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REVIEW

Developments on energy-efficient buildings using phase change materials: a sustainable building solution

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Abstract

Energy security and environmental concerns are driving a lot of research projects to improve energy efficiency, make the energy infrastructure less stressed, and cut carbon dioxide (CO_2) emissions. One research goal is to increase the effectiveness of building heating applications using cutting-edge technologies like solar collectors and heat pumps. Another study technique uses phase change materials (PCMs), which have high energy storage densities. There still needs to be a thorough analysis of how these two research methods, namely how PCM is used to heat buildings, fit together. A thorough explanation of PCM application in buildings, specifically in walls, floors, ceilings, and glazed sections, and the critical PCM properties have been included in this article. This paper gave a summary of the research done for different applications, including the types of PCM, the forms of PCM encapsulation, and the types of PCM units used in different applications. This was done so that PCM can be used effectively in building applications. By summarizing and talking about the research methods used in different applications, we can learn more about the study's possibilities and limits. From the study, authors conclude that the selection of appropriate PCM for a particular application requires careful consideration. The appropriate thermal conductivity, melting temperature ranges, coherence with building materials, and durability over time are a few factors that must be taken into account. Compatibility issues may arise when PCMs come into contact with other components or construction materials, which may lead to leakage or inadequate performance.

Scholars can use the important conclusions and suggestions for future research on these applications to help them with their work. A list of recommendations for future work that can increase the use of PCMs in building applications include the improvement in low thermal conductivity and boost system efficiency, PCMs' heat transfer properties can be improved, or heat transfer enhancement methods such as fins or heat pipes can be used. The next generation of studies aims to develop PCMs with enhanced robustness, durability over time, and little degradation following repetitive temperature cycling. Making PCM-based solutions commercially viable for various building projects requires robustness as well as inexpensive manufacturing procedures.

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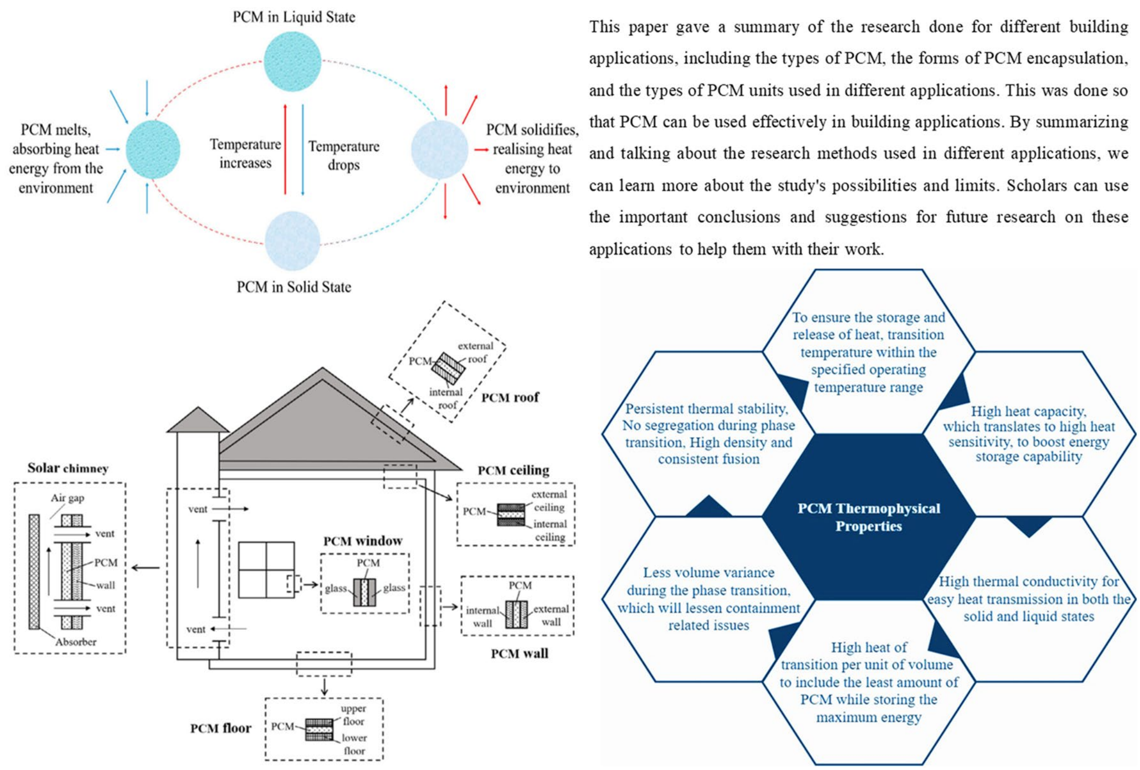
Graphical abstract



Keywords Energy efficiency · Cleaner environment · Phase change materials · Energy-efficient buildings · Building heating applications

Introduction

Due to rapid population expansion and rising energy consumption, the energy problem is still a significant worry in modern society (Li, Ding, et al. 2020b, c, d, a). By 2030, warming, will get considerably worse (Du et al. 2020). Numerous research approaches are encouraged to address the present energy and environmental issues. Reducing the energy consumption of building heating applications is one such research technique. Buildings use 40% of the energy produced worldwide (Agathokleous et al. 2019). Many nations have passed similar legislation to improve energy efficiency and lower CO2 emissions from buildings.

According to the United Kingdom's (UK's) "Clean Growth Strategy," industries and companies will increase their energy efficiency by 25% by 2030 (BEIS 2017). According to China's "13th Five-Year Plan," energy consumption per unit of Gross Domestic Product (GDP) will decrease by 15% during the plan's duration. According to the European Union's (EU's) "2030 Energy Strategy," energy efficiency will increase by at least 32.5% by 2030 (Li et al. 70 to 80% of the world's primary energy will continue to come from fossil fuels, which now dominate the global energy market (Waqas and Din 2013). Following that, issues with the environment brought on by fossil fuels, such as iceberg melting, frequent disasters, and global 2020). Heating, cooling, lighting, and ventilation account for the majority of energy consumption in buildings. Buildings' need for space heating and hot water can reduce energy use, which calls for sophisticated methods like passive (Aksoy and Inalli 2006) and active measures (Li and Huang 2019).

Significant issues concerning energy efficiency tend to be especially common in high-rise buildings. One of the greatest common causes of indoor thermal discomfort is caused by regular temperature variations and steep temperature gradients. Thermal discomfort increases the energy needed for ventilation and implies more reliance on mechanical appliances to maintain acceptable living conditions. Additionally, apartments have a significant outside impact due to their height and orientation. The sloping shape of the building plays a significant role in the heat increase caused by sunlight infiltrating the structure. Efforts to achieve energy savings for residences are required to reduce the energy consumption for both heating and cooling because of the variable heat-acquisition elements that flats experience from their external climate, which fluctuate based on the structure's height and alignment.

PCMs have evolved into an essential part of the solution to the energy concern confronting buildings because of their capacity to store sizable portions of heating or cooling throughout the phase change cycle via the utilization of latent heat storage. In order to preserve and regulate heat in buildings, PCMs are a particular kind of thermal energy storage medium. Substantial quantities of thermal energy can be absorbed and released by PCMs when a solid or liquid changes state into a gas. In order to store thermal energy, PCMs with high latent heat and excellent thermal conductivity are required. They must be reasonably priced and non-corrosive and possess a melting temperature which falls within an acceptable operating range.

Recent developments in phase change materials

Phase change materials (PCM), which are increasingly used in construction products to increase building energy efficiency, have the potential to reduce and redistribute energy use and possesses positive social, economic, and environmental impacts and will significantly contribute to several aspects of sustainable development.

Utilizing thermal energy storage (TES) effectively with PCM is another research technique. Utilizing TES, it is possible to significantly enhance the use of renewable energy sources (Ferrer et al. 2017), avoid the unpredictability of energy output from renewable/alternative energy sources (Ram et al. 2023), (Mohammadnejad and Hossainpour 2020), and boost the efficiency of energy systems (Bouhal et al. 2018). Sensible, latent, and thermochemical storage are the basic thermal energy storage techniques (Barreneche et al. 2015). The benefits of PCM over other heat storage materials include their ease, high dependability, extraordinary energy storage density, low power consumption, and almost isothermal phase transition temperature (Li, Ding and Du 2020b, c, d, a; Li, Zhang and Ding 2020b, c, d, a). As a result, it is frequently used to increase energy efficiency in many different industries, including free cooling (Kamali 2014), thermal management (Zhi et al. 2022), defrosting (Pardiñas et al. 2017), and air-conditioning (Violidakis et al. 2020).

Improving the energy efficiency of buildings' heating applications using PCM is a novel and significant trend in addressing energy security issues and ecological effluence. It combines the two methodologies mentioned earlier. Researchers have compiled extensive literature reviews on each method during the past few years. Su et al. (2018) examined the heating options for building applications in China, including gas boiler water heaters and ground-source and air-source heat pumps. Using spatial data analysis to find workable heating solutions in various Chinese regions is highly advised. The evolution of solar-assisted heat pumps for residential hot water usage in buildings was summarized by Wang et al. (2017a, b). The current state of solar water heater applications in Turkey was reviewed by Benli (2016). It was suggested that solar water heaters are installed in Turkey's northern and eastern regions. In order to increase system efficiency, Chandel and Agarwal (2017) analyzed the photovoltaic power operations with PCM that were utilized to cool solar panels. It is advised that more research are done to increase the PCM's economic benefits. The PCM building cooling methods were summarized by Saffari et al. (2017). Abdulateef et al. (2018) briefed the methods for using fins to boost the heat transfer influence (HTE) among the PCM and the heat transfer fluids. To the authors' acquaintance, however, only a few investigations thoroughly investigated both methods, particularly building heating applications with PCM.

Thanks to technological advancements in the energy and environmental domains, the vast surface area surrounded by construction materials is now a potential possibility for solar energy development. On either hand, by integrating the low thickness gained via the use of PCMs with adaptable construction solutions, resolutions with a better ability to familiarize with the life cycle analysis of structures may be obtained, resulting in a somewhat greener development. As a result, the construction sector must abandon its conventional conservatism and emphasis on creative technologies that solve problems over several years. TES and PCM have stimulated the interest of several academics worldwide in various fields in recent years, owing to their ability to reduce energy consumption using solar energy.

Using PCM in building materials has resulted in various studies being published in recent years. According to Fig. 1, there has been an upsurge in the publication of this topic after 2012, which tackles the principal issues raised by the research community on energy efficiency, green construction, and energy consumption. This increase in the number of papers published on PCMs is also linked to the objectives of the Sustainable Development 2030 Agenda, which include one of the primary apprehensions of the technical community's which is ensuring that everyone has access to inexpensive, dependable, sustainable, sustainable, and modern energy.

