated carbon composite had melting and solidifying temperatures of 29.2 °C and 31.6 °C, respectively, and latent heat values of 57.3 J/g and −57.2 J/g, respectively, as determined experimentally. Incorporating paraffin-OPKS-activated carbon composite into concrete allowed the material to attain a compressive strength of up to 25 MPa after 28 days. Figure 5 shows that the thermal conductivity dropped from the A to B mix designs as the percentage of composite PCM rose.

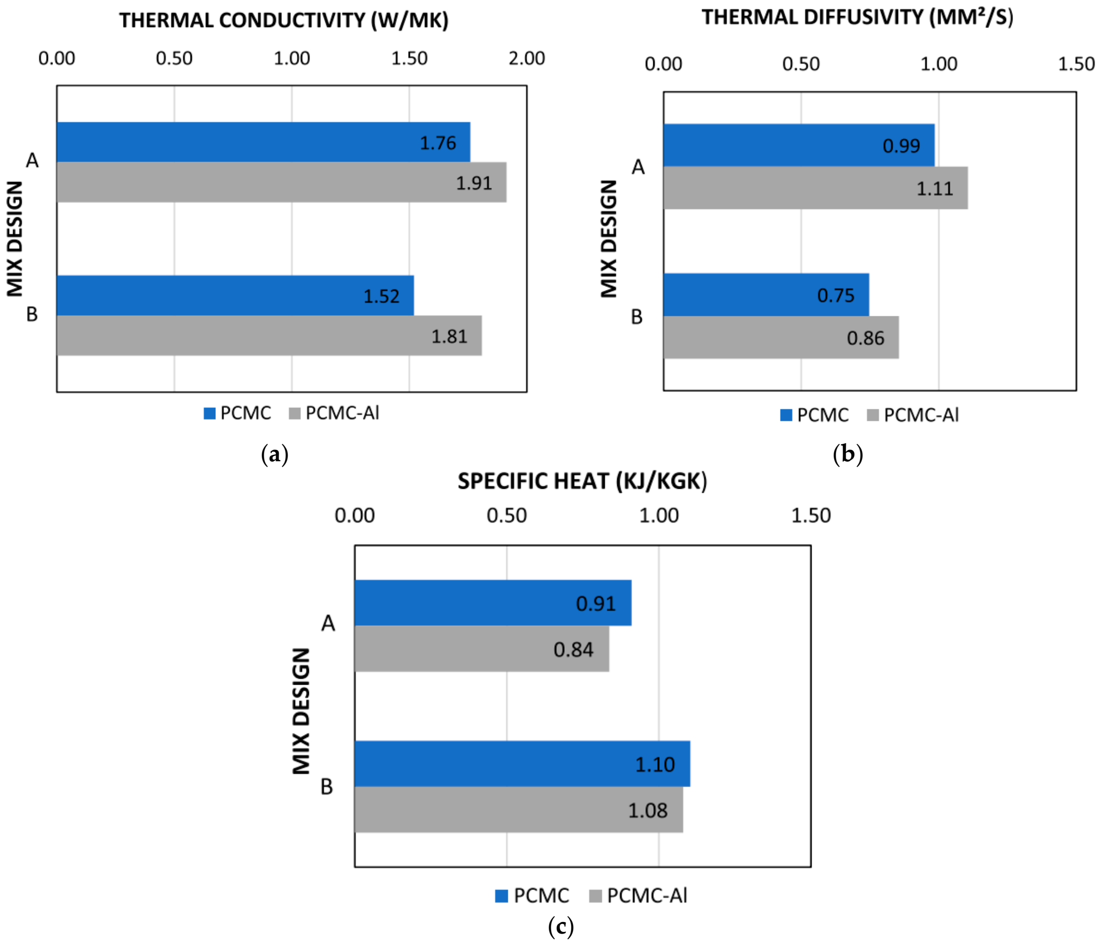


Figure 5. Properties of thermal energy storage concrete with mix designs: (**a**) thermal conductivity, (**b**) thermal diffusivity, and (**c**) specific heat. A= 1963 PCMA (kg/m^3), A= 2096 PCMA-Al (kg/m^3), B = 1844 PCMA (kg/m^3), B= 1959 PCMA-Al (kg/m^3) [62].

Benkaddour et al. (2020) [63] constructed a system consisting of a three-layer composite PCM/concrete wall, with the paraffin wax PCM having a thickness of e_m = 2 cm and the whole wall having a length of L = 20 cm. A solar water heat absorber was physically connected to the outer layer. Both the sun's rays and the surrounding air's convection contribute to the boundary conditions on the glass's exterior. The hourly weather reports of Casablanca, Morocco, were consulted. The advantage of adopting latent heat storage methods in such solar thermal energy systems is attained when the transmitted heat causes the water's temperature to gradually grow, melting PCM within the concrete wall. With further paraffin removal from the wall-mounted solar absorber, the PCM's latent heat storage capacity decreases.

The synthesis and characteristics of PCM composites integrating aerated/foamed geopolymer concrete (GFC) for improving heat storage capacity were described by Ramakrishnan et al. (2021) [64]. The chemical compatibility, mechanical characteristics, and thermal performance of aerated concrete with a form-stable PCM composite based on paraffin/hydrophobic expanded perlite were experimentally tested. Chemical compatibility and thermal stability with GFC have been confirmed by FT-IR and TGA testing of the PCM composite. The GFC incorporating PCM composite has a very high thermal energy storage capacity, as shown by experiments in simulated test rooms. The peak indoor temperature of the test room was lowered by 1.85 °C and 3.76 °C, respectively, when 15% and 30% PCM composite were included, while the thermal storage capability increased by 105% and 181%.

Using lauryl alcohol (LA)-impregnated rice husk ash (RHA) composite polymer cementitious material (PCM), Gencel et al. (2022) [65] created a novel kind of environmentally friendly foam concrete (FC). The leaking issue with LA was solved by using RHA, an agricultural byproduct, as a carrier material. As a result, a leakage-free composite PCM (LFCPCM) was developed, and for the first time, an RHA-based LFCPCM was successfully merged with cementitious FC. The results of tests on the FC-LFCPCM50 wallboard's solar thermoregulation performance showed that it kept the interior about 1.29 °C warmer during the cold weather hours compared to the reference FC (RFC) and about 2.8 °C cooler in the centre of the room during the day in hot weather. FC-LFCPCM50 wallboard may reduce daily energy use by 14.28 kWh. This level of energy conservation is equivalent to avoiding releasing 38 kg of CO_2 from burning coal, 37.7 kg of CO_2 from burning natural gas, and 6.19 kg of CO_2 from using electricity.

Kalombe et al. (2023) [66] used a variety of organic PCMs with good thermodynamic characteristics for heat storage at subfreezing temperatures to construct low-cost thermal energy storage aggregates (TESA). Different mixtures of paraffin wax, soybean oil, and coconut oil were employed as PCMs. The latex coating of TESA served to stop any potential leaks. Paraffin wax and soybean oil together demonstrated the greatest improvement in heat storage and time to freeze. Reducing the use of deicing salts and other winter maintenance while minimising environmental consequences and safety problems may be possible with the use of TESA concrete, which requires no operational administration.

Table 1 presents a summary of research on organic PCMs used in concrete for thermal energy storage.

Table 1. A summary of research on organic PCMs used in concrete for thermal energy storage and release applications.

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
D'Alessandro et al. (2018) [49]	Concrete innovations using paraffin-based polymer cementitious materials.	Experimental	Impact of adding PCM on density and compressive strength.	When PCM is added to concrete, the material's density drops by about double the weight of the PCM itself. While adding PCM reduces average compressive strength, it has less of an effect on the coefficient of variation, which bodes well for the structural dependability of the material.
Cao et al. (2018) [50]	Microencapsulated phase change materials (MPCM) are embedded inside a geopolymer concrete (GPC) matrix.	Numerical and experimental	Effect of MPCM quantity and concrete thickness.	With more MPCM and thicker concrete walls, it takes less energy to keep a room at a comfortable 23 °C. Using a concrete wall with 5.2 wt.% MPCM at 75 mm thickness led to a decrease in electricity consumption of about 35%.
Cao et al. (2018) [51]	From multi-phase phase transition materials to geopolymer concrete.	Experimental	Effect of MPCM size on the bonds between the microcapsules and the GPC matrix.	It was discovered that decreasing the size of the MPCM strengthened the bonds between the matrix of GPC and microcapsules, thereby increasing the capability of GPC for storing energy.
Qian and Li (2018) [52]	Shape-stabilised composite PCM made of n-octadecane (OC) as well as diatomite is introduced into the cement composite.	Experimental	Impact of PCM on thermal conductivity, thermal energy storage capacity, and the cement's chemical, mechanical, and thermal dependability.	Incorporating more OC/DC into cement mixes reduced its thermal conductivity and increased its thermal energy storage capacity, and the cement's chemical, mechanical, and thermal dependability remained mostly unaffected by the 400 melt-freeze cycles.
Moldgy and Parameshwaran (2018) [53]	Applications of organic PCM in waste heat recovery systems.	Experimental	Effect of organic PCM on thermal conductivity, thermal stability, and phase transition.	The organic PCM used has shown strong thermal conductivity, thermal stability, and a phase transition temperature of 60.8 °C, in addition to a high latent heat capacity of 164.28 kJ/kg.
Tian et al. (2019) [54]	Paraffin oil may be used to autoclave aerated concrete (AAC).	Numerical and experimental	Effect of paraffin on the thermal insulating properties.	Adding more paraffin lowers the thermal insulating properties of pure AAC because its thermal conductivity rises as its paraffin concentration rises.
Zéhil and Assaad (2019) [55]	Using XLPE scraps as an additive in cement.	Experimental	Effect of XLPE scraps on residual compressive strengths.	The residual compressive strengths of XLPE-modified concrete mixes decrease due to the thermal breakdown of XLPE after exposure to heat.
Afgan et al. (2019) [56]	To successfully encapsulate the aggregate holding phase transition materials, a nano-refined epoxy paste was created employing the optimal proportions of nano-silica fume and graphite powder.	Experimental	Impact of incorporating macro-encapsulated aggregates.	A compressive strength of over 15 MPa was shown by the thermocrete created by incorporating macro-encapsulated aggregates at a rate of 100%. This material has the potential to reduce energy consumption.
Pongsopha et al. (2019) [57]	Paraffin is blended with charred clay particles.	Experimental	Effect of paraffin blended with the charred clay particles.	Using PIA, regular burned clay aggregate concrete gained strength and thermal insulation.

