

Encapsulation of Waxes for Materials Providing Passive Absorption & Release of Thermal Energy

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Zásady pro vypracování

Materiály poskytující pasivní absorpci a uvolňování tepelné energie jsou zajímavé systémy využívané jako pasivní klimatizace budov. Materiály jsou složeny z nosného materiálu, např. LDPE, a komponenty poskytující fázový přechod, během něhož dochází k absorpci energie a následně její uvolnění. Komerčně zajímavý materiál s fázovým přechodem je vosk. Problém ovšem nastává v případě, že vosk není v polymerní matici stabilizovaný a časem z kompozitu vytéká. Řešením může být použití vosku ve formě kapslí, kde vnitřní vrstva je tvořena voskem a vnější vrstva tenkým polymerním obalem. Aby došlo kompletnímu roztavení vosku, je vhodné zvýšit tepelnou vodivost polymerního obalu nebo celé kapsle pomocí vhodného plniva.

Student se v práci bude věnovat syntéze voskových kapslí na bázi PMMA, vosku a částic s vysokou tepelnou vodivostí. Student vypracuje literární přehled na dané téma. V laboratoři provede sérii experimentů s cílem připravit kompozitní voskové kapsle. Připravené materiály bude charakterizovat pomocí DSC, kde bude stanovovat efekt reakčních podmínek na fázový přechod kapslí. Optimalizace reakčních podmínek povede k přípravě kapslí, které budou vykazovat entalpii fázového přechodu přibližující se hodnotě čistého vosku.

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1. Huang, Z., Stonehouse, A., Abeykoon, C. Encapsulation methods for phase change materials – A critical review. International Journal of Heat and Mass Transfer, 2023, 200, 123458. <https://doi.org/10.1016/j.jheatmasstransfer.2022.123458>.
2. Sangphil Parka, Yeongmin Leea, Yong Seok Kima, Hyang Moo Lee b, Jung Hyun Kima,
3. In Woo Cheong b, , Won-Gun Koh. Magnetic nanoparticle-embedded PCM nanocapsules based on paraffin core and polyurea shell. Colloids and Surfaces A: Physicochemical and
4. Engineering Aspects. <http://dx.doi.org/10.1016/j.colsurfa.2014.03.005>

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ABSTRAKT

Bakalářská práce se věnuje přípravě a charakterizaci voskových kapslí pro aplikace v oblasti pasivní tepelné regulace budov. Tyto materiály využívají fázový přechod vosku k akumulaci a následnému uvolnění tepelné energie, čímž mohou sloužit jako součást pasivních klimatizačních systémů. Kapsle jsou tvořeny vnitřní vrstvou z vosku a tenkou polymerní slupkou z polymethylmethakrylátu (PMMA), která zamezuje úniku vosku z kompozitu. Pro zlepšení tepelné vodivosti, a tím i efektivnější přenos tepla, jsou do kapslí přidávány částice s vysokou tepelnou vodivostí. Cílem práce je optimalizovat podmínky syntézy tak, aby výsledné kapsle vykazovaly co nejvyšší entalpii fázového přechodu. Charakterizace připravených vzorků byla prováděna pomocí diferenční skenovací kalorimetrie (DSC) a termogravimetrické analýzy (TGA), které umožnili posoudit vliv jednotlivých parametrů syntézy na tepelné vlastnosti výsledného materiálu. Stabilita, a tedy potenciální výkon výsledných PCM kapslí byly hodnoceny úbytkem hmotnosti v čase.

Klíčová slova: PCM, latentní teplo, voskové kapsle, PMMA, tepelná vodivost.

ABSTRACT

This bachelor's thesis focuses on the preparation and characterization of wax capsules for applications in the field of passive thermal regulation in buildings. These materials utilize the phase transition of wax to accumulate and subsequently release thermal energy, allowing them to function as part of passive climate control systems. The capsules consist of an inner layer of wax and a thin polymer shell made of polymethyl methacrylate (PMMA), which prevents the wax from leaking out of the composite. To improve thermal conductivity, and thus enhance heat transfer, particles with high thermal conductivity are added to the capsules. The objective of the thesis is to optimize the synthesis conditions so that the resulting capsules exhibit the highest possible phase transition enthalpy. The characterization of the prepared samples was conducted using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), which evaluated the influence of various synthesis parameters on the thermal properties of the final material. Stability and potential performance of the final PCM capsules were elucidated using mass change over time.

Keywords: PCM, latent heat, wax capsules, PMMA, thermal conductivity

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INTRODUCTION

With the growing global population, economic development and increased use of energy-consuming appliances, there is a rapid increase in global energy consumption and greenhouse gas emissions. This trend negatively impacts not only human health and the environment but also depletes the supply of traditional energy sources such as oil, coal and natural gas [1]. However, it is widely recognized that these energy sources are not eternal and pose a threat to our planet in the form of climatic vagaries.

