A Review on Shape-Stabilized Phase Change Materials for Latent Energy Storage in Buildings

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Abstract: Many countries in the Global South have hot and dry climates with large diurnal temperature variations, which leads to large demand for space cooling—which is likely to increase with climate change. A common approach to dampen the indoor temperature fluctuations and thus reduce cooling energy demand is the use of thermal mass. However, the use of lightweight structures in many cities (e.g., high-rise structures, or for earthquake protection) precludes the use of traditional forms of thermal mass. Therefore, phase change materials (PCMs) are being widely developed as thermal energy storage systems for building applications. However, challenges such as leakage of PCMs in liquid state and their low thermal conductivity, still limit their applications in buildings. In this paper, we review the potential of Form or Shape-Stabilized Phase Change Materials (SSPCMs), which are developed by incorporating the PCM into a supporting matrix to prevent leakage in liquid state whilst improving thermal conductivity. We review different methods of preparation and the resultant thermal properties and chemical stability. We find good evidence in the literature for SSPCMs to reduce PCM leakage in liquid state, dampen indoor temperature fluctuations, and potentially alleviate peak energy demand by shifting peak loads to off-peak periods.

Keywords: shape-stabilized; storage; building; PCM; SSPCMs

1. Introduction

The ever-rising population and demanding thermal comfort has led to the incessant growing energy consumption rates worldwide. This in turn has led to deterioration of the global climate caused by greenhouse gas emissions due to significant use of fossil fuel. Thus, the effectual energy conservation is an important matter these days. This review has been conducted by considering those countries in the Global South that have hot and dry climate with large diurnal temperature fluctuations. Figure 1 shows the global annual diurnal temperature range for 1164 stations computed from the National Centers for Environmental Information/National Oceanic and Atmospheric Administration (NCEI/NOAA) weather database. Of the overall energy consumption globally, approximately 40% energy is consumed by the building sector. To bridge the gap between energy supply and demand, latent heat storage technologies such as PCMs have gained wide attention of researchers. Phase change materials are considered to be one of the most effective technologies to stock thermal energy (TE) in the form of latent heat (LH), which helps to reduce the heating and cooling loads within a building and the capability to maintain near constant temperature. When PCMs are incorporated into the building envelope, these not only reduce the interior temperature swings but also enhance the thermal comfort. Many methods are being used to incorporate...
PCMs into building envelopes such as incorporation into construction materials as cement, concrete, gypsum, etc., adding PCMs into wallboards, hollow bricks, creating Trombe wall integrated with double layer PCM, and encapsulating PCM with shell materials etc. Also, using carbon-based material additives with PCM helps in providing a high thermal conductivity. However, leakage of PCMs during solid-liquid phase transitions is often encountered resulting in poor reliability in practical applications of PCMs. To tackle this issue, efforts have been made to prepare microencapsulated PCMs (MPCMs) by encapsulating PCMs into containers or shape-stabilized PCMs (SSPCMs) by impregnating PCMs into porous supporting materials such as expanded graphite, diatomite, metal foam, and other inorganic materials such as expanded perlite (EP), expanded vermiculite (EV), etc. However, the preparation process of MPCMs is quite complicated and expensive, thus making its mass production difficult and it also has limited application fields [1–12]. Alternatively, the preparation procedure of SSPCMs is attractive due to its simple preparation techniques and cost effectiveness, which has significant development potential. Inorganic porous material-based FSCPCMs have been reported as a simple and efficient method to overcome PCM leakage in liquid state [13–15]. Many researchers have conducted studies to combine SSPCMs in building structure enclosure such as floor, glazing, walls, and roofing but most of the studies have been focused on walls [16,17]. Anthony et al. [18] studied the selection of the appropriate metallic PCM and containers for the application of thermal storage. Also, previous authors studied the CALPHAD database, which contains over 100 eutectic compositions of various metallic PCMs. Meng et al. [19] reviewed asphalt-based PCM for their application in construction. However, still not enough is known about SSPCMs, therefore a review is needed.

Figure 1. Global annual diurnal temperature range for 1,164 stations computed from the NCEI/NOAA weather database available at https://www1.ncdc.noaa.gov/pub/data/ghcn/daily/. The dataset contains daily air temperature data (max, min, average) from years spanning 1944 to 2016, though not all stations contain multi-year records. We observe that countries in Asia, Africa, the Middle East, and South America generally show large diurnal variations, though there are large gaps in geographical coverage for these regions.