Table 1. *Cont.*

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Hassan et al. (2019) [58]	The volume ratios of 25%, 50%, and 75% were used to include innovative GP-L-PCM macrocapsules into GPC.	Experimental	Impact of innovative geopolymer-coated expanded clay-phase change material macrocapsules into geopolymer concrete (GPC).	Maximum surface temperatures on LECA and GP-L-PCM slabs are lower than those of GPC slabs by 5.6 °C and 8.0 °C, respectively, indicating decreased heat transfer.
Cao et al. (2019) [59]	The walls were made of GPC and MPCM.	Numerical	Effect of MPCM addition and concrete wall thickness on the energy efficiency of buildings.	The higher quantities of MPCM added to denser walls of concrete were found to enhance the construction's energy efficacy.
Chen et al. (2020) [60]	Mixed with porous asphalt concrete, this composite material comprises a shell of SiO_2 as well as a phase transition material of PEG.	Experimental	Impact of using a shell of SiO_2 and material of PEG.	The optimal replacement amount was found to be 1.4% of the total weight of aggregate, while the suitable particle size range for phase change composites was found to be 0.6–1.18 mm.
Kim et al. (2020) [61]	Paraffin wax, silicon carbide, and slag aggregate form a phase change material (PCM)/SiC-based composite aggregate used in concrete.	Experimental	Incorporation of PCM/SiC-based composite aggregate into the concrete construction.	The incorporation of PCM/SiC-based composite aggregate into the concrete construction led to a 3 °C reduction in both ambient and latent heat.
Chin et al. (2020) [62]	Up to 31% of the paraffin mass was retained by the activated carbon.	Experimental	Impact of adding paraffin-OPKS-activated carbon.	The thermal lag and peak temperature of the composite PCM phase transition are both increased in concrete panels that comprise paraffin-OPKS-activated carbon.
Benkaddour et al. (2020) [63]	Paraffin wax PCM is the intermediate layer of a three-layer composite PCM/concrete wall.	Numerical	Paraffin wax PCM has a latent heat storage capacity.	With further paraffin removal from the wall-mounted solar absorber, the PCM's latent heat storage capacity decreases.
Ramakrishnan et al. (2021) [64]	Composite integrated aerated/foamed geopolymer concrete (GFC) made from phase change materials (PCMs).	Experimental	Effect of composite integrated aerated/foamed geopolymer concrete.	The peak indoor temperature of the test room was lowered by 1.85 °C and 3.76 °C, respectively, when 15% and 30% PCM composite were included, while the thermal storage capability increased by 105% and 181%.
Gencel et al. (2022) [65]	Composite PCM made from rice husk ash (RHA) and lauryl alcohol (LA) is the basis for a novel kind of environmentally friendly foam concrete (FC).	Experimental	Impact of PCM made from rice husk ash (RHA) and lauryl alcohol (LA) on daily energy.	FC-LFCPCM50 wallboard may reduce daily energy use by 14.28 kWh.
Kalombe et al. (2023) [66]	Personalised concoctions of coconut oil, soy oil, and paraffin wax.	Experimental	Impact of coconut oil, soy oil, and paraffin wax on heat storage capacity and the rate at which water freezes.	A PCM consisting of both paraffin wax and soybean oil significantly increases heat storage capacity and reduces the rate at which water freezes.

4. Studies on Using Inorganic PCM in Concrete for Thermal Energy Storage

The salt hydrates (MnH_2O), nitrates, and metals with a high heat of fusion are examples of inorganic PCMs. These materials are well-suited for construction because of their strong thermal conductivity, low moisture absorption rates, and low flammability. The list of references [67–80] provides an overview of the relevant research.

Using a binary Eutectic Hydrate Salt/expanded Graphite Oxide (EHS/EGO) as well as an EHS/Poly (Acrylamide-co-acrylic acid) copolymer (EHS/P(AA-AA)) PCM, Liua et al. (2018) [67] constructed cement-based composites for thermal energy storage. Cement-based composites were made by adding the form-stable hydrate salt PCMs at 5%, 10%, 15%, and 20% by weight of sand. Figure 6 shows that the cement-based composites' mechanical strengths used for thermal energy storage diminish as the concentration of form-stable hydrate salt PCMs increases, but that these materials may still be used as building envelopes. In addition, the results of thermal performance tests show that cement mortars containing form-stable hydrate salt PCMs have beneficial exothermic and endothermic qualities, as well as helping to moderate the maximum temperature within.

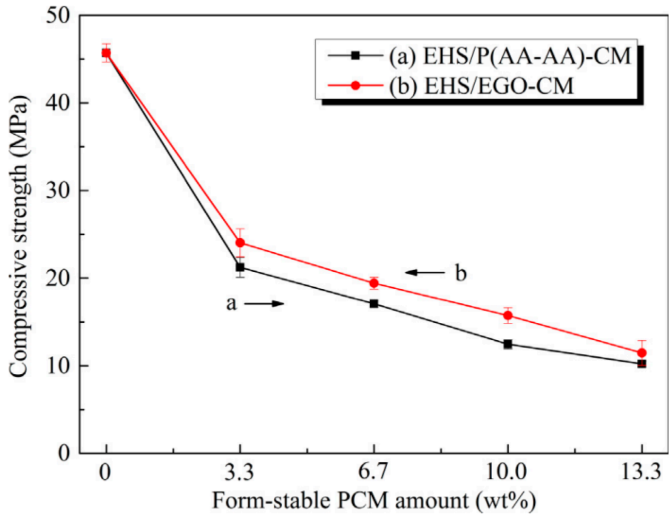


Figure 6. CM, EHS/EGO-CM, and EHS/P(AA-AA)-CM compressive strengths at 28 days with various contents of form-stable hydrate salt PCMs [67].

Using a wooden box fitted with infrared radiators and a cooler, Erlbeck et al. (2018) [68] studied cuboid, cylindrical, plate-shaped, and spherical phase-change packages. Salt hydrate was stored in airtight containers, which were then placed within a regular concrete block. Modifying the PCM's thermal behaviour may be carried out without affecting the PCM's mass by altering the package's design. It was determined that the optimal layout for maximum heat transmission included a large number of thin packages arranged in a certain pattern. Reduced heat transfer into interior spaces was achieved by the use of thermal shading and uniform PCM dispersion inside the concrete blocks.

To improve a building's energy efficiency, Bahrar et al. (2018) [69] zeroed in on the creation of facade features. New textile-reinforced concrete panels with microencapsulated PCMs in a selection of mix patterns are offered as a potential solution. To compare the thermal efficiency of various setups, an experimental characterization was carried out across many scales. As predicted, the addition of PCMs to the textile-reinforced concrete increased its heat storage capacity and thermal inertia. Further, an experimentally validated numerical model was created. As can be seen from the findings, the thermal conductivity of concrete is improved by including PCM particles in its mass, and this improvement is proportional to the amount of PCM used. Additionally, a heating/cooling test was conducted using a guarded hot box to assess the panels' heat storage capacity and highlight their melting and solidifying temperature ranges, respectively. A melting point between 23 °C and 27 °C was determined.

Lightweight concrete with high concentrations of PCM (up to roughly 7.8% by weight of concrete) was studied for its ability to store latent heat and energy by Sukontasukkul et al. in 2019 [70]. Polymer-coated metal (PCM) and Polyethylene Glycol (PEG) were injected into porous lightweight aggregates with weights up to 24%. At volumetric substitution ratios of 0%, 25%, 50%, 75%, and 100%, PCM aggregates were utilised instead of conventional lightweight aggregates. At the age of 28 days, the samples were subjected to a battery of tests, including compression, flexure, thermal conductivity, and phase change material thermal storage. The presence of PCM aggregates has been shown to have varying impacts on the mechanical and thermal characteristics of concrete. As the percentage of PCM aggregate increases, the mechanical characteristics seem to improve. Figure 7 displays the relationship between the PCM aggregate replacement rate and the latent heat.