Energy efficiency and energy poverty

One of the primary causes of our planet's unsustainable development is the mounting need for energy worldwide. The rise in global population and the premise that further people get access to power justifies this growth in energy

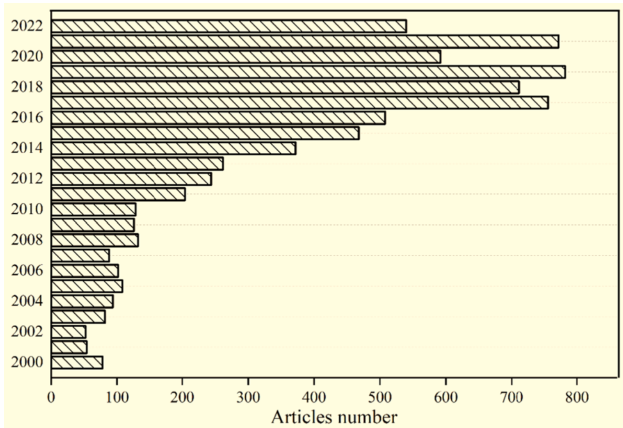


Fig. 1 PCM publications from 2000 to 2022

demand. Emissions of greenhouse gases and heavy energy expenditure are significant issues in the extraction or use of non-renewable sources of fossil fuels, which have a significant environmental impact. Energy fabrication is the leading source of greenhouse emissions, accounting for roughly 75.2 percent (Patiño-Cambeiro et al. 2019).

During recent years, there has been an international dialog about reducing energy demand to mitigate climate change. In 2012, the EU set a goal of cutting energy consumption and greenhouse gas emissions by 20% by 2020 compared to 1990. However, 2017 figures indicate that this objective will not be realized, even though the 2030 targets were proposed to be increased, with a decrease of roughly 27% in energy ingestion and 40% in the release of greenhouse gases (Patiño-Cambeiro et al. 2019). In this approach, a more significant amount of work is necessary to achieve these goals.

India, which is the most populated country on Earth, still relies heavily on imported fossil fuels to meet its energy needs, making it an energy-dependent nation. However, a significant initiative has been taken recently to address this issue, reducing both the importation of energy and the combustion of fossil fuels. In India, macro- and micro-hydroelectric, solar, and wind power plants currently produce around 33% of the country's electricity consumed domestically. Buildings account for more than 40% of all electricity use in India. So, cutting down on energy use inside buildings is our key goal. It takes much electricity to run the air-conditioners throughout the summer, which helps to keep the interior of the building at a constant temperature. It would be advantageous if we discover additional passive, affordable, and robust ways to replace this power requirement.

Additionally, the same passive systems can be utilized to replace the heaters used inside buildings during the winter, which will help further lower the heating loads. Incorporating PCM into buildings can assist lower cooling and heating loads, proving to be a long-term solution to these issues (Khudhair and Farid 2021). They have weak thermal conductivities, making it difficult for heat to travel through them effectively. Additionally, PCMs that convert solid to liquid has little volume change, which solves the containment problems (Sarbu and Sebarchievici 2018); (Cook et al. 2010).

Buildings account for roughly 38.9% of energy needs in the European Union, greater than transportation and industry, which account for approximately 33.1 percent and 23.3 percent, respectively (Patiño-Cambeiro et al. 2019). As a result, it is indeed a sector with a lot of promise and need for assistance. Rejuvenation of buildings to improve their low energy efficiency is one of the strategies to reduce energy usage. On the other hand, building energy rehabilitation is one of the United Nations' sustainable development metrics and goals until 2030 (Patiño-Cambeiro et al. 2019). Building energy efficiency has improved significantly in recent years, with the most substantial improvement occurring after the 1990s, thanks to the enforcement of tight construction rules. Residential buildings constructed in 2002 were found to have a 24 percent reduction in energy use. European annual building rehabilitation costs are estimated to be between 0.5 and 2.5 percent of total real estate stock (Patiño-Cambeiro et al. 2019). Because these figures are so small, implementing new operational construction materials with temperature regulation capabilities is a critical step toward solving the problem.

Energy poverty

Energy is used during every stage of a building's development, including the withdrawal and manufacturing of raw materials, building structure, and building maintenance expenditures throughout a structure's lifetime. As a result, there is currently the idea of energy poverty, which is associated with the indicator that families lack the means or spend more than 10% of their monthly income on maintaining comfortable indoor environments. Poor building quality, high energy costs, and meager family incomes are the primary contributors to energy poverty in India, for instance. Additionally, it is recognized that 32% of Indian families fall into this category, necessitating an immediate response (Patil et al. 2021). Families are willing to sacrifice their monthly budget for energy bill savings. Combating and attempting to eradicate its causes are necessary to combat energy poverty. Since it is impossible to alter the price of fossil resources or the income inequality of Indian families, the attention in this regard is mainly placed on enhancing the thermal characteristics of buildings. The exploitation of functional materials with thermal storage capability and other policies that endorse energy proficiency and the consumption of less expensive, greener energy sources can contribute to this growth.

Evaluation of PCM compatibility considering charging and discharging

Bricks with PCM integration have more thermal mass, more thermal resistance, and less heat flow through them. Only a portion of the energy entering PCM from the sun during the daytime passes to the interior, acting as a thermal capacitor. Only a portion of the heat stored is transported to the interior during the hours when it is not shining. As a result, the integration of PCM has a decreased overall influence on heat transfer to the interior. However, a thorough investigation is required to determine which PCM will be best for use from an Indian perspective. The appropriateness of the PCMs throughout their phase change temperature, which would be a crucial factor, has received little attention in the study done so far. PCMs must release the heat stored throughout the day when it is not sunny. (Saxena et al. 2019) conducted a study for Delhi to address this. This simulation study demonstrated that PCMs with melting temperatures of about 34 °C are appropriate for the application, providing they have low sub-cooling levels (i.e., the disparity in temperature between the phases of melting and solidification; PCM must always be chilled well below melting point before beginning to solidify). This keeps the PCM charged and discharged regularly and serves as a latent heat storage device in the summer. However, because the PCMs have chosen to have significant sub-cooling (about 7 °C), which was determined using differential scanning calorimetry (DSC) characterization, this study could not recommend any PCM for use.

A site's daily temperature variation causes PCMs to charge and discharge. The local climate is influenced by variables like the weather condition, temperature, air humidity, precipitation, wind speed, and solar radiation, which in turn depends on latitude, longitude, the time of day and year, the orientation of the surface, etc., that determines how the temperature varies in a given location. These variables influence the solar radiation that strikes the surface. The temperature of the solar air rises as solar radiation increases. The heat transfer is caused by the temperature difference between the interior surface and solar air temperature. For the phase change to occur while charging and discharging and for the latent heat to be active, the phase change temperature of the PCM needs to be within the range of the day's minimum and highest temperatures. This avoids large temperature swings during daytime.

Phase change materials

Operation principle

All materials have an impact on their environment, as is well-known. Most materials, though, cannot modify their characteristics to fit the requirements of the contexts in which they are utilized. The functioning principle of the PCM is to alter its status following the ambient temperature. As the temperature rises, the PCMs capture and accumulate energy, going from a solid to a liquid state. The substance, however, can expel the previously held energy when the temperature drops, changing the material from a liquid to a solid in this situation. Phase change occurs in various ways, as shown in Fig. 2. This diagram depicts the conversion of PCM from solid to liquid or gaseous phases or even to the solid phase via evaporation (Hasnain 1998). Evaporation causes a phase shift with a high enthalpy. A large volume and pressure variability through phase conversion are just one of the application issues it raises. Since there is little volume change throughout the phase transition, the solid–liquid transformation is chosen for TES (Liu and Ma 2002; Soares et al. 2016). Last, the solid–solid transition shares many traits with the solid–liquid transformation but has a far lower capacity to store energy (Liu and Ma 2002).

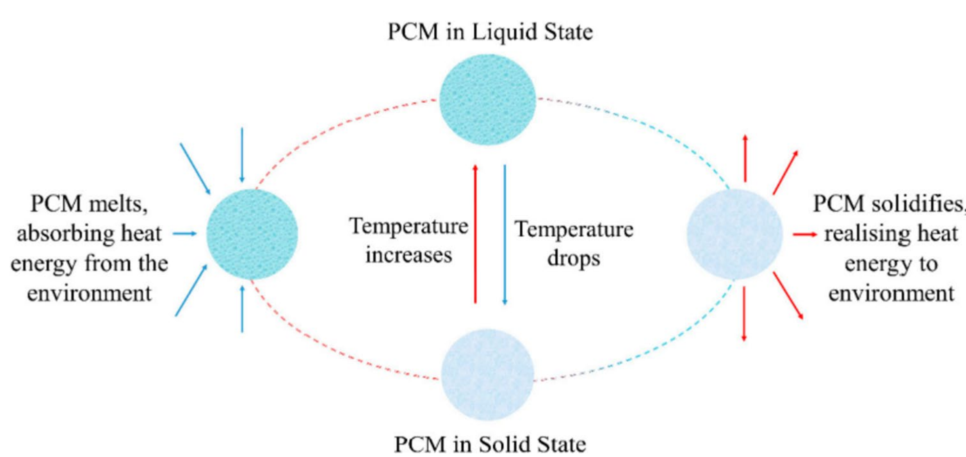


Fig. 2 Phase change materials undergoing through the phase transition process (Frigione et al. 2019)

PCM classification

Figure 3 represents the building applications classification with PCM for heating purposes. Both active and passive applications have been categorized; however, in this article, we will discuss passive applications (Fig. 4). There are several distinct PCMs with various melting points, which are categorized into three groups. The initial division of materials utilized for thermal storage into organic, inorganic, and eutectic mixes occurred in 1983 (Zalba et al. 2003).

Organic phase change materials

Paraffinic or non-paraffinic materials for organic phase changes are both possible. In most cases, they fuse congruently over time without degrading. They are made up of a chain of hydrogen and carbon atoms. For instance, paraffin waxes typically include 8 to 15 carbon atoms, but pure paraffin often has between 14 and 40. As more carbon atoms are added to form the chain, its melting point rises (Sharma et al. 2009).

Paraffin is secure, dependable, predictable, un-corrosive, inexpensive, chemically inactive, and stable at temperatures less than 500 °C with minor volume fluctuations. Another benefit of their utilization is the consistent melting process and good nucleation qualities. However, they also have significant drawbacks, such as solid flammability and poor thermal conductivity (Sharma et al. 2009; Cabeza et al. 2011).

The key benefits of this particular PCM category are established on its wide temperature range, congruent phase change, high latent heat of fusion, auto-nucleation characteristics, low liquid-phase undercooling abilities, high nucleation rate, low segregation rate, non-reactivity, non-corrosion, thermal and chemical stability, compatibility with building materials, and eco-friendly nature. However, these materials' primary drawbacks include low enthalpy, low density, poor thermal conductivity, flammability, substantial volume change, and high price (Sharma et al. 2009; Cabeza et al. 2011).