Scientists worldwide are actively searching for new renewable energy sources to create efficient and sustainable methods of storing energy such as storage devices, which play a key role in the advancement of new energy technologies [2; 3]. The largest portion of energy consumption in buildings is attributed to ventilation, heating and cooling systems [4]. Efforts to enhance energy efficiency in buildings has resulted in the development of diverse approaches to optimize energy management and conservation in heating and cooling applications [5].

Thermal energy storage (TES) is deemed crucial advanced energy technology [6], TES materials efficiently manage heat by absorbing and releasing it, which maintains indoor thermal comfort and minimizes electrical energy use especially for heating in winter and cooling in summer. This reduces the need for temperature regulation, providing both economic and environmental benefits [7].

Therefore, this bachelor thesis focuses on the development and characterization of polymer-based composite materials for latent heat thermal energy storage. Specifically, the study explores the encapsulation of paraffin wax RT28HC using methyl methacrylate (MMA), with and without the addition of expanded graphite (EG). The encapsulated wax systems are investigated in terms of their morphology, thermal properties, and polymerization behavior. The goal is to evaluate how the presence of EG affects the encapsulation process and enhances the thermal conductivity and stability of the resulting composite phase change materials (PCMs), making them more suitable for practical TES applications in building energy management.

I THEORETICAL PART

1 PHASE CHANGE MATERIALS

The rapid increase in global energy consumption, coupled with the finite nature of energy resources, has led researchers to explore new methods for energy harvesting and conservation across various sectors. PCMs, initially researched in the 20th century, have become widely utilized in diverse areas such as solar energy storage, industrial waste heat recovery, building energy efficiency, electronic components, and thermal management of batteries [8]. Buildings, in particular, account for the largest share of energy consumption worldwide, surpassing both the industrial and transportation sectors [9].

Moreover, the severe environmental effects of extensive fossil fuel consumption have driven the need for innovative solutions to improve energy efficiency. One such approach gaining attention is increasing the thermal inertia and thermal mass of buildings, which has shown promise in reducing energy consumption [10].

PCMs are capable of absorbing or releasing heat during their phase transition at a nearly constant temperature, making them excellent for latent heat storage [11]. By taking advantage of the properties of PCMs to store excess energy, the issue of uneven energy distribution can be effectively reduced. PCMs are classified into three main categories based on their chemical structure: organic, inorganic, and eutectic mixtures [11; 12].

Organic PCMs are particularly well-researched due to their high heat storage capacity, low undercooling, appropriate phase change temperature, non-corrosive nature, and stable properties. However, their practical application is often hindered by leakage during the solid-liquid phase transition. This challenge can be overcome by using biomass-based porous materials to absorb PCMs (mainly including polyethylene glycols, paraffins, fatty acids), which helps in the preparation of stable shape composite PCMs [13].

PCMs are typically categorized into three types based on their phase change states: solid-liquid phase change materials (SLPCMs), solid-solid phase change materials (SSPCMs), and liquid-gas phase change materials (LGPCMs). The use of LGPCMs is significantly limited due to the substantial volume changes that occur during the phase transition. SLPCMs, which include various inorganic salt hydrates, paraffin waxes, polyethylene glycols (PEG), fatty acids, and their eutectic mixtures, have been widely studied in recent decades for thermal energy storage (TES) applications [14; 15].

Efficient use of time-dependent energy sources, such as solar power, requires suitable TES systems to manage the mismatch between energy supply and demand. TES systems

offer significant flexibility by allowing energy storage from various sources, including solar heat, industrial waste heat, heat pumps, and off-peak electricity, either individually or in combination [16].

Solar energy applications particularly depend on large storage capacities, as solar radiation is intermittent. To maintain a consistent energy supply, it is generally required that storage systems have the capability to cover at least one to two days' worth of energy demand.

There are three main types of TES: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage. SHS stores energy by raising the temperature of a material. Although it is a simple and well-established method, SHS has low energy density, making it the least efficient among the three. LHS systems use PCMs that store and release energy during melting and solidification. These systems offer higher energy density, smaller system sizes, and nearly constant temperature during operation. However, they suffer from low heat transfer rates, primarily due to the increasing thermal resistance created as the solidified layer of PCM grows during phase transitions [17].

To address the limitations of both SHS and LHS, combined systems that integrate both storage methods have been developed. These hybrid systems aim to benefit from the simplicity of SHS and the high energy density of LHS, while reducing their respective disadvantages [16; 17].