2. Review Methodology

The literature review was conducted using the methodology described in Figure 2.
As shown in Figure 2, the methodology of the study starts with defining the scope of the review for building applications along with the problem statement with the context critical review of the existing studies and literature performed for 15 years (2005–2020). After understanding the literature, gaps and inconsistencies are figured out. Then, key advances in the field are highlighted, which may lead to high impact by reviewing recent papers of 2019 and 2020. Lastly, potential research areas to be explored for the future are highlighted.

The inferences drawn from the review of papers are discussed below. It includes identification and filtering out the relevant literature by using the keywords: “PCMs”, “TE storage”, and “SSPCMs”. To manage the vast literature, studies on PCMs used in building applications of past 15 years’ (2005–2020) were included as shown in Figure 3. The inconsistencies and gaps in the existing literature were identified.

If the melting temperature of a particular SSPCM lies in human comfort range (21–26 °C); what are the advantages and limitations of a particular SSPCM in terms of phase separation, PCM leakage, and thermal performance; and what is the melting enthalpy, freezing enthalpy, and latent heat for a SSPCM?

![Figure 2. Methodology adopted for the review.](image)

![Figure 3. Spread of published articles over the publication year, considered for review in this review article. It indicates that how the research has evolved during the last 15 years in the field of Shape-Stabilized Phase Change Materials (SSPCMs).](image)
3. Shape-Stabilized Phase Change Materials (SSPCMs)

SSPCMs, also known as Form-Stabilized Composite Phase Change Materials (FSCPCMs) are formed by embedding PCM into supporting material such as EV, EG, EP, diatomite, high-density polyethylene, butadiene, carbon nanotubes, styrene, etc. SSPCMs have attracted much interest in past decade due to their excellent ability to maintain shape even after large number of thermal cycles without any encapsulation [20–22]. SSPCMs integrated in building envelope can remarkably reduce indoor temperature swings, reduce energy demands, shift peak loads to off-peak periods, and maintain a comfortable interior thermal environment. Therefore, embedding SSPCMs into building enclosure can significantly improve the energy efficiency of building. Many researchers including [23–25] carried out studies on PCMs to improve energy conservation in a building. The authors of [24] developed paraffin eutectic mixture-based SSPCM using polypropylene as the supporting material. The resulting SSPCM had enthalpy and melting temperature of 126.8 J/g and 24.8 °C, respectively, which can assist in maintaining comfortable thermal environment in buildings. The authors of [23] developed a series of paraffinic SSPCMs using polyethylene of three types as supporting materials and studied the harmony of PCM with the supporting matrix. The authors found that paraffin/high-density polyethylene had the least compatibility among all three combinations; thus, paraffin/HDPE SSPCM is best to reduce indoor temperature swings in buildings among all three combinations. Tian et al. [25] prepared FSCPCM by using paraffin, carbon fibre, expanded graphite, and ethylene-vinyl acetate. The latent heat and melting temperature were found to be 167.4 J/g and 45.63 °C, respectively. Latent heat storage capacity of porous medium-based SSPCM depends upon the PCM mass fraction absorbed in the supporting material [25,26]. The higher the PCM mass fraction in the supporting matrix, the more the latent heat storage capacity will be. Inorganic porous materials like EV, EG, EP, etc., have been reviewed as supporting materials. Therefore, SSPCMs have a lot of potential in improving building energy efficiency, and further research is needed on this.

4. Preparation Methods of Inorganic FSCPCMs

Direct Impregnation Method (DIM) and Vacuum Adsorption Method (VAM) methods are utilized for the preparing inorganic porous medium micro-pore grade built FSCPCMs [9,27]. In direct impregnation, the mixing of PCMs and supporting materials can be carried out in two ways. First, the PCMs can be heated to molten condition and mixed afterwards with supporting materials. Second, the PCMs can be mixed with supporting materials in the form of solids and heated to molten status afterwards.

The first procedure is appropriate for preparing FSCPCMs with small phase transition temperature, while the second method is appropriate for preparing FSCPCMs with high phase transition temperature. Similarly, in VAM, besides surface tension and capillary force of porous materials, environmental pressure difference also helps in adsorption of liquid PCMs. Table 1 gives a brief on the work done by different researchers on PCMs, their advantages, and also the limitations of SSPCMs. The PCMs coated by paraffin have high melting enthalpy and also freezing enthalpy. This has poor thermal insulation due to enhanced thermal conductivity (‘K’ value). However, when the surface is coated with poly–vinyl-pyrrolidone, relatively low latent heat storage capacity is observed and there are no leakages reported. Similarly, shape-stabilization resolves the leakage issue of PCMs; it has good thermal stability, reliability, low thermal conductivity, large latent heat, and is non-flammable.
Table 1. Advantages and limitations of SSPCMs.