Inorganic phase change materials

Metal salts and hydrated materials are two categories of inorganic PCMs. The application of hydrated salts in TESs has been thoroughly investigated. Its most desirable characteristics are.

- The high thermal conductivity (nearly twice that of paraffin),
- The high heat of fusion per unit volume, and
- Minimal volume changes in the course of the phase transformation.

The hydrated salts are also inexpensive, plastic-compatible, and non-corrosive. Its drawbacks include a decreased nucleation rate and uneven salt formation (Sharma et al.

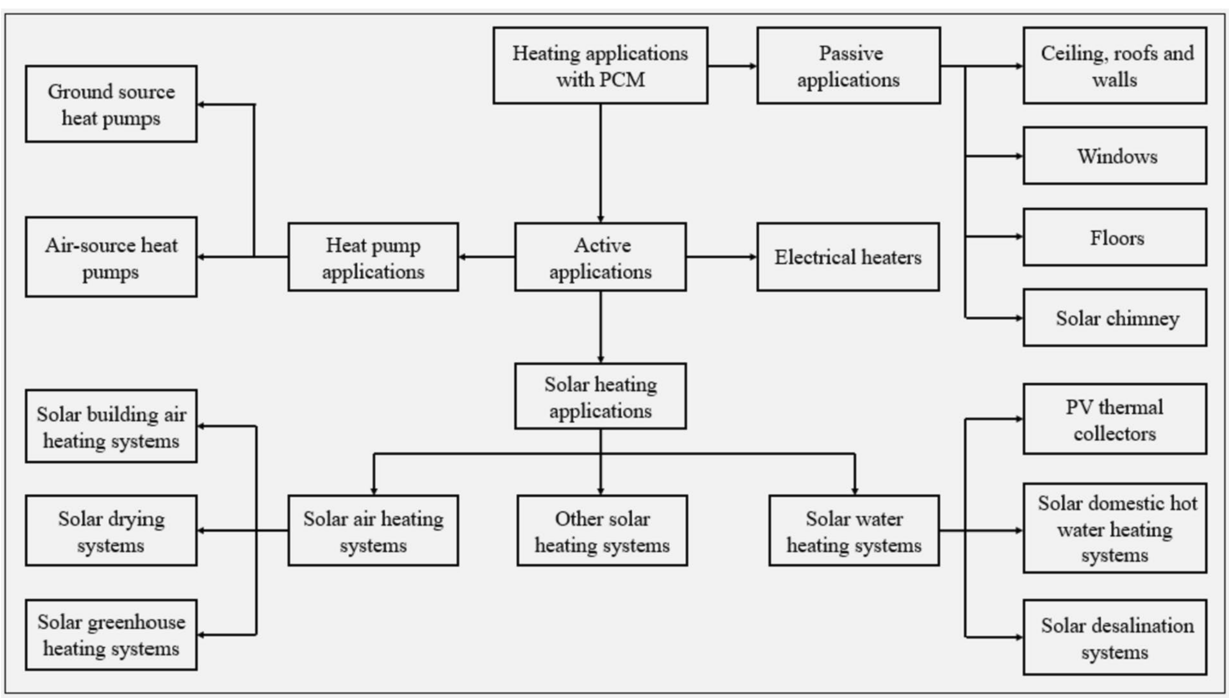


Fig. 3 Classification of heating-related residential and commercial buildings for phase change materials

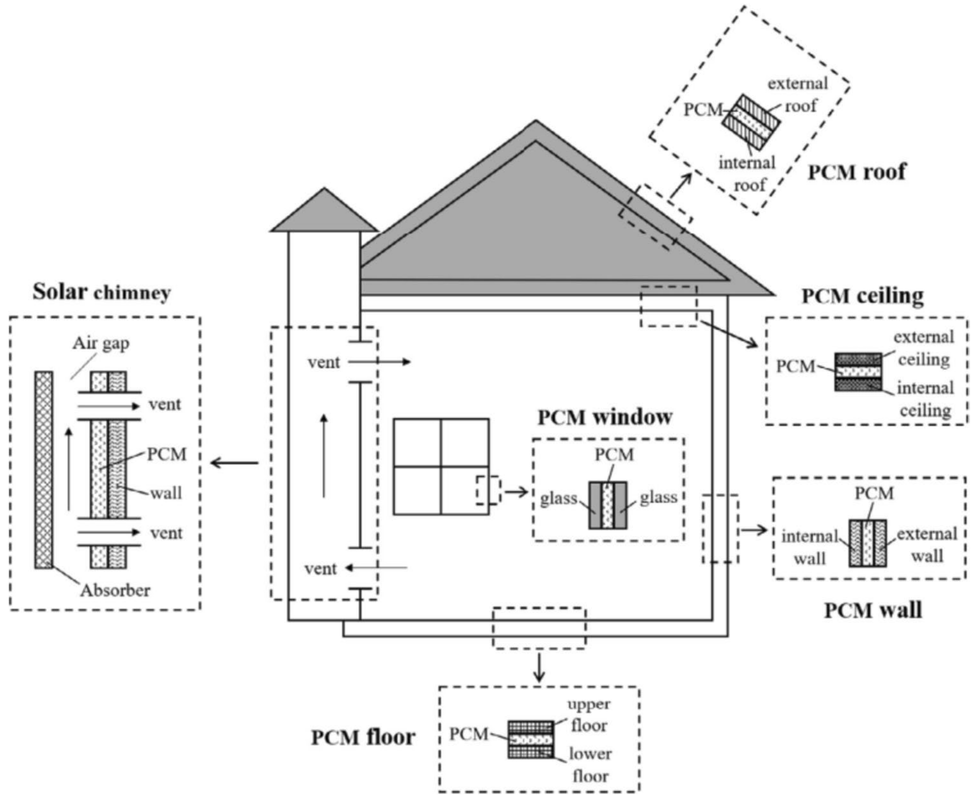


Fig. 4 Utilization of PCMs in passive applications (Li et al. 2020)

2009). Due to their weight, metal salts have yet to be given substantial consideration for thermal storage. However, they offer some potential because of the low volume changes, high fusion heat, and high thermal conductivity (Sharma et al. 2009).

In conclusion, the benefits of inorganic PCM include high enthalpy, lower price, ease of availability, substantial, large thermal conductivity, nonflammability, lesser volume fluctuations, compatibility with plastic vessels, and minimal ecological influence. Their primary drawbacks include liquid-phase sub-cooling issues, poor nucleation characteristics, inconsistent phase changes, poor thermal permanence, material separation issues during phase transitions, disintegration, inconsistency with some building constituents, metal corrosiveness, and mild toxicity (Sharma et al. 2009). It is reasonable to conclude that, in comparison with organic PCM, inorganic materials offer significantly more excellent thermal conductivity, lower flammability, and cheaper acquisition costs (Cabeza et al. 2011).

Eutectic blends

Suppose two or more organic/inorganic or PCM constituents are blended. In that case, eutectic mixtures with transition temperatures nearer to the scenario's requirements than the individual compounds are created. The aggregation of the mixture's two or more constituents has to be coordinated (Sharma et al. 2009).

The critical drawbacks of such constituents are their high price, which is generally 2 to 3 times higher than that of organic/inorganic PCMs, poor thermophysical performance, and an overpowering stench. The core benefits could be the optimal transition temperature, significant enthalpy content, and consistent phase change (Sharma et al. 2009).

PCM characteristics

The thermal conductivity, melting temperature, and energy storage density all affect how well phase change materials transport heat. Among the various varieties of PCM appropriate for TES, the substance with a rapid melting and solidification temperature is the best choice (Kasaeian et al. 2017). Table 1 represents various phase change materials' melting point temperatures and latent heat. Not every PCM on the market now can be utilized for thermal storage. A good PCM should have a few desired chemical, thermophysical, environmental, kinetic, and economic characteristics (Fig. 5). The chosen PCM must possess the following thermophysical properties (da Cunha and de Aguiar 2020):

Concerning kinetic qualities, the PCM must produce crystals quickly to avoid sub-cooling the liquid phase and adapt to environmental demands. For environmental and safety

Table 1 Latent heat and melting temperatures for different phase change materials

Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)
0.5% Nano Cu-PCM (Lin and Al-Kayiem 2016)	59.57	172.2	Myristic acid (Chaabane et al. 2014)	54	189	PCM-3 (Yang et al. 2014)	42–44	168
1.0% Nano Cu-PCM (Lin and Al-Kayiem 2016)	58.97	166.7	Na2SO4 10H2O (Li et al. 2014)	30–2	241	PCM303 (Li et al. 2015)	30	138
1.5% Nano Cu-PCM (Lin and Al-Kayiem 2016)	58.15	160.3	Na2SO4 10H2O (Ndukwu et al. 2017)	32	252	PCM307 (Li et al. 2015)	34	188
2.0% Nano Cu-PCM (Lin and Al-Kayiem 2016)	57.81	157.3	N-eicosane (Serale et al. 2016)	36–38	195	PCM311 (Li et al. 2015)	38	238
38% Urea + 62% acetamide (Y. Li et al. 2018a, b)	53	224	N-eicosane (Serale et al. 2015)	36–38	195	PCM-HDPE pellets (Biswas and Abhari 2014)	16.5–26.5	116.7
40% Oil + 60% wax (Akeiber et al. 2017)	40–44	232	Octadecane (Zhao et al. 2016)	28.2	242	PureTemp (PT) 20 (Barzin et al. 2016)	20	180
66% capric acid + 34% lauric acid (Qi et al. 2016)	20.4	138.8	Octadecane (Sobhansarbandi et al. 2017)	28.1	244	PureTemp 20 (Kara 2016)	Oct-28	100–400
75% capric acid + 25% palmitic acid (Browne et al. 2016)	17.7–22.8	189–191	Octadecane mixed with silica (Liu et al. 2017)	28.47	226.26	BioPCM (Q25) (Jamil et al. 2016)	27	–
Salt hydrate, AC27 (Arfaoui et al. 2017)	27	192.6	Mixture of bio-based PCM, OM 37 (Gaur et al. 2017)	37	211	Rubitherm (RT) 42 (Li et al. 2017)	38–43	174
Salt hydrate,AC27 (Bouadila et al. 2014)	27	192.6	Palmitic acid (Li et al. 2018a, b)	61	222	RT 42 (Liu and Li 2015)	38–43	174
Salt hydrate, AC27 (Kooli et al. 2015)	27	192.6	Paraffin mixed with polypropylene and elastomer (Kim et al. 2017)	19–26	62.24	RT 42 (Li et al. 2016)	38–43	174
BioPCM (Plytaria et al. 2018a, b)	25	175	Paraffin wax (Kant et al. 2017)	28.2	245	RT10 (Kheradmand et al. 2016)	10	150
BioPCM Q29/M91 (Plytaria et al. 2018a, b)	29	180	Paraffin wax (Saffari et al. 2017)	18–27	110	RT18 (Meng et al. 2017)	17–19	225
BioPCM Q29/M91 (M. T. Plytaria et al. 2019)	29	180	Paraffin wax (Goia et al. 2014)	35	170	RT-21 (Navarro et al. 2015)	21	134
BioPCM Q29/M91 (Plytaria et al. 2019)	29	175	Paraffin wax (Devaux and Farid 2017)	27–29	120	RT-21 (Navarro et al. 2016)	21–22	134
BioPCM Q29/M91 (Plytaria et al. 2019a, b, c)	29	210	Paraffin wax (Devaux and Farid 2017)	21.7	–	RT22HC (Osterman et al. 2015)	–	181 ± 9
Microencapsulated PCM (Kheradmand et al. 2016)	26	110	Paraffin wax (Royon et al. 2014)	27	110	RT-25 (Kant et al. 2017)	26.6	232
CaCl2 6H2O (Zhou and Pang 2015)	26 ± 1	180	Paraffin wax (Kabeel et al. 2017)	57	226	RT27 (Tokuç et al. 2015)	25–28	179