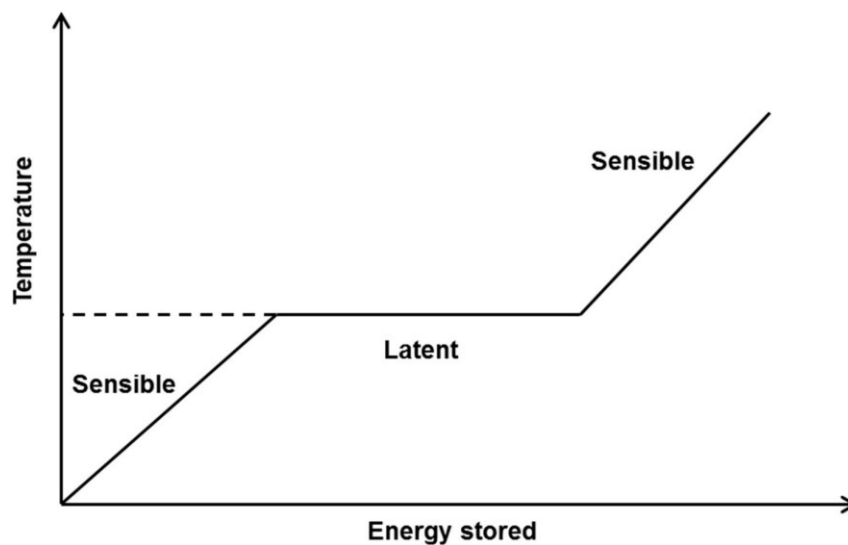


Figure 1. Performance Comparison of SHS and LHS in TES Systems [18].

1.1 Biomass-based Porous Materials

Recent studies have shown the effectiveness of using PCMs in buildings for energy savings and thermal adjustments [19; 20]. The development and construction of PCM-based building materials have become a key focus in this area. The direct addition of PCMs to building materials is a simple and cost-effective method. However, this approach can result in the leakage of PCMs due to poor compatibility with the materials. To address this issue, the use of phase change nano or microcapsules has been suggested as a solution. Yang et al. [21] developed nano-encapsulated PCMs through *in situ* polymerization and applied the composite material to energy-efficient building walls, which enhanced the heat storage capacity compared to conventional walls. However, the process of preparing nano or micro capsules is complex. An alternative approach is the adhesion of PCMs to porous materials, which provides an effective way to create shape-stable composite PCMs for building applications. The use of materials such as graphene aerogel, expanded graphite, and carbon nano-aerogel can effectively encase PCMs, resulting in the creation of shape-stable composite PCMs [20].

Biomass materials, like palm fibers, wheat straw, and banana peels, are affordable and abundant. These materials can be converted into porous forms through carbonization and then further processed to create composite PCMs that maintain their shape [20].

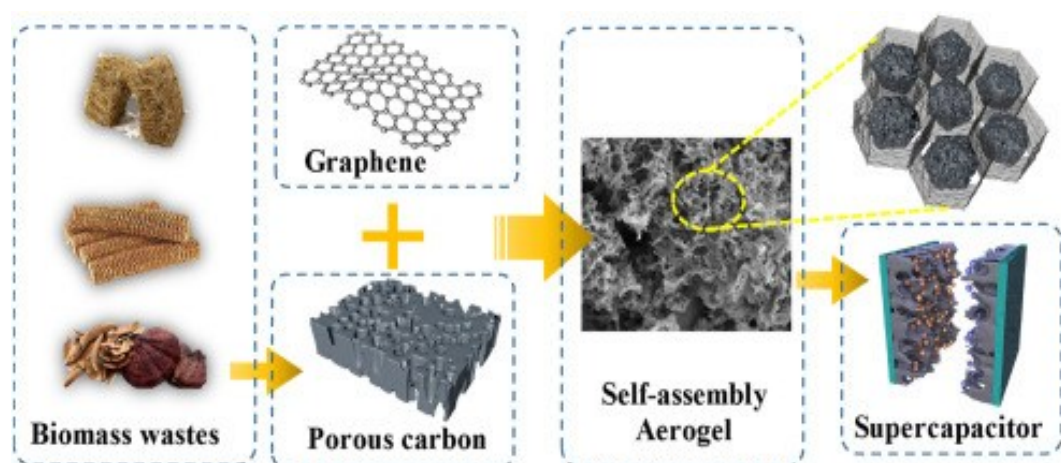


Figure 2. Synthesis procedures for biomass-based porous carbon/graphene [22].

1.1.1 Polyethylene Glycols

PEG and its derivatives are commonly used SLPCMs due to their key advantages, including non-toxicity, corrosion resistance, relatively high enthalpy, and a wide range of molecular

weight options. These characteristics make them ideal for use as phase change functional chains (soft segments) in the structure of polymeric SSPCMs [23].