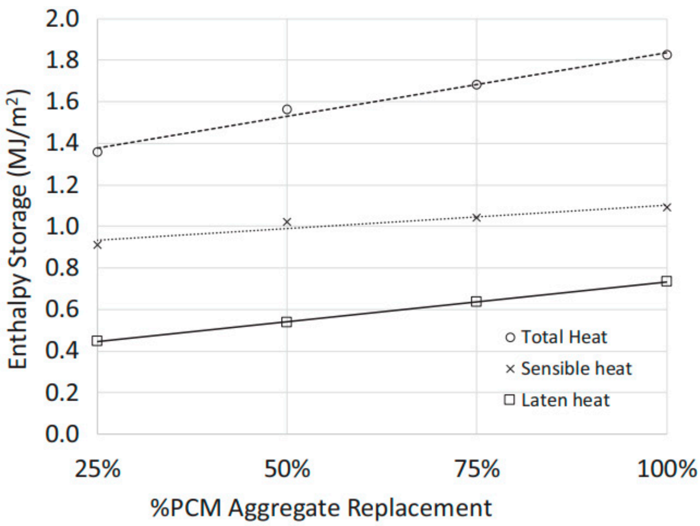


Figure 7. PCM Aggregate Replacement Percentage versus Heat Storage [70].

Using thorough experimental tests and numerical simulations, Vigneshwaran et al. (2019) [71] introduced the idea of creating a low-priced Concrete-based Thermal Energy Storage (CTES) system. An independent test facility was built to investigate the efficiency of high-temperature thermal energy storage systems that work at temperatures of up to 500 °C using air as the heat transfer fluid. The CTES module was constructed using a shell and tube design; 22 air openings were located in the tubes, while the shell was filled with concrete. Heat transmission was shown to be consistent and rapid along all radial planes, as seen by the spatial differences in temperature; however, as one moves down the length of the CTES module, the heat transfer rate decreases progressively owing to a decline in Heat Transmission Fluid (HTF) temperature. The parametric study revealed that a 40 °C shift in input temperature at a constant air velocity of 2 m/s resulted in a 48% and 29% reduction in charging and discharging times, respectively.

Concrete composed of macro-encapsulated inorganic PCM-lightweight aggregate (PCM-LWA) was studied by Mohseni et al. (2020) [72] to investigate whether a dual-layer coating technique might be used to increase leakage and corrosion resistance. The term "thermal energy storage aggregate" (TESA) is used to describe the coated PCM-LWA system. Compressive strength tests revealed a 6–9% decrease in TESA concrete when compared to LWA concrete (Figure 8). The thermal dependability of the TESA system is shown by the fact that TESA concrete did not suffer any strength loss after being exposed to temperature cycles between 15 °C and 40 °C. The analysis of differential scanning calorimeters as well as thermogravimetrics confirmed the PCM's thermal stability and dependability. The results of the thermal performance test validated the viability and utility of TESA for use in concrete buildings. The surface temperature of TESA concrete was found to be lower than that of the control mixture using an infrared thermography camera.

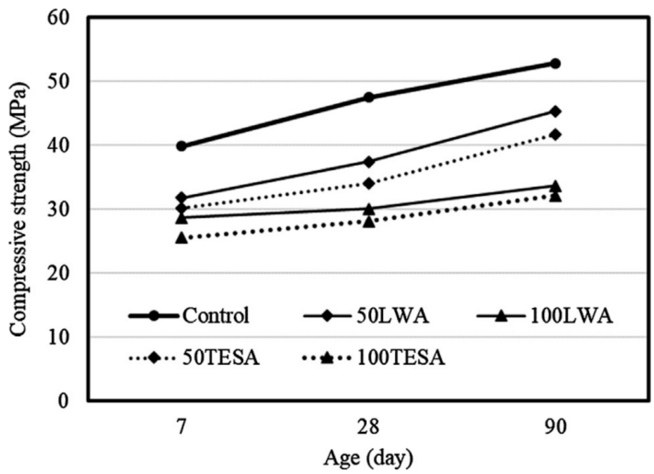


Figure 8. Concrete mixture compressive strength with time [72].

To reduce the summertime temperature peak and boost the financial viability of renewable energy systems, Qu et al. (2020) [73] created a novel phase variation foam concrete having a low thermal conductivity as well as an optimum temperature of phase variation. This research used the adsorption technique, in which paraffin was absorbed by fumed silica to generate composite PCM. This research determined that the composite PCM with a paraffin content of 45 wt.% had the greatest adsorption capacity and setting performance through morphology and liquid leakage tests. The suggested composite PCM inside the concrete was measured using a differential scanning calorimeter (DSC), and it was found to have an appropriate temperature of phase variation (around 41 °C) as well as phase variation latent heat (the procedure of endothermic is 113.3 J/g and the procedure of exothermic is −112 J/g) for preventing excessive heat buildup in the summer.

Using a unique coreshell structured phase change material aggregation (AGGsPCM), Drissi et al. (2020) [74] were able to absorb and store solar energy in the building envelope for space heating and cooling. Testing of AGGsPCM's thermophysical characteristics and thermal performance in a concrete panel was performed in the real world under southern Chinese climatic conditions. The findings show that the PCM leakage can be stopped and the concrete panel's thermal performance can be significantly improved. An increase in thermal comfort and possible savings on power bills resulted from the AGGPCM-concrete panel's ability to lower peak temperatures by 1 °C. Increasing the amount of MPCMs in AGGsPCM or choosing a PCM with a more appropriate phase transition temperature might improve the performance by facilitating a more effective heat storage and release procedure.

The efficacy of a Textile-Reinforced Concrete (TRC) composite adapted via the inclusion of PCMs was the subject of a multi-physics study published by Djamai et al. (2021) [75]. The promise of this composite material comes from the fact that it combines the low weight of TRC with the high heat storage capacity of PCMs. Mechanical and thermal assessments were made on the novel idea of a PCM-TRC slab and the result of reinforcing a PCM-adapted matrix with a textile grid. Slabs made of PCM-TRC retain their ductile and multi-cracking behaviours despite a decline in their mechanical performance. In addition, the effectiveness of the PCM-mortar matrix as well as the PCM-TRC slabs' mechanical performance are affected by the temperature and, by extension, the PCM state (solid or liquid). When comparing the thermal effectiveness of a 10 wt.% PCM-TRC slab (4.5 cm thick) to that of the reference TRC slab, the former yields a 37% saving of energy as well as a 4 °C drop in peak temperature.

Microencapsulated bio-based phase change material (MbP) incorporated into a micro-concrete composite (MbPMC) was created by Parameshwaran et al. (2021) [76] for use in thermal energy storage in buildings. According to the surface morphology data, the newly generated MbP particles were almost spherical and ranged in size from 2 nm to 10 nm. X-ray diffraction research verified the shell material's amorphous structure and the extremely crystalline character of the bio-based PCM chains. The chemical steadiness between the material of the shell and the core (phase change material) is further established by the Fourier transform infrared (FTIR) spectra. The MbP has shown excellent latent heat potential behaviour, with a value of 47.31 J/g, and consistent phase change behaviour. Rebound hammer test results for indicative compressive strengths of MbPMC specimens showed a pattern that was consistent with values determined from the Compressive Testing Machine (CTM) for varying amounts of MbP. These findings show that MbP included in micro-concrete composites (MbPMCs) may store thermal energy as well as provide passive cooling during construction without compromising their structural integrity during testing.

Essid et al. (2022) [77] used experimental and computational methods to study the thermal performance of PCM-concrete wallboards. In the first step, PCM-concrete mixes were made in the lab using varying PCM concentrations. To conduct a thermal examination of the compounds, an original bench test was developed using the transient plane source theory. In addition, a finite-element-based numerical simulation was performed, and its findings were compared favourably to those obtained from actual experimentation. The interior temperatures and thermal fluctuations of the various PCM wallboards were found to be significantly reduced in the numerical simulations. Additionally, the postponement of temperature peaks highlighted the improvement in the energy efficiency of PCM wallboards over conventional concrete, particularly in the case of the bilayer wallboard.

A novel PCM (concrete thermal energy storage system) was introduced by Martelletto et al. (2022) [78]. The PCM-enhanced mixture allows the system to work at temperatures up to 400 °C, making it ideal for use in industrial settings. Diatomite, a porous fossil flour, was utilised to absorb the PCMs, which were a salt combination consisting of 40% KNO_3 and 60% $NaNO_3$. In the lab experiments, the authors compared two different concrete recipes: one containing PCM (5 wt.%) and one without PCM. Joule's effect was used to power the charging phase, and compressed air was sent via the pipe to cool the module. The findings demonstrated that the inclusion of the PCM into the storage system significantly enhanced thermal performance. The greatest PCM integration percentage simulated was 40%, and this resulted in a doubling of the quantity of thermal energy stored and released.