| Reference      | PCM                                                                 | Key Innovation                                                                 | Melting Temperature/Enthalpy | Freezing Temperature/Enthalpy | Advantages                                                                 | Limitations                                                                 |
|----------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------|------------------------------|--------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Lv et al. [28] | Eutectic PCM: Na$_2$SO$_4$.10H$_2$O-Na$_2$HPO$_4$.12H$_2$O impregnated into expanded graphite. | Coated the composite PCM by paraffin.                                           | High melting enthalpy of 172.3 kJ/kg was observed at 32.05 °C. | Freezing enthalpy of 140.8 kJ/kg was observed at 17.1 °C.                  | No phase separation and leakage issues.                                      | Poor thermal insulation due to enhanced thermal conductivity.                |
| Wang et al. [27] | A composite was prepared by incorporating fatty acid eutectic PCM (capric acid-palmitic acid-stearic acid) into EV via vacuum impregnation. | Added 5% (by weight) Cu powder to improve the thermal conductivity. | Enthalpy and melting temperature were 117.6 kJ/kg and 19.3 °C respectively. | Freezing temperature and enthalpy were 17.1 °C & 118.3 kJ/kg respectively | Thermal conductivity increased by 49.58% by adding Cu powder.               | Low thermal insulation property observed due to increased thermal conductivity. |
| Xu et al. [29] | Paraffin/expanded vermiculite composite                               | Composite PCM was used as aggregate to develop light-weight cement-based composite. | The latent heat and melting temperature of the composite PCM were 27 °C. and 77.6 kJ/kg respectively. | -                              | Good thermal insulation property of PCM favours its capability to reduce room temperature. | Relatively low latent heat is observed.                                     |
| Tang et al. [30] | Prepared SSPCM by embedding eutectic hydrated salt (Na$_2$SO$_4$.10H$_2$O-Na$_2$HPO$_4$.12H$_2$O) into modified SiO$_2$. | Surface coated with polyvinylpyrrolidone (PVP) to improve thermal cycling performance. | Melting temperature: 30.1 °C and melting enthalpy: 106.2 kJ/kg observed. | -                              | No phase separation issue.                                                 | Relatively low latent heat storage capacity observed.                       |
| Zhang et al. [31] | Prepared eutectic acid/EV based SSPCM by incorporating Na$_2$SO$_4$.10H$_2$O-Na$_2$CO$_3$.10H$_2$O in EV by vacuum impregnation. | The resulting composite was shape-stabilized by EV through vacuum impregnation. | Melting temperature: 23.98 °C. Latent heat: 110.3 kJ/kg observed. | -                              | Shape-stabilization resolves the leakage issue of PCM.                     | Low thermal conductivity.                                                   |
5. Supporting Materials Types

In the construction field, the potential candidates for preparation of SSPCMs are nearly all clay mineral materials with large surface area and porous structures such as diatomite [32–34], kaolin [35], montmorillonite [36], sepiolite [3], vermiculite [37–39], expanded perlite [40–42], and fly ash [43]. The interactions of hydrogen bonds, and surface strain, with auxiliary materials and PCMs can effectively restrict phase separation and leakage issues of PCMs during solid-liquid phase transitions. Furthermore, inorganic supporting materials’ high thermal conductivity can enhance the heat conduction of SSPCM. Methods such as direct adsorption and vacuum impregnation can be used to prepare SSPCMs [10].

Among numerous inorganic porous materials, EV, EP, diatomite, and EG possess the characteristics of high porosity, large surface area, and moderate pore diameter (0.1 micron–100 micron). Moreover, these four supporting materials have the benefits of low price and wide sources, hence are ideal supporting medium to prepare SSPCMs [44,45]. The properties of the EV, EP, EG, and diatomite, why these are important and used in buildings is discussed herein.