Table 1 (continued)

Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)
Capric acid (Kant et al. 2017)	32	152.7	Paraffin wax (Sarhaddi et al. 2017)	56	226	RT27 (Jin et al. 2016)	27	179
Composite based on compressed expanded graphite (Haillot et al. 2013)	58	190	Paraffin wax (Arunkumar et al. 2015)	58–60	226	RT27 (Qi et al. 2016)	28–30	179
Microencapsulated PCM, CT00 (Kong et al. 2017)	39.5	132	Paraffin wax (Elfasakhany 2016)	60.5	166.7	RT35HC (Chow and Lyu 2017)	34–36	240
CT01 (Kong et al. 2017)	38.4	190	Paraffin wax (Khalifa et al. 2013)	46.7	–	RT42-graphite (Chaabane et al. 2014)	43	139.7
CT02 (Kong et al. 2017)	36.9	169	Paraffin wax (Bouadila et al. 2014)	56.3	189	RT44HC (Zou et al. 2017)	43	255
CT03 (Kong et al. 2017)	41.7	139	Paraffin wax (Fazilati and Alemrajabi 2013)	55	187	RT54 (Lu et al. 2015)	55	179
Cu-paraffin wax (Elfasakhany 2016)	59.6	160.3	Paraffin wax (Kanimozhi et al. 2017)	54	203	RT54HC (Wang et al. 2017a, b)	52	168
Dodecanoic acid (Murray and Groulx 2014)	42.5 ± 0.5	182 ± 5%	Paraffin wax (Mahfuz et al. 2014)	56.06	200.74	RT PX-21 (Arkar and Medved 2015)	19.6	86
DuPont Energain PCM (Soares et al. 2014)	18–26	70	Paraffin wax (Lin and Al-Kayiem 2016)	60.42	184.2	RT PX-21 (Arkar et al. 2016)	19.6	86
Energain PCM (Fateh et al. 2017)	–	–	Paraffin wax (Al Imam et al. 2016)	56	256	RT18HC (Llorach-Massana et al. 2016)	17–19	250
Enhanced acid (Qi et al. 2016)	20.4	138.8	Paraffin wax (Sardarabadi et al. 2017)	42–72	200–220	RT42 (Charvát et al. 2014)	38–43	174 ± 7.5%
Fatty acids eutectic (Berthou et al. 2015)	21.3	152	Paraffin wax (Kabeel et al. 2016)	54	190	RT GR35 (Thiele et al. 2015)	29	–
Microencapsulated PCM (Wang et al. 2016)	20–25.4	33.25	Paraffin wax (El Khadraoui et al. 2016)	56–60	214.4	RT GR41 (Thiele et al. 2015)	45	–
Granular PCM including paraffin wax (Belmonte et al. 2016)	27	44	Paraffin wax (Karthikeyan et al. 2014)	55.5–66.5	–	RT 28 HC (Soares et al. 2016)	27.55 ± 0.19	258.1 ± 5.1
Graphite-PCM compound (Padovan and Manzan 2014)	25–60	–	Paraffin wax (Shalaby and Bek 2014)	49	–	RT organic PCM (Saffari et al. 2016)	23	–
Honey wax (Kanimozhi et al. 2017)	58	217	Paraffin wax (Rabha and Muthukumar 2017)	58–60	–	RT organic PCM (Saffari et al. 2016)	25	–
Hydrotreated technical grade paraffin (Feliński and Sekret 2017)	58	217.6	Paraffin wax (Reyes et al. 2014)	56–58	200–220	RT organic PCM (Saffari et al. 2016)	27	–

Table 1 (continued)

Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)	Names of PCM	Melting temperature (°C)	Latent heat (kJ/kg)
Microencapsulated PCM 24 (Kheradmand et al. 2016)	24	162.4	Paraffin wax (Jain and Tewari 2015)	–	–	S19 (Vadiee and Martin 2013)	19	160
Microencapsulated PCM 28 (Kheradmand et al. 2016)	28	170.1	Paraffin wax (Baniasadi et al. 2017)	70	–	Sodium acetate trihydrate (Li et al. 2018a, b)	58	266
Micronal DS5001X (Soares et al. 2016)	25.67 ± 0.07	111.3 ± 1.4	Paraffin wax (Ziapour and Hashtroudi 2017)	53	188	Sodium acetate trihydrate + 10% graphite (Nkwetta et al. 2014)	58	–
Micronal DS5001X (Lachheb et al. 2017)	26	110	PCM-1 (Yang et al. 2014)	60–62	209	Sodium thiosulfate pentahydrate (Al-harahsheh et al. 2018)	48.5	208.5
Micronal PCM (Marin et al. 2016)	25	–	PCM-2 (Yang et al. 2014)	50–52	200	Low flammability PCM, SP24E (Lin et al. 2014)	21–25	190
Mikrotek 37D paraffin (Stathopoulos et al. 2016)	37	226.8–230	PCM27 (Mi et al. 2016)	27	–	SP29 (Meng et al. 2017)	28–30	190

reasons, phase transition materials should not degrade over an extended period and be non-explosive, non-combustible, non-poisonous, and non-corrosive to building components (Cabeza et al. 2011).

Low energy dissipation, easy isolation from other materials, great recycling potential, and minimal environmental effect from the standpoint of environmental properties are required for PCMs. The PCM should also be plentiful, accessible, and affordable in terms of purchase costs to compete effectively with other productive systems (Cabeza et al. 2011).

Issues with PCM implementation

Even when carefully choosing the PCM to be used, it occasionally needs to catch up on all the requirements. Phase separation, supercooling, and fire resistance are some of the more typical issues with the deployment of PCMs.

Phase separation

Phase change materials may malfunction as a result of phase separation. In a perfect world, when a solid material transitions to the liquid phase, it keeps its consistent configuration, and when it proceeds to the solid phase, it keeps that homogeneity and composition as well, constantly displaying the identical enthalpy and transformation temperature throughout its life cycle (Li et al. 2020).

It is crucial to confirm that the phase transition occurs in eutectic mixes at the same temperature; otherwise, phase separation could result when one of the necessary components is still solid, whereas the other is liquid. As a result, the material's original composition vanishes, and the initial transition properties are lost (Li et al. 2020); (Frigione et al. 2019). The mixture's viscosity is increased by thickening agents, keeping the mixture's constituent parts together (Cabeza et al. 2011).

Supercooling

Supercooling is the process of solidifying a material below the temperature of the phase transition. In essence, the phase transition material behaves well when heated but cannot release the energy it has been holding onto during cooling. As a result, for the material to finish working, the outside temperature must drop sufficiently (Frigione et al. 2019).

Inorganic phase change materials experience this issue more frequently. Supercooling does not occur in most paraffin-based organic phase change materials. However, using a nucleating agent is one technique to minimize this issue (Cabeza et al. 2011).

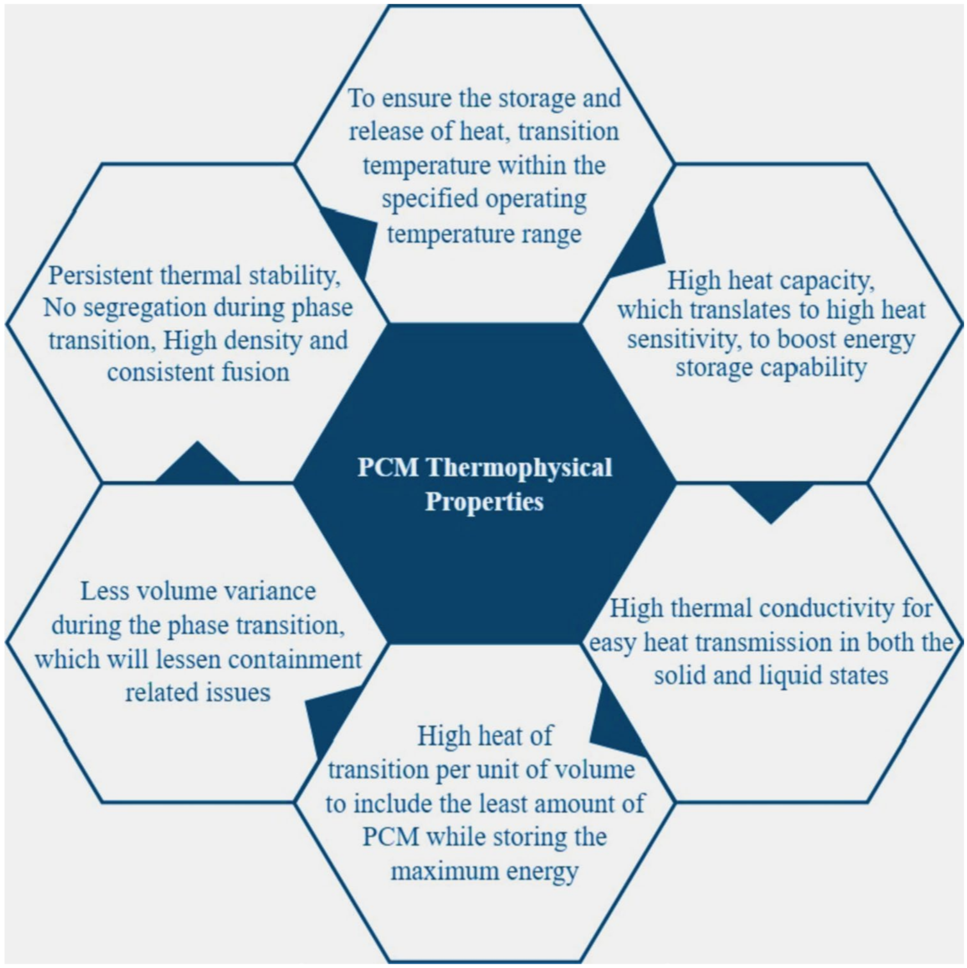


Fig. 5 Thermophysical properties of selected phase change materials

Fire resistance

In order to safeguard structures against fire dangers, there has been an increase in concern over fire resistance in recent years. The flammability risks presented by organic phase transition compounds, particularly paraffin waxes, pose questions concerning the fire resistance of products where these materials are used. The insertion of a stabilizer material with abilities to resist flames, such as magnesium hydroxide ($Mg(OH)_2$) and silica, is one remedy that has been examined (Song et al. 2010).