The effectiveness of PCMs as a thermal energy storage medium was evaluated by Tetuko et al. (2023) [79]. The concrete was made using a mix of water, sand, cement, and lightweight aggregate. In the concrete specimens (50 mm × 50 mm × 50 mm), copper tubes of varying shapes and sizes (12.7 mm in diameter and 50 mm in length) were embedded. Copper tubes were arranged in three different patterns: four squares, four crosses, and six rectangles. After that, the authors waited 28 days at room temperature to cure the concrete. The paraffin-magnetite combination, paraffin, and PEG were melted and poured into the copper tubes. Melting point, latent heat, thermal conductivity, and phase transition are only a few of the properties of PCMs that were studied. When compared to pure paraffin (0.32 W/m °C) and PEG (0.28 W/m °C), the addition of magnetite particles in paraffin may increase the thermal conductivity to 0.53 W/m °C. All three of these properties (melting point, latent heat, and thermal conductivity) played a role in how the PCMs behaved throughout their melting phase.

Frahat et al. (2023) [80] employed PCMs in environmentally friendly mortar to increase its thermal energy storage capacity and physico-mechanical characteristics by adding PCMs at concentrations of up to 50% of the cement content in lieu of sand. Twelve samples were made by combining cement and 100% natural sand to make mortars containing 0%, 12.5%, 25%, and 50% PCMs. The authors created eight distinct combinations, varying the percentage of ceramic fine aggregate from 25% to 50%, 75% to 100%, and the percentage of PCMs from 25% to 50%. Compressive strength was found to increase by 37.1% when ceramic was substituted for sand, while temperatures were found to decrease to 9.5 °C, and phase peaks were shifted ahead by 115 min for a mix of 50% PCM + 100CFA (ceramic fine aggregates) compared to 7.0 °C, and phase peaks were shifted ahead by 85 min for a mix of 50% PCM + 100NS (natural sand).

Table 2 presents a summary of research on inorganic PCMs used in concrete for thermal energy storage.

Table 2. A summary of research on inorganic PCMs used in concrete for thermal energy storage and release applications.

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Liua et al. (2018) [67]	Form-stable hydrate salt cement mortar.	Experimental	Impact of incorporation of form-stable hydrate salt PCMs on mechanical strength and energy storage.	Despite a drop in mechanical strength due to the incorporation of form-stable hydrate salt PCMs, thermal energy storage cement-based composites are nevertheless suitable for use in the construction of building envelopes.
Erlbeck et al. (2018) [68]	A wooden box with infrared radiators and a chiller for testing several shapes of phase-change packaging, including cubes, cylinders, plates, and spheres.	Numerical and experimental	Effects of thermal shading and uniform PCM dispersion inside concrete blocks.	Reduced heat transfer into interior spaces is achieved by the use of thermal shading and uniform PCM dispersion inside concrete blocks.
Bahrar et al. (2018) [69]	Microencapsulated phase change materials (PCMs) are being incorporated into new textile-reinforced concrete panels, which come in a wide range of mix patterns.	Numerical and experimental	Microencapsulated phase change materials (PCMs) are being incorporated into new textile reinforced concrete panels.	The thermal conductivity of concrete is decreased when PCM particles are mixed into the concrete's bulk, and this effect is amplified when more and more PCMs are used.
Sukontasukkul et al. (2019) [70]	Phase change material (PCM)-heavy lightweight concrete (up to roughly 7.8% by weight of concrete).	Experimental	Effect of incorporating phase change material (PCM)-heavy, lightweight concrete on the concrete's characteristics.	As the percentage of PCM aggregate rises, the mechanical characteristics seem to improve. It was discovered that when the PCM aggregate replacement rate increased, so did the latent heat.
Vigneshwaran et al. (2019) [71]	An efficient concrete thermal energy storage (CTES) technology.	Numerical and experimental	Effect of HTF temperature on the heat transfer rate.	As the temperature of the Heat Transfer Fluid (HTF) decreases throughout the length of the CTES module, the heat transfer rate decreases correspondingly.
Mohseni et al. (2020) [72]	Macroporous ceramic microsphere-lightweight aggregate (PCM-LWA) concrete.	Experimental	Impact of incorporating macroporous ceramic microsphere-lightweight aggregate (PCM-LWA) concrete.	Compared to the control combination, TESA concrete had a cooler surface temperature.
Qu et al. (2020) [73]	Low-thermal-conductivity phase-change foam concrete with an appropriate phase-change temperature.	Experimental	Impact of composite PCM inside the concrete.	The phase variation temperature (around 41 °C) as well as the phase variation latent heat of the suggested composite PCM inside the concrete are both acceptable.
Drissi et al. (2020) [74]	A new kind of phase change material aggregate (AGGsPCM) with a coreshell structure.	Experimental	Effect of phase change material aggregates (AGGsPCM) with a coreshell structure on phase transition temperature.	Increasing the amount of MPCMs in AGGsPCM or choosing a PCM with a more appropriate phase transition temperature might improve performance by making heat storage and release more efficient.
Djamai et al. (2021) [75]	Phase change material (PCM)-enhanced textile-reinforced concrete (TRC) composite.	Experimental	Effect of phase change material (PCM) on enhanced textile-reinforced concrete (TRC) composite.	The (10 wt%) PCM-TRC slab (with a thickness of 4.5 cm) reduces peak temperatures by 4 °C and reduces energy consumption by 37% compared to the standard TRC slab.

Table 2. *Cont.*

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Parameshwaran et al. (2021) [76]	Micro-concrete composite (MbPMC) with encapsulated bio-based phase transition material (MbP).	Experimental	Impact of MbPMC on storing thermal energy in buildings.	The effectiveness and durability of micro-concrete composites (MbPMC) for storing thermal energy as well as providing passive cooling in constructions.
Essid et al. (2022) [77]	Variations in PCM content in concrete compositions.	Numerical and experimental	Effect of PCM content in concrete compositions.	The delayed peak temperatures highlighted the improved energy efficiency of PCM wallboards over conventional concrete, particularly in the case of the bilayer wallboard.
Martelletto et al. (2022) [78]	PCMs were a binary salt combination of 40% KNO_3 and 60% $NaNO_3$, which was absorbed by the porous fossil flour diatomite.	Numerical and experimental	Impact of integrating PCM on the quantity of thermal energy stored and released.	The greatest PCM integration percentage simulated was 40%, and this resulted in a doubling of the quantity of thermal energy stored and released.
Tetuko et al. (2023) [79]	Lightweight aggregate, cement, sand, and water made up the components of the concrete that was made.	Experimental	Effect of the addition of magnetite particles to paraffin on the thermal conductivity.	When compared to pure paraffin (0.32 W/m °C) and PEG (0.28 W/m °C), the addition of magnetite particles in paraffin may increase the thermal conductivity to 0.53 W/m °C.
Frahat et al. (2023) [80]	PCMs in mortar are eco-friendly.	Experimental	Impact of PCMs on thermal performance.	The use of ceramic in lieu of sand was shown to improve thermal performance.

5. Studies on Using other Types of PMC in Concrete for Thermal Energy Storage

While organic PCMs are the most often used in concrete, there are other varieties available for specific uses. Due to their low cost and high heat of fusion, organic PCMs are the material of choice for concrete. References [81–101] provide an overview of related research (within this inquiry) concerning PCMs that was not included in the preceding sections.

Workability, mechanical strength, early age hydration temperature increase, and thermal characteristics of cement concrete were investigated as a result of the addition of macro-encapsulated PCM aggregate by Wang et al. (2018) [81]. Diatomite- and ceramsite-based thermal energy storage aggregates were created utilising a direct impregnation technique, with PCM provided by a ternary fatty acid eutectic comprising lauric acid, myristic acid, and palmitic acid. A 166.6 J/g latent heat as well as a 31.1 °C melting point were the measured properties of PCM. For ceramsite, the PCM adsorption volume in the pore system reaches 28.1%, while for diatomite, it reaches 89.8% of the total porosity. Slump, compressive strength, and thermal conductivity are all reduced when thermal energy storage aggregates are mixed into new concrete. The compressive strength of concrete with thermal energy storage aggregate at 80% by volume is more than 18 MPa. Early-age hydration temperature increases can be better suppressed by using a diatomite-based thermal energy storage aggregate as opposed to a ceramsite-based one.

The use of PCMs to prevent freeze-thaw damage to concrete roads was studied by Yeon et al. (2018) [82]. Utilising the latent heat of fusion of a paraffin-based organic PCM (N-Tetradecane) with a phase transition temperature of 4.5 °C was used to cut down on the predicted number of freeze-thaw cycles. Preliminary research confirmed that PCM microencapsulated (mPCM) with a melamine-formaldehyde resin was effective at heat storage and release. Even though its effect became minimal with prolonged exposure to an ambient temperature far below the transition temperature. Figure 9 shows that the low transition temperature of PCM has promising potential to extend the service life of concrete pavements against freeze-thaw deterioration. Incorporating PCM that has been microencapsulated was shown to reduce the mortar's compressive and flexural strengths but improve its volume stability at younger ages.