5.1. Expanded Vermiculite (EV) based SSPCM

EV is obtained from the calcination of mineral vermiculite at a high temperature. It is a lightweight conventional insulation material with sound and fire resistance properties and low thermal conductivity, which makes it suitable to be used as components for wallboards and roofs [46–48]. Vacuum adsorption and direct impregnation are commonly used methods to develop form- stable composite PCMs based on EV. Resulting PCMs have shown good thermal reliability and chemical stability. Chung et al. [14] studied its chemical stability and thermal properties by incorporating n-octadecane into EV by vacuum impregnation process. Maximum 80.65% by mass of n-octadecane was incorporated into EV. Wen et al. [49] incorporated lauric acid into EV with 70 wt% of lauric acid in FSCPCM composite with no leakage. At this composition, latent heat of FSCPCM was observed 126.8 J/g and melting temperature of FSCPCM was observed 41.9 °C. When pure PCMs possess too high a phase change temperature for building applications, then different PCMs can be mixed together in proper ratio to obtain a suitable phase change temperature [39]. Karaipekli and Sari [50] prepared Capric-myristic acid FSCPCM with EV as supporting material by vacuum impregnation technique and adjusted eutectic mixture phase change temperature at 25 °C by mixing myristic acid and Capric acid in 7:3 mass ratio. The eutectic mixture was then absorbed into porous EV with maximum 20 wt% of eutectic mixture without leakage. The latent heat and melting temperature of FSCPCM were 27 J/g and 19.8 °C, respectively. Even after 3000 thermal cycles the FSCPCM was chemically stable and thermally reliable.

Although FSCPCM based on EV possess good chemical and thermal stability, they suffer from low thermal conductivity and limited adsorption capacity, which hinders their use in thermal energy storage applications. Many researchers have conducted research to overcome the above-mentioned limitations. Jin and Zhang [51] firstly prepared modified EV by using nitric acid to treat TiO$_2$-loaded EV. The authors then prepared stearic acid/modified EV FSCPCM by using vacuum impregnation. On comparing with unmodified FSCPCM, the modified FSCPCM’s latent heat of fusion showed increase by 69.2 J/g. Nitric acid and methyl ammonium bromide were used by Wei et al. [37] to modify EV into carbonation EV (EVC). The authors then prepared capric acid-myristic acid-stearic acid/EVC FSCPCM. As compared to FSCPCM based on EV, the latent heat of FSCPCM based on EVC was 39.1% more. Deng et al. [7] used nano-silicon carbide to enhance thermal conductivity of polyethylene glycol/EV FSCPCM. With addition of 3.29 wt. % nano-silicon carbide, the thermal conductivity of FSCPCM was enhanced by about 96% as equated with FSCPCM minus nano-silicon carbide. Several authors like Zhang et al. [52], Deng et al. [7], etc., have also worked on increasing the thermal conductivity of FSCPCMs.

Karaipekli and Sari [50], Guan et al. [53], and Chung et al. [14] also conducted similar research. The authors observed that expanded vermiculite is not only an outstanding supporting material for adsorption of organic PCMs, it is also quite suitable for insulation because of its low thermal conductivity. According to Lin et al. [11], it is quite probable in the future to develop composite PCMs with wonderful insulation performance, large latent heat capacity, and non-flammability along with
low cost by impregnating inorganic salt hydrates into EV. Therefore, EVs have a lot of potential as a lightweight conventional insulation material possessing sound and fire resistance properties and low thermal conductivity, which makes it suitable to be used as components for wall assemblies and roofs. However, further research is needed on this to explore its impact on improving building energy efficiency.

5.2. Expanded Perlite (EP) Based FSCPCM

In EP-based FSCPCM, organic materials of small PC temperature are generally used as PCMs. The preparation methods mainly include vacuum adsorption after melt impregnation. Lu et al. [15] developed paraffin consisting FSCPCM with EP as supporting material with maximum 60 weight % of paraffin under a no-leakage condition. The melting temperature was 27.6 °C and latent heat of fusion of FSCPCM was at 80.9 J/g. Even after 2000 thermal cycles, the chemical stability and thermal reliability of FSCPCM was still maintained. Li et al. [38] prepared Capric acid in which the latent heat of fusion was reported as 98.1 J/g and melting point 31.8 °C. After 5000 thermal cycles, there was a 2.6% decrease in the latent heat of melting and 0.6% change in latent heat of freezing. Liu et al. [13] developed Lauric acid/EP-based FSCPCM by impregnation method. EP could adsorb maximum 70 wt. % of lauric acid under no leakage condition. The latent heat of FSCPCM was 105.6 J/g and melting temperature was reported as 43.2 °C.