PCM performance enhancement

The effectiveness of PCMs is frequently jeopardized when applied to plates, tubes, or objects with small thermal conductivity (Li et al. 2020). There are a few approaches to enhance the performance of PCMs, including the insertion of thickeners and nucleating proxies, high heat conductivity additives, fire additives, increasing the contact surface, impregnating the porous matrix, and using multiple PCM (Frigione et al. 2019).

Utilizing multiple PCM involves working with numerous PCM with various transition temperatures. The TES can continue to function and be more profitable over a more extensive temperature range in this way. Through numerical simulations, Mosaffa et al. (2013) assessed the effectiveness of a refrigeration method using various PCMs and found that it performed well. Shaikh and Lafdi (2006) do numerous mathematical simulations to examine the effects of various PCM setups on slabs. Energy storage has significantly improved, as seen by the overall amount of stored energy. The numerical outcomes also showed that using many phase change materials instead of a single PCM can save energy expenses. Heat conduction can be increased by impregnating porous media with high thermal conductivity through PCMs.

For procreation, there is a perfect matrix porosity level that does not compromise thermal conductivity because thermal conductivity declines with increasing porosity. Mesalhy et al. (2005) conceded a research project, wherein they infused PCM into a graphite matrix after demonstrating that the porous matrix's emergence significantly affects the heat transmission rate and energy storage of the PCM.

The matrix's reduced porosity causes the melt to move more quickly. It has also been discovered that using a dense matrix with high permeability and high heat conductivity is the most excellent method for boosting PCM's storage efficiency.

PCM incorporation techniques

There are several ways to introduce the PCM into building materials, including direct inclusion, immersion, encapsulation, and stabilization (Memon 2014). The ability to apply both microencapsulation and macroencapsulation makes encapsulation (Fig. 2) the most often used PCM inclusion approach. Approximately, 70% of the work performed using the encapsulation approach utilizes microencapsulation, with the remaining 30% utilizing macroencapsulation. Conversely, direct integration and shape stabilization are procedures with fewer produced works, but they are still quite promising.

Direct incorporation

The easiest and most cost-effective way to use PCM is by direct integration, in which the material is produced alongside the building supplies. However, it is anticipated to show several drawbacks, including the influence of hydration products, a weakening of the binding among the aggregate and paste binders, a reduction in mechanical characteristics, and a decrease in robustness (Hawes et al. 1989).

As early as a few years ago, it was considered that the direct inclusion of PCM into building ingredients led to waste products as it could become more mobile once applied. Aguiar and Cunha (2016a, b) demonstrated that this highly effective technique results in no PCM losses. To investigate PCM performance in the liquid and solid states, the authors produced considerable work, including free phase change materials in mortars and assessing their activities at various temperatures (Fig. 6). It was feasible to see that the PCM-added mortars consistently had a reduced capacity to absorb water than those without phase change material accumulation (Cunha et al. 2016a, b).

Encapsulation

This method ensures that the PCM stays put where it was applied during the liquid phase by encapsulating it before incorporating it into building materials. In addition to serving as a barrier for protection, the PCM enclosure must be robust mechanically, flexible, corrosion resistant, and thermally stable. Additionally, it needs to have enough surface

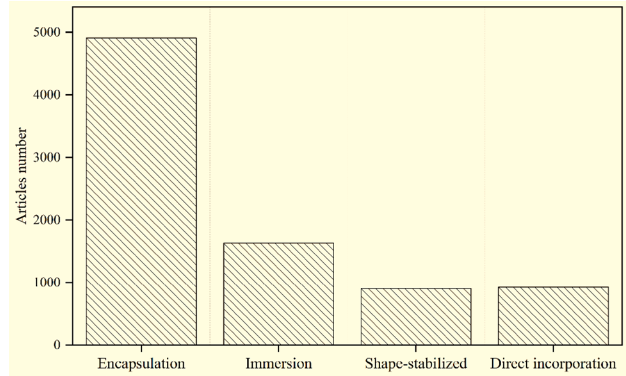


Fig. 6 Utilization methods for PCM inclusion

area for heat transfer, structural stability, and simple material handling (Regin et al. 2008).

Microencapsulation and macroencapsulation are the two basic types of encapsulation (Cabeza et al. 2011). The macroencapsulation method relies on injecting PCM into tubes, panels, or other sizable containers, often ones with a diameter of more than one centimeter. This method can contain a sizable aggregate of PCM in a single vessel. The key benefits of this approach are its simplicity in handling and transport, the potential for customizing the encapsulation for the intended use, more excellent material compatibility, and a decrease in exterior volume changes (Memon 2014). Low thermal conductivity, the requirement for containment devices to prevent destruction, and the potential for PCM to solidify in the junctions and edges, which would reduce heat transfer, are the drawbacks.

A pronounced way to include phase change material into assembled walls and roofing is through macroencapsulation. The basic materials (concrete, mortar, etc.) are not mixed with PCM in this process to prevent the loss of the basic materials' mechanical properties. Containers in the shape of panels are one use for PCM macroencapsulation. These vessels must have a high heat conductivity, such as metal vessels, to provide superior thermal performance (Marani and Nehdi 2019).

Steel containers were employed by Shi et al. (2014) to macroencapsulate PCM in concrete sandwich panel walls. According to their findings, the minimum interior temperature has increased, and the maximum indoor temperature has significantly decreased, which lessens indoor temperature swings. Navarro et al. (2015) examined the thermal behavior of PCM macrocapsules in some concrete blocks with an active hollow core. Conclusion: The charge/discharge process of the PCM could be carried out by the suggested PCM-concrete slab in about 70% of summer and winter days. In particular, the positioning of the PCM macrocapsule, the microenvironment conditions, the arrangement of the structural component, the thermal characteristics of the construction materials, and the category of PCM have a significant influence on the efficiency of the PCM macroencapsulation (Marani and Nehdi 2019).

A minor molecular mass is encapsulated in tiny particles coated in high-performance polymers. The microcapsules have a diameter of less than 1 cm and can be spherical or asymmetrical. The recommended diameter, however, is between 1 and 60 m. Due to the increased specific surface area of this encapsulation method, heat transmission is improved (Tyagi et al. 2011). PCM microcapsules can be purchased as a powder or an aqueous dispersal. The microcapsule's nucleus is mainly responsible for its designation. These could be mononuclear microcapsules with a single nucleus inside the shell or polycyclic microcapsules through several nuclei in the same shell and a matrix with evenly dispersed nuclei inside the shell (Navarro et al. 2015). Chemical, physical–chemical, and mechanical processes can all be used to create microencapsulation. The hedge of the microcapsule is generated in situ by chemical processes such as polymerization and polycondensation. Physical–chemical techniques use preformed polymers to form walls through actions like solvent removal.

Mechanical procedures comprise a diversity of spray techniques, fluid deposition coating procedures, and micronization. Among the most common techniques for PCM, microencapsulation involves dispersing PCM droplets in an aqueous solution and creating polymer hedges all around droplets employing techniques like co-precipitation, interface polymerization, and various in situ polymerization procedures. Because the subsequent application of the microencapsulation technique and the material used to make the capsules be influenced by their physical, mechanical, and chemical stability, these decisions are crucial.

As shown by scanning electron microscope (SEM) pictures in numerous studies (Lecompte et al. 2015; Aguayo et al. 2016), a possible issue with integrating PCM microcapsules is the microcapsule breaking through the concrete's blending or loading operation. Cryo-scanning electron microscopy was used by Pomianowski et al. (2014) to evaluate the final state of the microcapsules after mixing. The results showed that the PCM microcapsules had some damage. Hu (2009), for instance, looked at the PCM microcapsules' compressive strength, comprised of formaldehyde and melamine. The microcapsules, ranged in diameter from 1 to 12 m, were crushed amid parallel faces, released, and then compressed again till they ruptured. The outcomes exhibited that the capsules had about 19% elastic elongation and nearly 70% abounding. Sun et al. (2002) later examined the mechanical resistance of microcapsules made of gum arabic-gelatin, urea–formaldehyde, and melamine–formaldehyde. For melamine–formaldehyde and urea–formaldehyde, the various tested capsules exhibited an elastic behavior of up to 19 and 17%, respectively. The arabic-gelatin capsules only displayed elastic behavior after being extended by 50%.

Since it has a greater surface area and more efficient heat transfer rate/volume, the microencapsulation has benefits such as increased incorporation possibilities in different construction materials, improved stability against volume changes for the period of phase transitions, chemical solidity, and enriched thermal consistency. The lower mechanical qualities of the building constituents and the more significant cost of this approach are its drawbacks (Memon 2014).

Typically, PCM microcapsules are employed immediately in the construction material mixing procedure, mostly to replace aggregates partially. Using two different PCM microcapsules, Cunha et al. (2014) done an investigation to assess their effects in lime-gypsum mortars. It was feasible to confirm that the employment of various PCMs microcapsules results in a variety of mortar characteristics, which are connected to the sort of polymer utilized in the microcapsules' wall structure and their dimensions.

Submersion

In the submersion procedure, liquid PCM is dipped into the construction goods to allow capillary absorption of the material. However, the PCM can impair construction materials' mechanical qualities and longevity by interfering with their hydrating byproducts (Hawes et al. 1989).

This method is typically used to integrate PCM into light, porous aggregates. In the past few years, several studies have suggested various porous aggregates impregnated with PCM that used a range of adhesive and required materials (augmented clay, concrete aggregate block, and extensive vermiculite), in addition to a range of impregnation techniques (vacuum and direct impregnation) (Suttaphakdee et al. 2016). The lightweight aggregates' porous design makes them the best choice for keeping the PCM contained in concrete. These materials must, however, have the appropriate aggregate size, pore size, permeability, and surface area.

Augmented slate, shale/clay, vermiculite, gypsum, and pumice are four forms of lightweight aggregates studied by Aguayo et al. (2017). It was feasible to conclude that these materials' ability to absorb PCM can be influenced by their porosity and pore diameter. According to Kheradmand et al. (2015), as the smaller pebbles' potential for absorption was more extensive, the aggregate size can affect the PCM absorption ability.