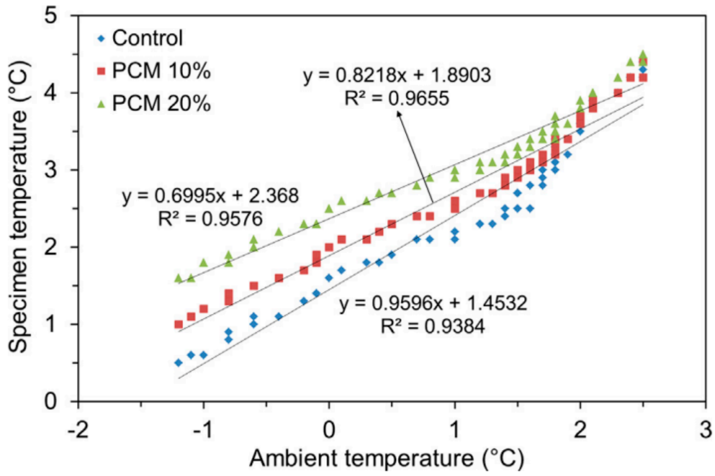


Figure 9. Specimen temperature change rates during phase transition (solidification) [82].

Urgessa et al. (2019) [83] investigated the thermal response of concrete slabs when microencapsulated low-transition temperature PCM additions were made. An inert PCM was encased with a melamine-formaldehyde resin through an emulsification method prior to incorporation into the concrete mixes to avoid the PCM's direct interaction with the hydration products of cement as well as the probable seepage following the liquefaction. Over a 14-month course, including two cold winter terms, the temperatures of three large-scale concrete slabs measuring 500 mm × 500 mm × 150 mm were monitored with and without PCM. A freeze-thaw degradation model suggested that the service life of concrete slabs might be prolonged by as much as 5.2–35.9% when microencapsulated PCM was added. This was due to a reduction in both the extreme drop in temperature as well as the frequency of the freeze-thaw cycle experienced by the slabs through the winter months. For instance, PCM was shown to be most effective when temperatures fluctuated around the transition temperature (mild-cold seasons) and least effective when repeatedly exposed to harsh climatic extremes like freezing winters and scorching summers.

Nayak et al. (2019) [84] used a finite element analysis-based numerical simulation framework to determine how PCMs affect the concrete pavements' thermal response in areas with severe winters. Multiple scales of analysis were performed. The latent heat related to various phase-change materials was effectively incorporated into the framework of the simulation. Furthermore, continuum damage mechanics was used in the numerical simulations of the framework for assessing the impact of PCMs upon freeze-thaw-induced concrete damage. The incorporation of PCMs into concrete was shown in simulations to significantly reduce freeze-thaw-caused damage. The numerical simulation framework was used to efficiently optimise the composition and microstructure of such long-lasting PCM-incorporated concretes for pavements.

To learn more about how to use the heat stored in PCMs to delay or avoid ice formation in concrete, Li et al. (2019) [85] looked into the manufacture and evaluation of mortar-PCM systems. After considering their thermal and physical qualities, desirable PCMs and light-weight aggregates (LWA), which carry the PCMs, were chosen. Multiple LWA formulations, including PCMs, were made and evaluated. The findings showed that when the LWA-PCMs were coated in a certain fashion, chemical processes or significant losses in latent heat were not necessary for the steady absorption of PCMs in LWAs. Exothermic/endothermic processes linked with phase changes of the pore solution and PCM confirmed the PCM's capacity to postpone or prevent ice formation in mortar. Furthermore, as shown in Figure 10, when up to 50% vol. of the LWA was substituted as carriers of PCM, the PCM produced enough heat to prevent ice formation.

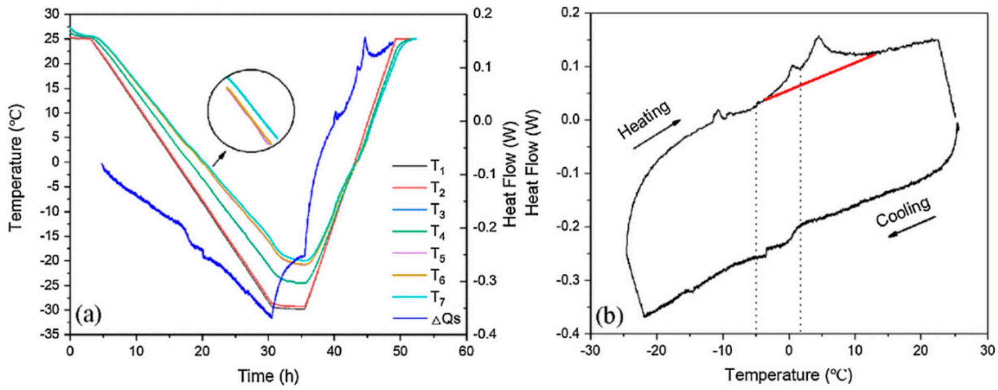


Figure 10. (**a**) Thermal response of 50% NT-A/OP3E/CC mortar and (**b**) Heat flow vs. mortar temperature [85].

To examine how seasonal changes, human comfort temperature, and wall design influence the thermal performance of a single-family home outfitted with multilayer walls containing PCMs in the climate conditions of Oslo (Norway), Cao et al. (2019) [86] created a numerical model depending upon the technique of Finite Differences. Given their relative neglect in the past, the effects of adding insulation and varying the anticipated human comfort temperature were given special consideration. Microencapsulated phase change materials (MPCM) integrated into geopolymer concrete and pure phase change materials (PCM) added to multilayer walls were shown to greatly increase thermal performance. A yearly energy savings of 28–30% was achieved under ideal circumstances (a thick PCM layer and a thin insulating layer). It was discovered that PCM performed better when placed in a more natural setting. The energy needed to run a heating and cooling system may be drastically cut down by increasing the thickness of the insulating layer and decreasing its thermal conductivity. However, this has the unintended consequence of making the MPCM/PCM less efficient at using its high heat storage capacity. The multilayer walls performed best in the summer, with a decrease in energy use of up to 32% at temperatures below the bottom limit of the accepted human comfort zone (18 °C).

Doretti et al. (2019) [87] introduced a straightforward computational model based on lumped capacitance. The algorithm enables a time-dependent thermal and energetic study of concrete TESs. ENEA (the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development) conducted experiments with two distinct concrete mixes while heating and cooling them using mineral oil as the working fluid, and those results were used to verify the accuracy of the new simulation code. Furthermore, two distinct TES thermal efficiencies were provided based on the energetic analysis to assess the charge or discharge development over time. This straightforward model can drastically cut the amount of time spent simulating the TES, and it can be readily integrated into the simulation models of any concentrated solar power plant (CSP) and associated energy conversion plant for rapid assessment of the entire system's efficiency. According to the simulations, efficiency improves with increasing oil mass flow and time, eventually reaching an asymptotic value.

To avoid the leaking of PCMs, Ren et al. (2020) [88] created an encapsulated thermal storage aggregate (ETSA) by mixing PCMs with ceramite or pumice and coating the mixture with a multi-layer shell. The results suggested that ETESC is acceptable to be used as thermal insulation construction covers, even when ETSA totally replaced regular lightweight particles in the concrete. The ETESC's compressive strength was more than 5 MPa. The greatest increase in heat conductivity with ETSA included was 15.8% when compared to the control lightweight aggregate concrete. Furthermore, the electric thermal storage performance findings showed that the maximum temperature decrease of the centre point in the room model supplied with ceramsite-based ETESC reached 4.7 °C, while the maximum temperature reduction of the centre point in the room model provided with pumice-based ETESC reached 8.7 °C.

The properties of lightweight concrete made from highly porous aggregates impregnated with PCM were studied by Uthaichotirat et al. (2020) [89]. Autoclaved aerated concrete (ACC) production byproducts were utilised as aggregates in this application. Paraffinic carbon microspheres (PCM) were employed to impregnate the blocks at a weight of around 65%. By volume, from 25 to 100 percent, the non-PCM aggregates were switched out for PCM aggregates. The results revealed that when the percentage of PCM aggregate was raised, the density, compressive strength, and flexural strength all improved. As PCM aggregates increase, so does their thermal conductivity. However, it was shown that when PCM aggregates were increased, the loss of sound transmission decreased.

An investigational examination of PCMs integrated into layers inside a concrete block for thermal management was given by Arivazhagan et al. (2020) [90]. Two identical concrete building blocks were created, and the thermal performance of each was compared under natural conditions with and without PCM incorporation. Analysis of temperature changes reveals that PCM-integrated concrete blocks are more stable than those without PCM. The results show that the concrete block treated with PCM has a maximum air temperature that is 3 °C lower than the control block. The temperature profile within the concrete block is also smoothed out once PCM is added. Figure 11 depicts the results of an analysis of the impact of varied PCM thickness, which show that a thickness of 12 mm is optimal for the used concrete block space.