Desirable PC temperature is possibly achieved by mixing multiple PCMs and adjusting their composition ratio. Jiao et al. [54] developed Capric acid-stearic acid-based EP FSCPCM by using vacuum adsorption. Melting temperature 33 °C & 33.5 °C, and latent heat of FSCPCM initially and after 1000 thermal cycles were reported to be 131.3 J/g and 131.1 J/g, respectively. Zhang et al. [55] prepared Capric acid-palmitic acid by vacuum adsorption method. EP could adsorb maximum 65 wt. % of eutectic acid. The latent heat of FSCPCM was reported as 88.4 J/g and melting temperature was 24.1 °C. Nomura et al. [56] observed that FSCPCM prepared by vacuuming can store more latent heat as compared to that prepared without vacuuming. Although EP-based FSCPCM possess excellent thermal properties, due to low λ value of EP, their ‘K’ value is low. Also, on using EP-based FSCPCM with a lower melting temperature than ambient temperature, in cementitious composites, undesired adverse effects of FSCPCMs such as leakage were observed [48].

Researchers such as Ramakrishnan et al. [57] studied measures to avoid FSCPCM leakage. To improve the thermal conductivity of EP-based FSCPCM, Xiaofeng et al. [36] modified EP through in-situ carbonization with sucrose solution and obtained an EP composite with a carbon layer on the surface (EPC). The authors then used vacuum impregnation to prepare polyethylene glycol/EP FSCPCM. The ‘K’ value of modified FSCPCM was found to increase by 2.9 times as compared to unmodified FSCPCM. The ‘K’ value enhancers such as EG were also used by some researchers in EP-based FSCPCM. On adding 5% graphite, Sun et al. [58] increased the ‘K’ value of paraffin by 113.3%. Ramakrishnan et al. [41] observed that adding 1 wt. % nano-graphene to EP-based FSCPCM increases its thermal conductivity by 49%. Ramakrishnan et al. [57] added 2 wt. % EG to ternary fatty acid/EP FSCPCM and observed 95% increase in the thermal conductivity. Ramakrishnan et al. [6] incorporated EP-based FSCPCM in cement and then measured its heat storage capacity. The peak temperature observations for two consecutive days showed 2.7 °C reduction in peak temperature in PCM-enhanced test cells as compared to cement test cells, which shows the improvement in cement heat storage capacity on integrating FSCPCM based on EP.

Therefore, EP-based FSCPCMs have a lot of potential to improve the thermal conductivity significantly, which makes it suitable to be used as components for wall and roofing assemblies. However, further research is needed on this to explore its impact on improving building energy efficiency in India.

5.3. Diatomite based FSCPCM

Diatomite mainly consists of amorphous silicon dioxide and small fractions of Fe₂O₃, Al₂O₃, MgO, CaO, TiO₂, etc. PCMs such as paraffin, polyethylene glycol, fatty acids, etc., can be used to prepare
Diatomite-based FSCPCMs are observed to show good chemical stability and thermal reliability [10]. Fu et al. [59] used the melt impregnation technique to develop Capric acid. Diatomite could adsorb a maximum of 40% Capric acid without leakage. The melting temperature of 40.9 °C and latent heat of fusion of FSCPCM was reported as 57.4 J/g and its solidification temperature and latent heat of freezing were 38.7 °C and 57.2 J/g, respectively. For surrounding temperature less than 57 °C, FSCPCM possessed good thermal stability. Li et al. [60] used the melt impregnation method to adsorb capric-lauric acid in diatomite. A maximum of 47% eutectic acid was adsorbed in diatomite. The latent heat of the FSCPCM was reported as 66.8 J/g and melting temperature 16.7 °C.

Although FSCPCM based on diatomite possess good chemical and thermal stability, their thermal conductivity, storage capacity, and adsorption performance are unsatisfactory. The PCM material in diatomite-based FSCPCM mainly decides the latent heat of FSCPCM just like FSCPCM based on EP and FSCPCM based on EV. With the increase in diatomite’s adsorption capacity, its latent heat capacity also increases. Methods such as preserving, boiling, etc., can be used to increase diatomite’s pore volume and surface area and thus increase its adsorption capacity [60]. The ‘K’ value of diatomite-based FSCPCMs can be improved by adding components possessing high ‘K’ value such as EG, carbon nanotubes, and silver nanoparticles [10]. Xu and Li [61] found that adding 0.26 wt. % of multi-walled carbon nanotubes resulted in a 42.5% increase in the thermal conductivity of diatomite-based FSCPCM. Li and Qian [62] observed that adding 7.2 wt. % Ag nanoparticles resulted in a 127% increase in thermal conductivity of FSCPCM.

Therefore, diatomite-based FSCPCMs have a potential to improve the ‘K’ value by adding components possessing high ‘K’ value as EG, carbon nanotubes, etc. However, further research is needed on this to explore its impact on improving building energy efficiency in India.