Shape stabilization

In light of the possibility of PCM leakage in its liquid state, a number of researchers have put up a novel method called shape-stabilization (Jeong et al. 2015). This procedure involves melting the PCM and the reference material and combining them at a high temperature; then, the combination is cooled till it solidifies. PCM is stabilized using high-density polyethylene, styrene, and butadiene. The fundamental benefits of this strategy include high heat transfer properties and preservation of PCM stabilization all across the phase transformation period without the need for a vessel (Memon 2014).

The choice of the supplementary material and the manufacture of the PCM in a shape-stabilized form are essential variables that significantly impact the thermal properties. Porous materials having high heat conductance, such as diatomaceous, clay, silica fume, and charcoal/graphite, are most suited for creating shape-stabilized PCMs (Marani and Nehdi 2019).

PCM contribution to sustainable construction

Buildings' thermal comfort and energy efficiency are increased by the PCM integration in construction materials. Based on these materials' contributions to the social, economic, and environmental facets of sustainable development, their use in buildings contributes greatly to sustainability (Cunha et al. 2014).

The PCM's potential makes it available for thermal storage, and its benefit to the social dimension is linked to a decrease in the requirement for heating and cooling. Throughout an extended amount of time, the temperature within the buildings remains steady or fluctuates less noticeably.

While this technique relies on solar energy, its contribution to the environmental component is tied to a decline in non-renewable energy sources. On the other hand, as climatization requirements decline, air-conditioning system usage declines, reducing the number of harmful gases released into the atmosphere.

Lastly, the economic aspect relates to the decline in the building's maintenance expenses, more notably in the costs associated with energy use. It is crucial to use this technology, and the associated expenditures should be minimal and easily absorbable by building occupants.

Utilization of PCM in construction

There are several sizable urban regions with significant thermal limitations for the building and rehabilitation industry. Any solution should help lower energy consumption and enhance the living circumstances of buildings, whether for new construction or renovation projects.

Phase change materials have been used for thermal energy storage in buildings before 1980. Telkes (1978) and Lane (1981) conducted preliminary investigations on such materials for use in heating and cooling. Due to the growing popularity of thermal energy's heating and cooling uses, society and the scientific community are currently very interested in storing thermal energy. Thus, by lowering the occurrence of interior temperature swings and maintaining the temperature near the ideal range for an extended amount of time, building thermal comfort is significantly increased by thermal energy storage (Chen et al. 2009). Structures that consume a lot of energy and electrical energy costs that make thermal storage affordable compared to alternative energy sources are particularly intriguing applications for thermal storage systems (Verma and Singal 2008).

The following are a few benefits of this technology:

- Homogeneity in the energy network's request, which would lessen the load and prevent the imminent demise of the supply systems;
- Relocating temporary energy use during periods of inactivity will reduce costs associated with the electric bill;
- Improvements in thermal comfort inside a residential building, storage, and utilization of heat linked to solar energy (especially for winter heating), and conditioning connected to ventilation systems (especially for conditioning during the summertime), leading to a reduction in the usage of systems for air-conditioning (Shaikh and Lafdi 2006).

Including PCM in construction materials to modify their thermal characteristics is the most intriguing application of PCM in structures. There are several options to consider: In addition to being a component of the more complicated thermal system, which may include heat pumps and solar panels, PCM can also be included in the wall, floor, or ceiling (Li et al. 2018a, b). The large surface they provide for heat transfer and storage makes PCM an excellent choice for construction.

The number of publications is more significant for the wall applications (Fig. 3). It should be mentioned that the walls are the construction part of a structure with the broadest area of influence, which explains why the scientific community is more interested in this constructive aspect.

The fact that panels, masonry, concretes, and mortar rounds appear to be the majority of popular with the highest number of publications is significant, when it comes to the construction goods with PCM integration (Fig. 4). This scenario can be explained via the statistic that these materials can be utilized in many structure construction components and that there are numerous options for incorporating PCM.

Temperature variations and allocation of PCM material

Depending on the demand for industrial, commercial, and residential activities, power consumption changes dramatically during the day and at night. Effective energy consumption management offers significant economic benefits due to this variance. This variation can only be eliminated by using thermal storage, which can move a portion of the peak load to the off-peak period (Fig. 7).

The solution's superior performance is greatly influenced by compatibility between the ambient and PCM transition temperatures. It is vital to remember that the PCM considers changes in ambient temperature. Therefore, if the PCM transition temperature is chosen incorrectly, it may not operate or charge/discharge heat to the surroundings. Castell et al. (2010) provided evidence of the applicability of many PCMs for incorporation into gypsum boards. Despite having a significant thermal storage capacity, the PCM used could not function properly because the PCM transformation temperature did not fall within the comfortable range of temperature.

In order to improve PCM performance, it is crucial to select the right enthalpy. On the other hand, the maximum amount of PCM that can be included in building materials should be considered. A study conducted by Lai et al. (2010) allowed for the evaluation of the contribution of various PCM components included in gypsum boards. It has been feasible to conclude that a more significant PCM content in the constructive product results in a rise in thermal storage capacity.

As a consequence of their comprehension of the PCM potential benefits, several researchers contrasted the efficacy of a particular remedy with PCM with a conventional solution. For instance, calcium chloride hexahydrate, a PCM with a temperature transformation of 29 °C, was used by Sharma et al. (2009) to study wall heat storage. The outcomes made it possible to conclude that a wall made of PCM had greater thermal efficacy than a brick wall with a 40-cm thickness (Fig. 8).

The PCM's positioning in the acceptable solution is crucial; subsequently, it must detect changes in the ambient temperature before it can function. In order to fully utilize this technology, Jin et al. (2014) investigated to identify the PCM's most effective condition and optimal position. The outcomes demonstrated that the PCM is more effective when it is close to the inside of the spaces. It is understood that PCM can exist in three phases: solid, transitional condition between solid and liquid, and absolute liquid. There was no doubt that the PCM state significantly impacted how well the constructive solution worked. The PCM could release the latent heat more quickly when partially liquid.

A study on predicted gypsum with PCM integration was conducted by Schossig et al. (2005), advancing to a new method of using PCMs. For their investigations, the researchers fabricated two test cells coated in gypsum, one with and one without PCM insertion. One solution used gypsum with a 6-mm coating and 40% PCM, whereas the other used gypsum with a 15-mm layer and 20% PCM. It was feasible to monitor that throughout the measurement, the solution's 6-mm layer kept the cell's temperature down by about 4 °C. For three weeks, the PCMs contributed so significantly to thermal comfort that the PCM cell experienced temperatures above 28 °C for approximately five hours, compared to about fifty hours in the reference cell. Accordingly, it was feasible to accomplish that the PCM's location greatly impacted its condition, how well it performed during PCM phase changes, and how well the building walls were insulated.

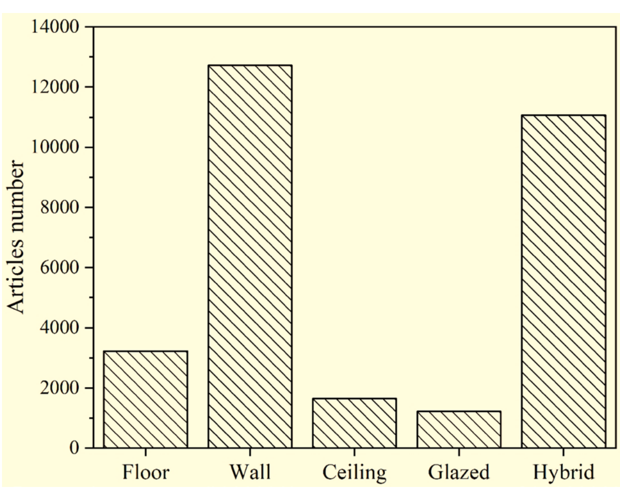


Fig. 7 Publication on the utilization of PCM in various building materials

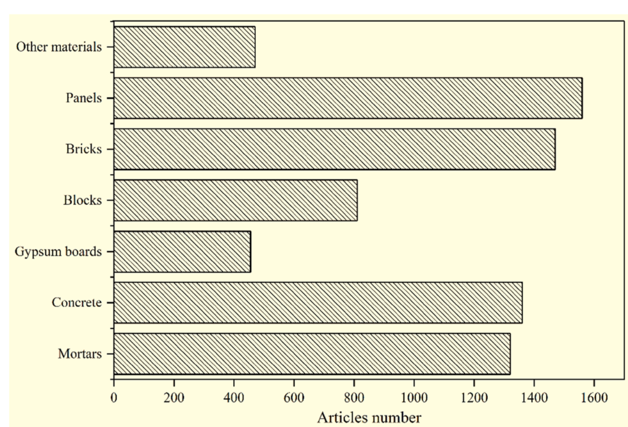


Fig. 8 Publication frequency in accordance with the inclusion of PCM in various building materials

Walls applications

The best method for utilizing PCM's potential is to install it inside the walls. Due to PCM's low cost and wide range of applications, it has been the focus of numerous studies to incorporate PCM into gypsum boards. However, different building materials can use the latent heat storage principles (Sharma et al. 2009).

Mortars

Mortars are a crucial component of structures since they coat a wide range of surfaces and can be made with various compositions to suit new construction or renovation projects.

Recently, different PCM microcapsule concentrations (0, 20, 40, and 60%) have been examined in mortars established on various binders (mortar, plaster, aerial lime, and hydraulic lime). The results of the tests indicated that more water, which also increased porosity, decreased the mechanical behavior of the PCM mortars (Cunha et al. 2015a, b). Similar scholars investigated the endurance of PCM mortars using a variety of binders. They found that the presence of PCM makes mortars more vulnerable to attack since the increase in porosity makes it easier for aggressors' agents to penetrate them. However, all of the mortars showed satisfactory behavior as their job progressed.

Additionally, it was feasible to observe that Mortars made of PCM-doped cement functioned better. However, the inclusion of PCM microcapsules was more sensitive to lime-based mortars (Cunha et al. 2017). The thermal performance was also assessed based on seasonal temperature guidelines characteristic of the Indian environment for every season during the year (Cunha et al. 2016a, b). Based on the results of this investigation, it was feasible to confirm that using PCM microcapsules decreased maximum temperature, increased minimum temperature significantly delayed the occurrence of extreme temperatures and reduced the demand for heating and cooling. The heating and cooling requirements might be done away with in the spring and the autumn, respectively.

The same team of experts also assessed the mortars' exposure to extreme temperatures. Incorporating PCM into mortars reduced operational efficiency across all examined temperatures (20, 200, and 600 °C). Cement-based mortars showed more extraordinary performance because they were less sensitive to exposure to high temperatures. Instead, aerial lime-based mortars displayed a more significant degradation and exhibited a more sensitive behavior (Cunha, Aguiar and Pacheco-Torgal 2015a, b). Additionally, it can be said that the incorporation of PCM microcapsules had no impact on the behavior of the mortar at high temperatures.