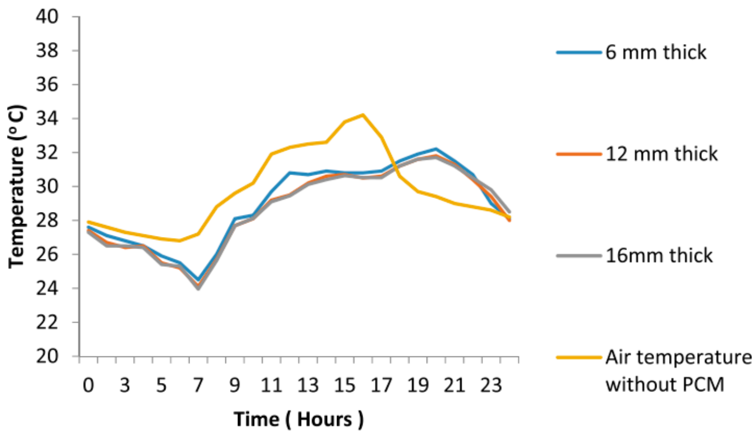


Figure 11. Air temperature variation with PCM thickness [90].

Ram et al. (2020) [91] attempted to use a combination of Ground-Granulated Blast Furnace Slag (GGBS), superplasticizers as cement alternatives, and fly ash. After PCM and nanomaterials were added to the cement concrete at several concentrations (from 0% to 20% in 5% increments), the mixing procedure was improved. A typical compressive strength of 20 MPa was attained by the as-prepared composite, attesting to its structural stability. The experimental findings also show that the PCN-PCM composite has a high latent heat potential, allowing it to store thermal energy and maintain a constant 24 °C in the test room's air.

To protect concrete from premature frost damage at subzero temperatures, Liu et al. (2020) [92] created a new synthetic heat storage form, including PCMs (SHSPCM). Continuous curing of concrete was achieved by using electric heating connected inside to provide PCMs with enough heat energy to cause a phase shift repeatedly. PCMs have a large amount of latent heat, which was put to good use. Concrete cured using this innovative heat storage technology obtained good mechanical strength and hastened hydration at a temperature of −15 °C, according to the findings of curing experiments. Heat transmission and temperature change over a single curing session were simulated using a numerical model.

When preparing the aggregate of PCM-CLSC as well as the blocks of PCM-concrete thermal storage with various weight percentages (0%, 2%, 4%, and 6%) of PCM, Shen et al. (2021) [93] used Clastic Light Shale Ceramsite (CLSC) to absorb paraffin, which increased the PCM-concrete's heat storage capability, solved the PCM leakage problem, and decreased the heat storage cost. The research showed how an active thermal storage system's efficiency changed depending on the PCM weight percentage and the HTF features. The experimental findings demonstrated the high absorbency and compatibility of the PCM-CLSC aggregate. The average specific heat capacity of PCM-concrete thermal storage blocks rose via 12.54% (2 wt.% PCM), 31.60% (4 wt.% PCM), and 41.23% (6 wt.% PCM), whereas the compressive strength and thermal conductivity decreased with the weight percent increase of PCM.

Activated silica fume (ASF) was first used as a tumble machine surface coating by Pongsopha et al. (2021) [94]. The experimental series examined the effects of heat and cold cycling on the characteristics of PCMA and ASF-coated PCMA, as well as the effects of mixing PCMA and ASF-coated PCMA with rubberized concrete (RC). After being put through 100 heat/cool cycles, the ASF coating was shown to significantly decrease PCM leakage by about 5.4 times. Mixing RC with ASF-PCMA somewhat improved its mechanical qualities compared to mixing it with PCMA alone. Depending on the condition of the PCM, the ASF coating may have either a positive or negative influence on the thermal conductivity (K) of RC. Mixing RC with ASF-PCMA reduced the loss in latent heat storage capacity compared to mixing with PCMA.

The thermal performance of concrete bricks containing PCM was investigated experimentally by Al-Yasiri and Szabó (2021) [95]. The thermal performance of four concrete bricks (three with macroencapsulated PCM and one without PCM, representing the reference) was evaluated in a hot environment. At a constant PCM concentration, the research analysed how increasing the heat transfer area of the PCM encapsulation affected the thermal performance of the brick. There were three distinct configurations of PCM capsules in PCM bricks: (1) one large capsule (Brick-B, $4 \times 4 \times 10$ cm^3), (2) two capsules (Brick-C, $4 \times 4 \times 5$ cm^3), and (3) five capsules (Brick-D, $4 \times 4 \times 2$ cm^3). The highest PTR (peak temperature reduction), HTRc (conductive heat transfer reduction), and TD (time delay) were achieved by Brick-D, relative to the reference brick, at maximum outside temperatures of 156.5%, −61%, and −133%, respectively.

Using a hollow steel ball (HSB), Cui et al. (2022) [96] obtained PCM-HSB aggregates by macro-encapsulating the PCM. In addition, steel fibres were inserted into the PCM-HSBs to boost the thermal and mechanical qualities of the material. The mechanical and thermal qualities of the steel fibre-strengthened PCM-HSB concrete were studied in relation to the volume content of the steel fibre (0.35, 0.7, and 1.05 vol.%) as well as the HSB thickness (0.3 and 1 mm). The results of the tests showed that the steel fibre content and HSB thickness greatly influenced the PCM-HSB concrete's thermal conductivity and compressive strength. Owing to the dispersed steel fibres' bridge function in the matrix of concrete, the 0.35% steel fibre inclusion increased the PCM-HSB concrete's heat conductivity by 71%. By increasing concrete's heat capacity and bearing capacity, the suggested fibre-reinforced PCM-HSB may secure energy piles' future uses.

To make use of the benefits of both materials, Wu et al. (2022) [97] suggested integrating PCM and a bio-based hygroscopic material (hemp concrete) into a unique multilayer building envelope. To investigate how PCM and its placement affect the hygrothermal behaviour and energy performance of the integrated envelope, four envelope designs were tested experimentally. The findings showed that PCM is useful for postponing the peak temperature of the envelope, decreasing energy consumption, and decreasing the amplitude of temperature and relative humidity (T/RH) fluctuations. It was suggested that the PCM be placed in the centre of the envelope and maintained in a semi-molten condition. The peak temperature was delayed by 70.4%, the T/RH amplitude was lowered by 50%/60%, and energy consumption was reduced by 15.3% compared to the setup without PCM.

In 2022, Sawadogo et al. [98] created biosourced PCM hemp concrete and characterised its properties. Vacuum-impregnated CA was included in 53% of the hemp shaves. PCM hemp concrete was made from a shape-stabilised hemp shives/CA composite. DSC and SEM were utilised for characterising the materials' morphology as well as thermophysical features at each step (from the neat CA to the hemp concrete PCMs) and to compare them to the reference state (hemp concrete without PCMs). The results revealed that the PCM hemp concrete had excellent thermo-regulating ability, with an ultimate period shift of 30 min and a discrepancy in temperature of roughly 4.6 °C between the reference and PCM hemp concrete.

Dora et al. (2023) [99] found that adding PCM to the foam concrete mix enhanced the building envelope's thermal performance. Lightweight expanded vermiculite (EV) was used in the initial development of PCM by impregnating it with capric acid (CA) and ethyl alcohol (EA) in a vacuum. Several composite foam mixtures were made and tested in the lab. The authors generated foam concrete by replacing the fine aggregate (Msand) with varying percentages of EV, CA-EA/EV-based PCM, and PCM with additional nanosilica and coir fibre combinations (PSC). Based on the results of the liquid leakage test, it was determined that PCM with a CA to EV ratio of 55% (wt.) exhibited the highest levels of adsorption and stability. The mechanical, hydration, durability, and thermal properties of PCM-enhanced foam concrete composites were all significantly increased. The greater heat storage capacity of the PSC-5%, as shown by the thermal analysis tests, ultimately leads to higher levels of thermal comfort in buildings.

Acid activation, spray drying, and calcination of palygorskite (Pal) as a raw substance were described by Li et al. (2023) [100] as an efficient technique for manufacturing hierarchical porous composite microspheres (PCN). To create PCN, Pal nanofibers and cellulose nanocrystals were cross-linked in a certain ratio, yielding a spherical, hierarchical, porous structure. The elevated stability of shape, the elevated efficiency of photothermal transformation, and the elevated latent heat storage capability of the Paraffin-PCN (P-PCN) composite PCMs were synthesized. The natural cooling of P-PCN from 35 °C to 30 °C preserves heat for almost twice as long as P-Pal. With the P-PCN, the melting enthalpy increased to 130.2 J/g, indicating clear benefits in the thermal management of buildings.

The thermal behaviour of PCM layer/capsules made from concrete bricks was experimentally investigated by Al-Yasiri and Szabó (2023) [101] amid the sweltering heat of southern Iraqi summers. One brick (BL) was merged with a PCM layer, another brick (BC) was integrated with PCM capsules, and the third brick (BR) was left naked without PCM for comparison. Bricks' thermal performance was evaluated by measuring their average surface temperature fluctuation reduction as well as the difference between their inner and outer surfaces' temperatures, the time lag between temperature changes, and the decrement factor. In addition, the author looked at how each brick lost some of its mechanical strength over time to demonstrate its usefulness in actual buildings. Based on experiments, BL and BC worked better than BR, which reduced brick temperature by up to 5 °C with a lag time of 30–60 min. Overall, the PCM layer made from bricks performed better thermally, while the PCM capsules had higher mechanical qualities.

Table 3 presents a summary of research on other types of PCMs used in concrete for thermal energy storage.

Table 3. A summary of research on other types of PCMs used in concrete for thermal energy storage and release applications.