5.4. Expanded Graphite (EG) based FSCPCM

Natural flake graphite, when treated by electrochemical or chemical intercalation followed by instantaneous heating, forms high-temperature expansion that results into formation of EG. Apart from many benefits of natural graphite, EG also possesses features like greater reactivity, high specific surface area, porous structure, compressibility, and higher elastic modulus; thus, it possesses outstanding adsorption capacity. Therefore, EG-based FSCPCMs possess the benefits of comparatively high latent heat and also enhanced thermal conductivity [27–30,63,64]. Zhang et al. [65] thermally treated EG and then prepared paraffin/EG FSPCM. FSPCM contained 85.56 wt. % paraffin. The latent heat of FSPCM was reported as 161.4 J/g and melting temperature 48.8 °C. As a result of which the inherent structure of expanded graphite and solid-liquid phase change temperature of paraffin is not changed. Not only this, but the thermal storage capacity and thermal conductivity turns out to be high leading to more latent heat of paraffin with the large thermal conductivity of graphite.

Therefore, expanded graphite-based FSPCMs have a lot of potential to enhance thermal conductivity and also high latent heat. Thus, further research is needed to explore the potentials on improving building energy efficiency in India.

6. SSPCMs for Building Envelope Applications

The building envelope consisting of floors, roofs, windows, walls, and skylights plays a vital role in exchanging heat between exterior and interior environments. Conventional building enclosure possesses limited thermal capacity due to which changes in outdoor thermal environment affects indoor thermal environment significantly. Thus, to enhance building thermal capacity and make the indoor thermal environment less complex than the outside thermal environment, PCMs can be incorporated into building elements like windows, floors, roofs, and walls.

6.1. Walls

Of the existing studies on the building envelope, nearly 60% have focused on building walls because of their large surface area and significant contribution to energy load. Many researchers
including Wang et al. [66], Li et al. [67], Barreneche et al. [68], Kong et al. [69], etc., conducted experiments to evaluate the performance of PCMs in reducing heating/cooling energy loads. Kong et al. [70] tested the performance of SSPCM in summer, autumn, as well as winter. The authors embedded SSPCM in mortar bricks with the following composition: Portland cement 37.5%, yellow sand 22.5%, and SSPCMs 40% by weight, and observed that with PCM the heating and cooling loads were reduced by 10–30% and 24.3%, respectively. Kong et al. [69] integrated PCM panels in buildings and studied its performance. The authors observed reduced temperature fluctuations, reduced peak temperature, and improved thermal inertia. Barreneche et al. [68] evaluated acoustical and thermal performance of SSPCM layers in a building between 4 June to 4 September in the year 2013. As compared to reference cubicles, up to 4 dB noise was insulated by the new SSPCM plate and a 3 °C reduction in indoor room temperature was observed for the room with PCMs. Jin et al. [71,72] numerically estimated the location of a PCM wallboard. The authors recommended that with increasing thickness, melting temperature, and heat of fusion, the PCM layer must be close to the external side whereas with an increase in internal wall surface temperature, the PCM must be located close to the internal side. Zhou et al. [54,73,74] integrated SSPCM wallboards in an office building in Beijing and modelled its thermal performance under night ventilation. From the modelled data, it was found that with SSPCM and night ventilation cooling, energy demand could be reduced by 76%, which improves the daily indoor thermal environment.

In Singapore, Lei et al. [75] evaluated PCM performance in summer to lower energy demand in air-conditioned structures. The 10mm thick PCM layer with a 28 °C melting temperature was fixed on the exterior wall surface. Numerical data showed 21–32% reduction in heat gain through walls, which is more obvious in the tropical climate as compared to other climatic regions. The Design Builder software was used by Auzeby et al. [76] for demonstrating the efficiency of PCMs in lowering overheating issues during summers in residential buildings of the UK and also identified the influential factors. It was proposed by authors that for residential buildings in the UK, generally having natural ventilation, PCMs can be capable of handling rising summer temperature. Additionally, both construction-related and environmental factors would affect the performance of PCM, so choice of PCM must be case-specific. Diaconu et al. [77] developed a SSPCM wall and investigated its heating and cooling energy saving potential in continental climate. The external wallboard worked during summer and the internal wallboard worked during winter. The external wallboards had melting temperatures more than that of the internal wallboards. The authors observed 12.8% and 1.0% reductions in heating and cooling loads, respectively, whereas reduction in peak heating and cooling loads was 35.4% and 24.3%, respectively.