As a consequence of the treatment that the materials experience during encapsulating, using microencapsulated PCM entails substantial expenses, since this method enables the creation of mortars, including the potential for thermal regulation at a cheap cost, it was explored how PCM in free form—that is, non-encapsulated—could be directly incorporated into mortars. It should be mentioned that using a non-encapsulated PCM lowers the cost of making mortars because this primary material can be acquired for less money, and the mortars' manufacturing process may be made simpler. In a demonstration using directly incorporated non-encapsulated PCM in cement-based mortars, Cunha et al. (2016a, b) found that the incorporation of non-encapsulated PCM did not significantly change the significant features of the mortars. On the other hand, because the PCM was trapped in the mortar's pores, it was still feasible to see that it did not leave its interior.

Gypsum boards

Numerous investigations have been conducted since 1990 on including PCMs in gypsum panels. Others (Athienitis et al. 1997; Shilei et al. 2006) were focused on the numerical solution of the heat capacity, whereas several of them (Feldman et al. 1995; Cunha et al. 2016a, b) were concentrated on physical description. Gypsum panels are widely employed due to their accessibility, abundance in buildings, and particularly their location in such systems. Gypsum panels are typically used as a lining element in partition walls on the interior side, ensuring that most of the thermal inertia is utilized (Oliver 2012).

Incorporating PCM into gypsum boards reduces the severe temperatures inside buildings and the amount of non-renewable energy used. For instance, Athienitis et al. (1997) conducted both computational and experimental assessments established on applying PCM-incorporated gypsum boards to building walls. The maximum temperature has decreased by around 4 °C due to this investigation. Several years later, Shilei et al. (2006) also researched using 9.5-mm-thick Gypsum panels with a 20.3 to 17.9 °C transition temperature and a 26% PCM composition. A study confirmed that a decreased temperature oscillation was conducted in test cells laminated with PCM materials. Subsequently, similar examiners (Shilei et al. 2007) created gypsum panels that included a PCM in a test room's mutual wall surface to lessen the cooling burden.

After evaluating the room with PCM wall to the precedent room, it was determined that the PCM implementation was productive in using cooling systems. In order to compare a test room incorporating PCM over similar circumstances without and with gypsum panels, other experts conducted an experimental and numerical investigation on a summer day to determine the exterior temperature and the irradiation flux. According to the findings, PCM was applied to the walls to reduce oscillations in air temperature and improve thermal comfort (Kuznik et al. 2008).

Darkwa et al. (2006) looked into the behavior of dual PCM solutions because there was a high likelihood that PCM would be incorporated into gypsum boards. To immediately contrast with a typical gypsum board 10-mm thick and laminated with 2 mm of coated PCM, a PCM-coated gypsum board with a thickness of 12 mm was employed in one face. 17% of PCM was incorporated in both situations. The outcomes showed that using laminated PCM is more effective since it helped to raise the minimum temperature by about 17%. These outcomes are related to rising thermal inertia as well.

Concrete, blocks, and bricks

In addition to gypsum boards and mortars, the inclusion of PCM into construction components, including blocks, bricks, and other traditional materials, was also researched. Cabeza et al. (2007) created concrete test cells and observed their behavior with and without 5% PCM microcapsule incorporation. The roof and the south and west walls were constructed using concrete that has PCM incorporated into it. The highest temperature surface in the west wall varied by around 3 °C during the summer, with a 2-h time lag. The inclusion of PCM microcapsules into textile-reinforced concrete panels was further explored by (Bahrar et al. 2018), who noted a rise in the heat storage capacity and thermal inertia.

Greater thermal mass increased thermal resistance and decreased heat transfer are all effects of PCM incorporation in bricks. As a thermal capacitor, the PCM functions (Saxena et al. 2019). A macroencapsulation technique can incorporate the phase change materials by filling the spaces between the bricks. Castell et al. (2010) conducted an experimental investigation on the utilization of PCM in traditional and alveolar bricks with macroencapsulation for passive structure cooling. The two materials were used to build several test cells with and without PCM integration. The findings demonstrated that the PCM could reduce peak temperatures and balance out daily fluctuations. Additionally, in the summer of 2008, the PCM-equipped compartments' energy consumption was lowered by 15%. Due to these energy savings, CO2 emissions have decreased by approximately 1 to 1.5 kg/year/m2.

Saxena et al. (2019) studied the impacts of PCM inclusion in bricks on the Delhi climate. The temperature across the bricks was reduced by 5–6 °C compared to typical brick, and they examined two distinct PCMs (Eicosane and OM35); the heat transfer rate was decreased by 8 and 12%, respectively.

Panels and other materials

Additionally, several researchers have expressed interest in the use of PCM in panels. The experiment by Ahmad et al. (2006) concentrated on a new category of polyvinylchloride (PVC) alveolar boards with a 25-mm thickness, 20 kg of PCM, and a transition temperature of 21 to 25 °C. A sample cell was constructed using the panels, and its effectiveness was assessed to that of a reference test section. The magnitude of the temperature inside the PCM-equipped cell decreased by 20 °C over the summer. The phase change material's insertion in the regulation of interior temperature had a positive impact during the winter since it prevented the interior temperature from dropping below − 9 °C. The thermal performance of a panel intended to encase PCM was assessed in another study by Santos et al. (2019) and compared to a viable PCM board solution. They created two distinct examples, one conventional with nine boards and the other with seven PCM boards. A 30% increase in material over the current module is produced by the new design panel's 17.5 kg increase in PCM. The findings indicated that the more PCM material in the new panel lengthens the time it takes for the PCM to melt and solidify compared to the previous panel. As seen, PCM has several uses in conventional building materials. However, some materials also have less common applications in the construction sector. For instance, Jin et al. (2013) created PCM-filled pouches made of aluminum foil to insert into building walls. The outcomes demonstrated that this material's use decreased the peak charging time.

Floor applications

Numerous investigators have studied the insertion of PCMs in floors as a potential option. These options are diverse. Productive solutions include the use of a single layer for PCM incorporation (Entrop et al. 2011), a multi-layer solution containing different material properties and various types of PCM (Nagano et al. 2006), solutions with capillary channels for PCM circulation (Tian et al. 2020), and sometimes even their assimilation into more complex processes utilizing heat pumps (Bellos et al. 2016).

Using PCM integration on the floor, Nagano et al. (2006) created a structure. The structure was composed of a 3-cm-thick permeable PCM layer with a 20 °C transition temperature implemented beneath the floor and placed on a concrete block with an air box. According to the findings, the phase shift of the PCM took place between 17 and 22 degrees Celsius through an enthalpy of 31 kJ/kg. Besides a daily energy storage of 1.79 MJ/m2, the internal temperature could be preserved for 1.5–2.1 times longer than from a test sample. A 52 °C temperature transition electric underfloor system was created by Lin et al. (2005) using polyethylene boards impregnated with PCM. The tests were carried out in a chamber with an electric heating system running from midnight to eight in the morning every day. A temperature of 20 °C indoors and 13.6 °C outside were recorded throughout the observation time. Additionally, it was confirmed that 54% of the electric energy used, or around 3.3 kW/h, was shifted to empty hours.

Adding PCM to the raw materials that make up the construction goods is another way to use it. For instance, Kheradmand et al. (2015) investigated the viability of impregnating light inclusions for flooring solutions with phase change materials. The achieved results demonstrate the effectiveness of the PCM impregnation strategy in aggregates due to the high density of TES. This method may be ideal for applications where the PCMs cannot be directly included.

Purposes for the ceiling

Numerous researchers (Griffiths and Eames 2007; Chou et al. 2013) have also looked into the use of PCM-based technologies in ceilings. For PCM circulation, there are a few capillary network-equipped ceiling panel options (Koschenz and Lehmann 2004; Griffiths and Eames 2007). For illustration, Koschenz and Lehmann (2004) developed steel-based ceiling panels that allow the flow of PCM microcapsule-doped gypsum plaster throughout a web of capillary tubes. The panels have a phase transition temperature of 22 °C, a thickness of 5 cm, and a PCM density of 13 kg/m2. This amounts to around 23% of the panel's total mass. The melting process lasts approximately 7.5 h under a heat load of 40 W/m2, with 290 Wh/m2 stored energy. This outcome is significant because it permits operations to take place during hours close to the workday, helping to regulate the interior temperature. Griffiths et al. (2007) used PCM microcapsules in an aqueous medium made by BASF having a transformation temperature of 18 °C. The PCM was used in a ceiling cooling solution. Because of the small dia of the suspended PCM microcapsules, this was easy to pump the solution into the heating and cooling circuits of the roof using pumps that are readily accessible in the marketplace. The outcomes showed that even a 40% PCM content in an aqueous dispersion could be used as a fluid that transfers heat in a real-world application.

Alternative methods for including PCM in selling solutions were also developed, including a concrete slab incorporation approach and a macroencapsulation approach using a metallic panel (Pasupathy et al. 2008; Chou et al. 2013). Pasupathy et al. (2008) examined the effects of a 2.5-cm PCM board between two slabs on the roof, one composed of masonry including a thickness of 12 cm and the other consisting of mortar and brick having a thickness of 10 cm. The PCM used a transformation temperature of 26–28 °C and 188 kJ/kg of latent heat. In terms of the maximum and minimum surface temperatures, there were variances of 2 and 3 °C, respectively.

Chou et al. (2013) created a novel metallic ceiling with PCM in around 48% of their area. The study's primary objective is to employ the PCM to capture the heat flow of solar irradiation and distribute it all through exterior convection at night time. The outcomes provided for confirmation that the revised design effectively reduces the cooling load and heat flow through the building.

Researchers have also become interested in practical solutions built on the shape-stabilized PCM. Zhou et al. (2007) examined how a room wrapped with boards with PCM inside the ceilings and walls would behave at a transformation temperature of 21 °C. According to the findings, it can conserve roughly 47% of the energy during the day, or about 12% overall, throughout the heating season.

Glazed applications

Due to the growing use of glass areas in buildings, solutions with PCM aggregation for usage in such fields have indeed been created in recent decades. Windows, glazed façades, and roofs are all glazed units that are crucial components of a building. Glazing enables visibility, air circulation, passive solar gain, and day luminance. However, their low thermal efficiency, when compared to other components, dramatically impacts how much energy buildings use (Liu et al. 2018). As a result, using PCM in glazed units is a successful strategy for reducing building energy consumption and enabling daylighting inside (Khadiran et al. 2016).