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Wang et al. (2018) [81]	The PCM was a ternary fatty acid eutectic comprising lauric, myristic, and palmitic acids, and the thermal energy storage aggregates were made from diatomite and ceramsite.	Experimental	Impact of PCM on the compressive strength of concrete and energy storage.	The concrete's compressive strength with the aggregate's thermal energy storage at a volume fraction of 80% is more than 18 MPa. Early age hydration temperature increases can be better suppressed by using a diatomite-based thermal energy storage aggregate as opposed to a ceramsite-based one.

Table 3. *Cont.*

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Yeon et al. (2018) [82]	A melamine-formaldehyde resin was used to microencapsulate PCM.	Experimental	Effect of incorporating PCM on the mortar's compressive and flexural strengths and volume stability.	Incorporating PCM that has been MPCM was shown to reduce the mortar's compressive and flexural strengths but improve its volume stability at younger ages.
Urgessa et al. (2019) [83]	The concrete was microencapsulated with phase change material (PCM) that had a low transition temperature.	Experimental	Impact of incorporating PCM on transition temperature.	It was discovered that PCM worked best when temperatures fluctuated near the transition temperature (mild-cold seasons), but lost its significance when exposed to severe climatic extremes like freezing winters or scorching summers for an extended period of time.
Nayak et al. (2019) [84]	Concrete pavements using phase-change materials.	Numerical	Impact of incorporating PCMs into concrete on the damage caused by freeze-thaw cycles.	Incorporating PCMs into concrete significantly reduces the damage caused by freeze-thaw cycles.
Li et al. (2019) [85]	Preferred Phase-Change Materials and Low-Weight Aggregates.	Experimental		When PCM carriers made up as much as half the volume of the LWA, the amount of heat emitted by the PCM was significant enough to prevent ice formation.
Cao et al. (2019) [86]	Phase-change material-equipped multilayer walls.	Numerical and experimental	Effect of phase-change material equipped with multilayer walls.	Although the high heat storage capacity of the MPCM/PCM may be mitigated by increasing the insulating layer's thickness and decreasing its thermal conductivity, doing so greatly affects the efficiency of the heating and cooling systems.
Doretti et al. (2019) [87]	Using a single-phase working fluid flowing via a tube implanted in the concrete, a parallelepiped-shaped concrete module may be heated (during the charging phase) or cooled (during the discharging phase).	Numerical and experimental	Effect of oil mass flow on effectiveness.	The effectiveness maximises at an asymptotic value as the oil's mass flow and time rise.
Ren et al. (2020) [88]	To inhibit the leaking of PCMs, ceramite or pumice may be infused with PCMs and then covered with a multi-layer shell.	Experimental	Impact of incorporating PCMs.	Maximum decreases in central room temperature while using ETESC made from ceramsite and ETESC made from pumice were 4.7 degrees Celsius and 8.7 degrees Celsius, respectively.
Uthaichotirat et al. (2020) [89]	Concrete has a low specific gravity because it is made by soaking porous particles in PCM.	Experimental	Effect of incorporating PCM on density, compressive strength, and flexural strength of concrete.	There are strong correlations between PCM aggregate composition and density, compressive strength, and flexural strength. Increasing PCM aggregates is also associated with better thermal behaviour.
Arivazhagan et al. (2020) [90]	Concrete blocks have layers of phase-change materials embedded in them.	Experimental	Impact of the addition of PCM to concrete blocks.	The addition of PCM to concrete blocks led to a 3 °C decrease in the maximum air temperature compared to blocks without PCM.
Ram et al. (2020) [91]	Cement may be replaced by a mixture of fly ash and ground-granulated blast furnace slag (GGBS).	Experimental	Impact of the PCN-PCM composites.	The PCN-PCM composite's latent heat potential was high, meaning it was able to store thermal energy and maintain a constant 24 °C in the test room's air.

Table 3. *Cont.*

Authors (Year) [Reference]	Configuration/Composition	Type of Study	Studied Parameters	Results/Findings
Liu et al. (2020) [92]	This new SHSPCM synthetic heat storage format makes use of phase change materials.	Numerical and experimental	Effect of PCM on mechanical strength and hydration.	Using this innovative heat storage technology, concrete treated at a temperature of −15 °C obtained exceptional mechanical strength and rapid hydration.
Shen et al. (2021) [93]	To improve PCM-concrete's heat-storage capabilities, we added clastic light shale ceramsite (CLSC).	Experimental	Impact of adding clastic light shale ceramsite (CLSC) on PCM-concrete's heat-storage capabilities.	The average specific heat capacity of PCM-concrete thermal storage blocks rose via 12.54% (2 wt.% PCM), 31.60 (4 wt.% PCM), and 41.23% (6 wt.% PCM), whereas the thermal conductivity and compressive strength decreased with the increase in PCM weight percentage.
Pongsopha et al. (2021) [94]	Coated PCMA (ASF-PCMA) and polymethyl methacrylate.	Experimental	Impact of using coated PCMA (ASF-PCMA) and poly(methyl methacrylate).	After being put through 100 heat/cool cycles, the ASF coating reduced PCM leakage by around 5.4 times.
Al-Yasiri and Szabó (2021) [95]	Incorporating the PCM into the blocks of concrete.	Experimental	Impact of incorporating phase change material (PCM) into concrete blocks.	The highest PTR, HTRc, and TD are achieved by Brick-D, relative to the reference brick, at maximum outside temperatures of 156.5%, −61%, and −133%, respectively.
Cui et al. (2022) [96]	To produce PCM-HSB aggregates, a hollow steel ball (HSB) is used to macro-encapsulate the PCM.	Experimental	The effect of using fibre-reinforced PCM-HSB.	By increasing concrete's heat capacity and bearing capacity, the suggested fibre-reinforced PCM-HSB may secure energy piles' future uses.
Wu et al. (2022) [97]	PCM and a bio-based hygroscopic material (hemp concrete) are merged to create a unique multi-layer building shell.	Experimental	Impact of PCM and a bio-based hygroscopic material.	When compared to a setup without PCM, the peak T was delayed by 70.4%, the T/RH amplitude was decreased by 50%/60%, and energy usage was decreased by 15.3%.
Sawadogo et al. (2022) [98]	Hemp-PCM concrete is made with renewable materials.	Experimental	Impact of hemp PCM concrete.	With an ultimate period shift of 30 min as well as a discrepancy in temperature between the reference and the PCM hemp concrete of about 4.6 °C, the PCM hemp concrete has excellent thermo-regulating potential.
Dora et al. (2023) [99]	Different types of foam concrete using EV, PCM made from CA-EA and EV, as well as PCM with nano silica and coir fibres added (PSC).	Experimental	Impact of using different types of foam concrete on the thermal analysis.	Results of the thermal analysis tests showed that the PSC-5% has a higher heat storage capacity, leading to higher levels of thermal comfort in buildings.
Li et al. (2023) [100]	Spray-dried microspheres of hierarchical porous composite (PCN) material.	Experimental	Impact of spray-dried microspheres of hierarchical porous composite (PCN) material on the thermal management of buildings.	P-PCN's elevated melting enthalpy of 130.2 J/g demonstrates considerable improvements in the thermal management of buildings.
Al-Yasiri and Szabó (2023) [101]	PCM layers and capsules are made from concrete bricks.	Experimental	Impact of PCM layer/capsules on the thermal and mechanical characteristics.	The PCM layer made from bricks performed better thermally, whereas the PCM capsules performed better mechanically.

6. Critical Evaluation of the Utilisation of PCMs in the Concrete Industry and Their Improvements

PCMs are being used more frequently in the concrete sector as a way to improve the thermal characteristics and energy efficiency of concrete structures. As a passive form of temperature control, PCMs have the capacity to store and release thermal energy during phase transitions.

The illustration of the associated research on utilising PCMs in the concrete industry (Sections 3–5) introduced the fact of experiencing different types of PCMs. Specifically, microencapsulated PCMs (MPCMs), macroencapsulated PCMs, and PCM-embedded concrete are common categories that have been widely elucidated. MPCMs are tiny capsules that spread throughout the concrete matrix and can withstand mechanical pressure. However, macroencapsulated PCMs are larger capsules that are implanted in the concrete and affixed to the surface. Although they provide simple installation and replacement, the effectiveness of heat transfer may be constrained. The third type involves the direct addition of PCM into the concrete mixture to substitute for cement or aggregate. Nevertheless, the discussed studies assure the capability of PCMs to efficiently store thermal energy during the day and release it at night. In other words, PCMs can assist in maintaining indoor temperatures and lessen the demand for extra heating and cooling systems. In terms of energy efficiency and comfort for users, the use of PCMs in the concrete industry delivers substantial benefits. Undoubtedly, the utilisation of PCMs in concrete mixtures would result in energy savings and a reduction in carbon emissions due to a reduction in the heating and cooling energy requirements of buildings. Furthermore, there are a number of signs that PCMs can enhance the mechanical characteristics of concrete, increasing its longevity and reducing cracking. However, it should be realised that PCMs can be rather expensive. Thus, adding them to concrete may raise the entire cost of a building project. In addition, the PCM type and distribution inside the concrete can directly affect the efficiency of thermal energy storage and release and thus may retard the heat transfer rate. There is also a possibility of experiencing a volume shift throughout the phase transitions of organic PCMs. This, in turn, would cause microcracking in the concrete.