Meng et al. [19] suggested a room with distinct SSPCM wallboards positioned at different locations, which could work actively in summer as well as winter. The authors used TRNSYS 17 software to develop PCM model and experimentally validated it. The room with PCM experienced 4.3 °C and 14.2 °C reduction in indoor temperature swings during summer and winter, respectively, as compared to the room without PCM. Yao et al. [78] proposed a paraffin/EP-based SSPCM wallboard and developed its 1-D mathematical model on TRNSYS software and experimentally validated it. The simulation results for this SSPCM wallboard, integrated in a non-residential building, showed 9.2 ºC reductions in room air temperature during summer. Many other researchers such as Kim et al. [79,80], Kong et al. [70], and Biswas et al. [81] studied an innovative PCM supported by expanded graphite nanosheets, which are highly conductive, and allow enhanced thermal storage and energy distribution. Also, this PCM wallboard helps in reducing peak cooling loads.

Therefore, further research is needed on the impact of SSPCMs on reduction in heating and cooling loads, reduced temperature fluctuations, reduced peak temperature, and improved thermal inertia on different types of walling assemblies’ integrated PCM panels in buildings and study their real-time performance.

Xuetung et al. [82] demonstrated that AcCNF-encapsulated paraffin can be used for sustainable solution for efficient thermal energy conversion and storage.
6.2. Floor

PCM floors possess considerable ability to save energy as they store a significant portion of latent heat as they directly absorb solar energy during sunny days. Ye et al. [83] used an energy saving index to analyse the performance of paraffin/graphite foam-based SSPCM floor in a residential room. It was observed from the results that SSPCM performed well during the summer season and worse during winter, whereas the insulation material performed well throughout the year. Royon et al. [84] optimized the amount of PCM integrated in building floor. The PCM panel utilized in an existing false ceiling under the floor with cylinder-shaped cavities were dipped with paraffin and polymer. The authors then carried out numerical simulation on Comsol Multi-physics software and then validated the results by experiment. Several other researchers as Karim et al. [24], Belmonte et al. [85], Jin et al. [51], Zhou et al. [20], etc., evaluated the performance of PCM when integrated in the floor.

Therefore, further research is needed on the impact of SSPCMs on reduction in heating and cooling loads, reduced temperature fluctuations, reduced peak temperature on different types of floor assemblies’ in buildings, and study their real-time performance.

6.3. Roof

Of all the building enclosure components, roofs receive the highest fraction of solar radiation, hence it is quite important for the indoor thermal environment of a building. According to [33], SSPCMs incorporated into the roof can reduce the indoor temperature variations. Safari et al. [86] numerically optimized the UHI (urban heat island) effect on a cool PCM roof and revealed that PCMs with a high phase transition temperature are capable of reducing thermal stress during summer whereas those with a low phase transition temperature were suitable to reduce energy demand during winter. Roman et al. [87] used EnergyPlus software to evaluate UHI effect on a cool roof as well as a PCM roof in some cities of the United States. The study revealed that under a wide albedo range, maximum heat flux by PCM roof was 54% less than that by cool roof. Simultaneously, under varying albedo, maximum sensible heat flux was reduced by 40% for the PCM roof as compared to the cool roof. Jaworski [88] and Pasupathy et al. [46,89] have evaluated the performance of SSPCM embedded roofs.

Therefore, further research is needed on SSPCMs to improve the indoor thermal environment on different types of roofing assemblies’ integrated PCM panels in buildings and study their real-time performance.

6.4. Windows

Only a few studies are available on SSPCMs integrated in building windows evaluating the advantages of SSPCMs in window shutts. During summer excessive solar heat enters a building via glazed facades leading to high cooling energy demand, and during winter a significant portion of energy is lost through windows [33]. Thus, the influence of PCMs in improving building windows’ performance is very important to explore. Silva et al. [90,91] studied the effect of a window glass light filled with PCM and a window shutter (located outside the experimental room) made of aluminium frame and filled with RT28HC paraffin as PCM. The maximum room temperature with PCM shutter was observed as 37.2 °C, which was 16.6 °C less than without PCM shutter. Thus, window shutters with PCM not only enhanced energy efficiency, but also regulates the indoor temperature of the building. Xiang et al. [34] numerically investigated the influence of PCMs on windows. Therefore, further research is needed to study the real-time performance and impact of SSPCMs integrated in building windows on reducing the excessive heat entering a building in different tropical regions.

7. Conclusions and Future Outlook

This study has critically examined and also analysed the preparation, performance analysis, thermal, and chemical stability of SSPCMs used in building applications. Building energy demand reduction has been discussed with regard to integrating SSPCM with building materials and the effect
of adding supporting matrix to the PCM. The change in thermal conductivity of PCM and latent heat energy storage capacity has also been discussed.