Several researchers have pioneered their work in this field by using PCM in the glazing unit (Ismail and Henŕiquez 2001; Li et al. 2018a, b). Ismail and Henriquez (Ismail and Henŕiquez 2001) studied the thermal performance of single and double glass windows with PCM-filled airboxes. The PCM was preserved in a liquid tank throughout the experiment, pumped, and then solidified in the area between the panes, preventing heat loss through the window and maintaining an almost constant interior temperature. When PCM filled the area between glasses, a 55% reduction in transmitted energy was achieved. The effects of solar irradiation, melting temperature, and PCM layer thickness in three different parameters were explored by Liu et al. (2018) to determine a PCM-glazed thermal and visual characteristics. Since the glazed unit's transmittance is 50% when the PCM is liquid, it was able to deduce that glazed modules packed with PCM have increased thermal performance. The thermal performance of glazed units is also impacted by solar irradiation and PCM layer thickness because increased PCM thickness reduces heat loss. Work on glazing protection systems was developed by other researchers (Sharma et al. 2009; Silva et al. 2016). For instance, Silva et al. (2016)

designed a shutter structure for use in the glazed exterior that incorporates phase change materials. This system is left open during the day to absorb heat from the sun's rays. The system is closed and turned on to distribute heat into the rooms at night. With this solution, the interior temperature can be raised by around 2 °C.

Hybrid PCM applications

One PCM may need help to utilize the maximum thermal storage capacity in some severe weather situations with varying cold and hot seasons. In order to provide a solution that can operate over a more comprehensive temperature range, hybrid solutions have been developed by combining two or more PCM kinds, each of which has unique properties.

Pasupathy and Velraj (2008) experimented with investigating the thermal properties of a two-layer composite PCM solution on the building roof. The outcomes made it possible to confirm a reduction in internal temperature variations and an improvement in thermal comfort.

Jin and Zhang (2011) also studied floor solutions integrating two PCM layers, where each PCM layer had a unique transformation temperature and operated in both extremes of temperature. According to the findings, the surface temperature fluctuation and heat flows were reduced. Additionally, the machine can generate thermal energy even after the heat pump or cooler connected to it has been off for a long time. While compared with the conventional approach, which excludes PCM, it was shown that the peak heat dissipated by the floor containing PCM would rise by 41.1 and 37.9%, respectively, all through the heating and cooling periods.

Kheradmand and colleagues invented this kind of solution application in walls (Kheradmand et al. 2016). The investigators employed three distinct PCMs (hybrid solution) for interior coating mortars. Based on plausible temperature laws, it was determined how well the hybrid PCM solution improved the thermal efficiency of the mortars. Comparing the prototype to reference settings, it was possible to see a more substantial attenuation of the thermal amplitudes (either through single PCM or without PCM). It was also able to conclude that this solution is more advantageous than traditional methods that use a single PCM, which often has a more restricted impact because it combines numerous PCMs with different melting points that span a more excellent temperature range. On the other hand, a poor choice in PCM temperature transitions may even cause behavior worse than what would be anticipated in a conventional mortar.

The critical details of the many experimental works that were previously given are compiled in Table 2. No matter the PCM's location inside the structure, the transition temperature, or the incorporation method used, PCM use has consistently been proven to be an efficient way to raise a building's energy efficiency. This increase in minimum temperature, drop in maximum temperature, and reduction in temperature variance inside the structures make them much more constant, improving the buildings' energy efficiency. As a result, minimizing the amount of energy needed for heating and cooling buildings is possible, which will lessen the need for heating, ventilation and air-conditioning (HVAC) equipment, the amount of non-renewable energy used, and the negative environmental impacts incurred.

Future research directions and implications

In order to reduce thermal impacts, energy use, and overall greenhouse gas emissions, PCM can be added to building materials, envelops, walls, roofs, floors, and related components like windows and shading appliances. This comprehensive review of PCM's application in the building industry demonstrates these potential benefits. The simulation-based models discussed in this article, which were created for various configurations and experimental settings, encompassed a sizable number of associated research studies. The main conclusions of this review's study may be helpful in shedding light on future advancements, approaching developments pertaining to the investigation of energy storage materials, and prospective novel applications in the building industry.

According to the findings of the present investigation, there are a number of PCM constraints that need to be solved in future research. Here are some of them:

(1) Some PCMs might only work across a restricted temperature range, rendering them more suited to certain weather patterns or seasons although less practical in regions with significant temperature swings.
(2) Choosing the appropriate PCM for a particular application requires careful consideration. The appropriate thermal conductivity, melting temperature ranges, coherence with building materials, and durability over time are a few factors that must be taken into account. Compatibility issues may arise when PCMs come into contact with other components or construction materials, which may lead to leakage or inadequate performance.
(3) For PCMs to function at their best, heat must be transported effectively throughout the charging and discharging cycles. Due to heat transfer limitations brought on by some PCMs' limited thermal conductivity, charging and discharging rates may be slowed.
(4) It is crucial to ensure PCMs' stability over time and resilience if they are to be utilized successfully in building applications. PCM effectiveness as well as reliability may deteriorate with time due to factors like heat cycling, aging, and possible chemical degradation.

Table 2 An overview of experimental research

Constructive solution localization	PCM incorporation method	Constructive solution	PCM temperature transition (°C)	Concluding remarks
Wall	Immersion	Gypsum Boards	50	Energy cost reduction for the HVAC systems and transmission to the maximum demand for electricity
			20	Temperature reduction at maximum and rise at minimum
	Microencapsulation		22	Relatively low changes in temperature
	–		18	The minimum temperature was raised by the PCM's improved performance when it was placed close to the surface of the gypsum board
	Microencapsulation	Concrete	22	Air temperature reduction and lagging latency
			25	Improved thermal inertia and heat efficiency
	Macroencapsulation	Brick	35	Reducing the temperature and heat transfer
			25	Reduce the highest temperature, daytime thermal gradients, and electricity utilization
		Panels	30	Greater capacity for storing energy
			21	Reduce the intensity of the temperature
		Bags	34	Reduce the peak charging period
	Microencapsulation	Mortar	24	Raise the minimum and reduce the maximum temperature along with reduction in the heating and cooling requirements and lag time delay
	Microencapsulation (Hybrid solution)		10, 24, 26 and 28	Greater thermal amplitude attenuation
Ceiling	Macroencapsulation	Metallic panel	46	Diminution of cooling load and thermal flow
			22	A better internal temperature control system
	Shape-stabilization	Ceiling	21	Energy conservation during daylight hours
	–	Concrete	26	Reduce the highest temperature while raising the lowest temperature
	Microencapsulation	Panels	18	Decrease in volume flows
	Macroencapsulation (Hybrid solution)	Metallic panels	26 and 28	Reduce interior temperature swings and improve thermal environment
Floor	Macroencapsulation	Concrete	20	Prolonged periods of constant temperature
			23	Raising the minimum temperature while lowering the maximum temperature
	Shape-stabilization	Boards	52	Without increasing the temperature gradient, raise the temperature inside
	Macroencapsulation (Hybrid solution)	Panels	14, 16, 18, 20, 22, 30, 34, 38, 42 and 46	Decrease in the variability of surface temperatures and heat flows

Table 2 (continued)

Constructive solution localization	PCM incorporation method	Constructive solution	PCM temperature transition (°C)	Concluding remarks
Glazed	Macroencapsulation	Shutter system		Raise the temperature inside
				Maintaining the internal temperature at a somewhat consistent level
	Macroencapsulation (Hybrid solution)	–	18, 26 and 32	Improve the glazed unit's thermal efficiency when loaded with PCM

(5) The high cost of PCMs may be a significant barrier to their widespread usage in construction operations. Some PCMs, especially those with exceptional features, can be rather expensive.

A list of recommendations that can increase the use of PCMs in building applications includes the following as an illustration:

(1) Future research should consider the optimization of PCMs' quantity and temperature according to the intended use and local weather conditions.
(2) In order to guarantee PCMs can be used in a variety of climate zones, their nominal temperature range must be expanded.
(3) It would be interesting to know what are the most accepted properties of PCMs that would satisfy the current circumstances of the climate.
(4) To ensure optimum PCM selection and compatibility with diverse building materials, extensive research and testing are required.
(5) To tackle the low thermal conductivity and boost system efficiency, PCMs' heat transfer properties can be improved, or heat transfer enhancement methods such as fins or heat pipes can be used.
(6) Exciting new PCM technological advancement research includes the possibility of a dynamically adjustable as well as programmable phase change temperatures.
(7) The next generation of studies aims to develop PCMs with enhanced robustness, durability over time, and little degradation following repetitive temperature cycling.
(8) If subsequent parametric tests demonstrate that PCM technology has the potential to reduce consumption and save energy, utility subsidies may be made available.
(9) The relationship between PCMs and energy efficiency in building enclosures under different environmental conditions has not been sufficiently studied in real-world experiments.
(10) Since developers will eventually require to appraise the thermal effectiveness of confinement frameworks using PCMs, additional research is required to determine how well-suited these units are for use with current modeling software and to determine performance metrics that can be used for determining and assessing real heat exchange across various wall structures.
(11) Making PCM-based solutions commercially viable for various building projects requires robustness as well as inexpensive manufacturing procedures.

Conclusions

The globe's overconsumption is mainly responsible for the massive emission levels of greenhouse gases into the environment and the reliance on non-renewable resources that contribute to global climate change and the exhaustion of fossil fuels. A stringent set of laws governing buildings' energy efficiency has recently been enacted. Although these rules and actions had a good impact on their implementation, they needed to be more sufficient to significantly reduce the issue of excessive energy use in buildings. In this sense, using building materials that require less energy is today a pertinently essential and urgent issue.

Various thermal insulating materials are currently available on the market, but they have several drawbacks regarding toxicity and effectiveness. The ability of phase change materials to reduce indoor temperatures makes them an up-and-coming technology. It should be emphasized that the proper use of the PCM and attainment of its maximal efficiency depend on how well its transformation temperature matches the atmosphere wherein it will be used and the enthalpy involved in the phase shift. In contrast, their thermal enactment and, as a result, human well-being are directly impacted by the PCM properties. The choice of PCM must therefore be made in light of its economic, chemical, kinetic, thermal, physical, and ecological characteristics.

The introduction of PCM into building materials has numerous options. However, when choosing the inclusion technique, the category of material to be doped, its use in structures, and the expense of improvement and application should all be considered.

PCM has several uses because it may be used in building materials for floors, ceilings, and walls. It should be emphasized that in every study examined; it was always possible to conclude the positive impact of PCM inclusion on building thermal performance. Subsequently, in a real-world scenario, the operational duration of the air-conditioning units in a structure would be significantly decreased; there has been a decrease in severe temperatures and lesser temperature variations, leading to efficient energy saving. Thus, PCMs offer a favorable technological solution for lowering buildings' high energy consumption and harmful environmental effects.

Additional research is required in direct integration and shape-stabilized techniques, implications for outer building elements, and developing low-cost building materials doped with PCM.

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