The structural stability and long-term performance of the concrete depend on the PCM and concrete mix being compatible. Lastly, restoration and replacement of deteriorated or damaged PCM containers can be difficult and expensive in the case of macroencapsulated PCMs.

With reference to the points raised in this review, the authors are able to list a number of advancements made in PCMs in relation to their use in the concrete industry for the period between 2018 and 2023. These developments are meant to improve the thermal performance, energy effectiveness, and general sustainability of concrete structures. A few of the significant upgrades include:

1. Microencapsulation and macroencapsulation technology advancements have improved PCM leakage and degradation protection. The consistency and endurance of PCMs within the concrete are ensured via encapsulation, making them more appropriate for long-term uses.
2. PCM decreases concrete's mass density by almost twice its weight. The higher quantities of Microencapsulated PCM added to denser concrete walls were also shown to improve the energy efficiency of buildings. As the paraffin concentration rises, so does the heat conductivity, reducing the insulating properties of otherwise perfect autoclave-aerated concrete.
3. The mechanical strengths of the thermal energy storage cement-based composites have been reduced by raising the content of the form-stable hydrate salt PCMs. Nevertheless, they can still be used as covering subtractions for construction elements. The quantity of thermal energy saved and released also increased with PCM integration, doubling at the highest PCM integration percentage simulated (40%).
4. Integrated PCM and a bio-based hygroscopic material (hemp concrete) have strong thermoregulation abilities, with an ultimate period shift of 30 min and a discrepancy in temperature of about 4.6 °C between the reference and PCM hemp concrete. Energy piles may be used if the suggested fibre-reinforced PCM-HSB can greatly increase concrete's heat capacity and bearing capacity. Density, compressive strength, and flexural strength all showed upward increases with PCM aggregate content. As PCM aggregates increase, so does their thermal conductivity.

5. To store and release more thermal energy during phase transitions, scientists have been creating novel PCMs such as Microencapsulated PCMs and Macroencapsulated PCMs with an 18 °C phase transition temperature and greater latent heat capacities. In concrete structures, high-performance PCMs can result in improved temperature control and increased energy savings.
6. Research into creating PCMs with phase change temperatures that are best suited for particular regions and structural needs is expanding. PCM-enhanced concrete can be tailored to the appropriate indoor temperature range by adjusting the melting and solidification points.
7. Efforts have been undertaken to improve PCM compatibility with different concrete mixtures, making sure that their incorporation does not compromise the concrete's structural integrity or lifespan.

Based on the above discussion, it is crucial to carefully analyse the kind of PCM used, how it is distributed within the concrete, and any potential downsides, such as price, a limited capacity for heat transfer, and material compatibility. For concrete construction to successfully integrate and gain long-term benefits, proper design, material selection, and consideration of building requirements are essential. In construction projects looking for ecological and energy-efficient solutions, PCM-enhanced concrete may become more common as technology develops and costs fall. More importantly, it is plausible to remember that PCM technology is always evolving, and there may have been more breakthroughs beyond those mentioned above. Researchers and business experts are still focusing on improving PCM embedding in concrete structures to increase their sustainability, energy efficiency, and comfort for residents. For instance, the innovative solid-solid phase change materials (SS-PCMs), which overcome the leakage issues normally seen in solid-liquid PCMs, are of tremendous significance for implementation in thermal energy storage systems. Due to this property, they can be incorporated into other materials without the necessity for encapsulation, such as for thermal energy storage in gypsum or concrete used in buildings [102,103].

7. Conclusions

This study summarises the findings of prior research on the effectiveness of PCMs in concrete and their connection to the overall energy efficiency of buildings. Different forms of PCM utilised in concrete for various purposes, construction features, and climates were discovered and addressed. During this review, several important findings were made, which can be stated as follows:

1. The PCM layer made from bricks had greater thermal qualities than the PCM capsules, while the latter had better mechanical properties.
2. The results of thermal analysis studies showed that PSC-5% has a higher heat storage capacity, leading to higher indoor thermal comfort.
3. With the maximum PCM integration percentage simulated, corresponding to 40%, the quantity of stored and released thermal energy doubled from its initial value.
4. The postponement of temperature peaks highlighted the improved energy efficiency of PCM wallboards as compared to conventional concrete, particularly in the case of the bilayer wallboard.
5. When compared to a setup without PCM, the peak temperature was delayed by 70.4%, energy usage was cut by 50%/60%, and T/RH amplitude was lowered by 15.3%.
6. Energy piles may be a viable option because of the suggested fibre-reinforced PCM-HSB, which increases concrete's heat capacity and bearing capacity.
7. Adding 15% as well as 30% PCM composite has decreased the maximum indoor temperature by 1.85 °C and 3.76 °C in the test room, respectively, while increasing the thermal storage capacity by 105% and 181%, respectively.
8. Increasing the amount of microencapsulated phase change material aggregation in a unique coreshell or choosing a PCM with a more appropriate phase transition

temperature might improve performance by facilitating a more effective heat storage and release procedure.

9. In the model of the room with the ceramsite-based encapsulated thermal storage aggregate, the highest temperature drop at the centre point was 4.7 °C, while in the model of the room with the pumice-based encapsulated thermal storage aggregate, it was 8.7 °C.
10. When PCMs are added to concrete, freeze-thaw damage is significantly mitigated.

8. Recommendations for Future Works and Challenges

Indicators of PCM-concrete's thermal performance and its composition may now be visualised thanks to the updated research, as summarised in Tables 1–3. The following is an example of a collection of suggestions for further study:

1. Further research is needed to investigate novel PCM materials with increased latent heat and acceptable phase change temperatures for particular environments, climates, and applications.
2. The distribution of PCM inside the concrete mixture has an essential effect on the rate of heat transfer. Thus, a specific line of research to optimise the distribution and content of PCM is required to increase thermal conductivity and boost heat transfer effectiveness.
3. Examining the durability and suitability of PCMs for use with various concrete mixes is interesting research to consider any potential volume changes and micro-cracking that may occur during phase transitions.
4. Future research is needed to assess the real freeze-thaw performance of Microencapsulated mortar since this property depends not only on the heat cycles but also on the material's strength.
5. More research into the effects of specimen size, material composition, and environment on PCM's thermal efficiency, as well as cost-effectiveness analysis and durability evaluation, is needed.
6. To get an accurate prediction of the wall of an encapsulated ceramsite-based encapsulated thermal storage aggregate, it will be necessary to conduct a long-term examination of thermal storage stability and to design an adequate matching temperature programme control system.
7. The same methodology may be used in the study of encapsulated PCMs with increased heat storage capacity. The suggested mix design allows for the construction and examination of models of large-scale buildings.
8. Examine the best building orientation and architectural layout for optimising the advantages of PCM-enhanced concrete in various temperature zones.
9. Conducting an economic evaluation to determine whether PCM integration in the concrete industry is cost-effective is important. However, it should consider both immediate building costs and long-term energy savings.

Author Contributions: Conceptualisation, F.L.R. and M.A.A.-O.; methodology, F.L.R., A.D. and A.H.; software, H.B.M.; validation, F.L.R., L.F.A.B., H.B.M. and A.H.; formal analysis, M.A.A.-O., L.F.A.B. and M.A.E.; investigation, F.L.R.; resources, A.D. and A.H.; data curation, F.L.R., A.D. and M.A.A.-O.; writing—original draft preparation, F.L.R., M.A.A.-O., A.D., L.F.A.B., H.B.M., M.A.E. and A.H.; writing—review and editing, F.L.R., M.A.A.-O., A.D., L.F.A.B., M.A.E. and A.H.; visualisation, F.L.R.; supervision, F.L.R. and A.D.; project administration, F.L.R. and A.D.; funding acquisition, A.H., L.F.A.B. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The financial support of Kerbala University and the University of Warith Al-Anbiyaa in Iraq is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

PCMs	Phase-change materials
DSC	Differential scanning calorimeter
GPC	Geopolymer concrete
DSC	Differential scanning calorimeter
MPCM	Microencapsulated phase-change materials
AAC	Autoclave-aerated concrete
XLPE	Cross-linked polyethylene
PIA	Paraffin-impregnated burnt clay aggregate
LECA	Lightweight expanded clay aggregate
PEG	Polyethylene Glycol
OPKS	Oil palm kernel shell
RHA	Rice husk ash
LFCPCM	Leakage-free composite PCM
TESA	Thermal energy storage aggregates
EHS/ EGO	Eutectic hydrate salt/expanded graphite oxide
CTES	Concrete-based thermal energy storage
HTF	Heat transfer fluid
TRC	Textile-reinforced concrete
MbP	Microencapsulated bio-based phase change material
CSP	Concentrated solar power plant
ETSA	Encapsulated thermal storage aggregate
ACC	Autoclaved aerated concrete block
GGBS	Ground-granulated blast-furnace slag
SHSPCM	Synthetic heat storage form that incorporates phase change materials
ASF	Activated silica fume
HSB	Hollow steel ball
TES	Thermal energy storage

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