**Summary of the Research Carried Out in the Area of SSPCMs**

SSPCMs have shown to be a promising approach to reduce PCM leakage in liquid state. Many researchers have studied the energy efficiency and thermal stability of SSPCM walls, roof, floor, and windows and have found that SSPCMs incorporated in the building envelope can reduce indoor temperature variation, reduce peak energy demands, and shift peak energy loads to off-peak periods. According to Jeong et al. [92], by using SSPCM concrete, the peak temperature can be reduced by up to 8.5 °C and time lag to reach peak temperature can be reached up to 1 h depending upon the position of SSPCM. Therefore, embedding SSPCMs into building enclosures can significantly increase building energy efficiency. Among the inorganic porous materials discussed, EG is found to be the most commonly used supporting material to adsorb PCMs due to its simple preparation process and low cost. Its compatibility with many surfaces and interconnected open pores provides outstanding adsorption capacity (80 wt.%–93 wt.%) as compared to EV, EP, and diatomite. The adsorption capacity of EV and EP was around 60 wt. % and that of diatomite was around 50 wt. %. A major portion of research done in this field consists of simulation studies to investigate the thermal performance of SSPCMs integrated in building envelope.

These studies include factors such as PCMs properties, PCM walls orientation, PCM wallboards location, and ambient conditions to analyse the effect of PCM on buildings’ thermal performance. Yifan et al. [93] found various insufficiencies in current research in the field of PCM when external field conditions are different (i.e., magnetic and electric field, ultrasonic waves, and mechanical vibrations). Jun et al. [94] worked on finding the potential fillers (granular materials) between macro-encapsulated PCM. Therefore, reduction in void space using different granular materials can be researched for higher storage efficiency of the same. Kapsalis and Karamanis [95] critically analysed the various mechanisms in the heat transfer and examined the recent state of the methods. They also classified the applications to reflect the better effects of the latent energy storage to the indirect and direct heat pump energy consumption, respectively. Atinafu et al. [96] worked on a shape-stabilized composite PCM based on a three-dimensional (3D) porous-connected metal–organic framework (MOF) and polyethylene glycol (PEG). It resulted in a composite material exhibiting a high transition enthalpy (159.8 kJ/kg) with an encapsulation efficiency. Also, Jia et al. [97] worked with boron nitride (BN)@chitosan (CS) scaffolds with three-dimensional (3D) porous structures; as a result of which, effective thermal conductive pathways were created in the resultant scaffolds. Qian et al. [98] reported that polyethylene glycol (PEG)/diatomite form-stable phase change composite (fs-PCC) with single-walled carbon nanotubes (SWCNs) as a nano-additive exhibits excellent chemical and thermal durability and has potential application in solar thermal energy storage and solar heating. Yang et al. [99] chose Polyethylene glycol (PEG) and tetraethyl orthosilicate (TEOS) as the phase change substance and the silica framework precursor, respectively.

The results showed the silica framework strongly confined the crystallization of PEG. The crystallinity and thermodynamic performance of the composites were undesirable for PEG with molecular weight of 1500 even when the PEG content reached 80 wt. %. Zhang et al. [100] worked on novel polyethylene glycol (PEG)/White Carbon Black (WCB) form-stable composite phase changes materials (FS-CPCMs) and prepared one that is super-ultrasound-assisted, which decreased the reaction time. Test results showed that PEG does not easily leak from the fluffy network structure of WCB during solid-liquid phase transition.

**8. Further Research**

Based on the literature review, gaps have been identified and further research is needed on the following:
• Existing studies have focused either on heating or cooling applications of PCMs. Therefore, PCMs are highly required for both heating as well as cooling applications in buildings. Further research on the performance of PCM in maintaining thermal comfort for a whole year is being carried out by the authors.

• Most of the studies in the literature have focused on walls, and less research reported on incorporating PCMs with roof, floor, and windows. Thus, further research on these areas is needed and authors are researching on it.

• Most of the studies have been conducted at laboratory level and not in a full-scale room. Therefore, real-time, full-scale, experimental studies are essential to analyse the practicability and reliability of SSPCMs under real weather conditions. Hence, the authors are exploring a full-scale prototype in a composite climate where both cooling and heating requirements exist.

• Similarly, further studies with a focus on environmental and economic analysis as a result of incorporating PCMs in building materials are required, as currently these topics are least researched. Further studies are needed to improve the long-term thermal stability and chemical reliability of SSPCMs in buildings, under real weather conditions. The authors are researching it.

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