The ability to control the molecular weight of PEG allows for tailored properties depending on the average molecular weight. **Table 1** outlines the properties of several common PEG types. As the molecular weight increases, both the phase change temperature and latent heat of PEG generally increase. In practical applications, PEG can be selected according to the specific needs of each application.

Table 1. Phase change characteristics of PEG at varying molecular weights [11].

Polyethylene Glycols (PEG)	Melting Process		Freezing Process	
	T_m (°C)	ΔH_m (J/g)	T_f (°C)	ΔH_f (J/g)
PEG-1000	42.8	129.3	23.6	129.8
PEG-2000	51.0	185.4	34.52	184.8
PEG-4000	60.5	172.4	41.96	207.0
PEG-6000	61.7	178.6	35.3	169.9
PEG-8000	64.6	180.0	44.3	167.9
PEG-10000	63.7	189.2	39.1	167.3
PEG-20000	67.7	160.2	42.9	155.7
PEG-35000	64.4	174.0	48.9	173.9

Overall, biomass-based composite PCMs made with PEG exhibit excellent thermal performance and resistance to leakage, making them promising materials for use in environmental protection and energy-saving applications [11].

1.2 Organic PCMs

Organic phase change materials (PCMs) are carbon-based substances derived from both fossil and renewable, sustainable sources. Numerous studies have explored the use of various organic matrices such as PCMs, including composites made from biomass, polyamide nanosheets/aerogels, polyvinyl alcohol, fiber membranes, and polyethylene glycol. These materials have found applications in energy storage and conversion systems, such as photothermal conversion, solar thermal energy systems, electromagnetic radiation absorption, the textile industry, and electronic devices [24].

The use of organic PCMs in building applications has gained significant attention, largely due to their advantages over inorganic alternatives. These include their ability to avoid supercooling, excellent thermal stability, high latent heat of fusion, non-corrosive nature, and compatibility with construction materials, making them highly suitable for energy-efficient applications in the built environment [25; 26].

The two main types of organic PCMs are paraffins and non-paraffins. Paraffin wax is the most frequently used PCM in commercial energy storage applications. Non-paraffin organic PCMs include a variety of materials such as fatty acids, fatty esters, and alcohols [27].

1.2.1 Paraffins

Paraffins, mainly consisting of straight-chain n-alkanes, are characterized by their high latent heat, absence of undercooling, excellent thermal stability, and rich sources, which makes them highly promising as phase change materials [28].

With its high biological safety, reliability, affordability, and large heat storage capacity, paraffin wax offers significant potential for various applications. However, its susceptibility to leakage during the solid-liquid phase transition poses a major challenge, limiting its practical use [29].

Table 2 below displays the properties of several common paraffins. Their phase change temperatures are relatively close to ambient temperature, making them particularly suitable for heat storage applications that rely on phase change [11].

Table 2. Phase change behavior of common paraffins [11].

Paraffins	Melting Process		Freezing Process	
	T_m (°C)	ΔH_m (J/g)	T_f (°C)	ΔH_f (J/g)
n-Dodecane (C12)	-6.1	219.0	-16.5	218.8
n-Tetradecane (C14)	5.88	225.8	2.15	225.4
n-Hexadecane (C16)	20.84	254.7	16.78	250.6
n-Octadecane (C18)	28.74	209.1	21.16	209.8
n-Eicosane (C20)	39.17	237.1	32.93	239.7
n-Docosane (C22)	42-46	234.4	36-39	233.6

Unfortunately, PCMs, especially paraffin wax, have low thermal conductivity, which reduces the overall thermal performance of thermal storage systems. This limitation causes PCM to melt at higher temperatures, closer to the heat source, due to its inability to efficiently conduct heat [30; 31].

1.2.2 Fatty acids

Fatty acids consist of a carboxylic acid group attached to an aliphatic chain containing between 2 and 80 carbon atoms [32]. These acids are classified as either saturated or unsaturated, depending on whether the hydrocarbon chain includes double bonds [33].

Common PCMs in the fatty acid category include stearic acid (SA), lauric acid (LA), decanoic acid (DA), capric acid (CA), myristic acid (MA), and palmitic acid (PA). These fatty acids are valued for their high latent heat, strong thermal stability, absence of supercooling, low cost and availability from renewable bio-sources [34].

Figure 3 illustrates the research trends for capric, palmitic, stearic, lauric, and myristic acids from 1989 to 2024. The graph shows a clear increase in studies involving these fatty acids, highlighting the rising interest in their use as PCMs due to their desirable properties and renewable sources.

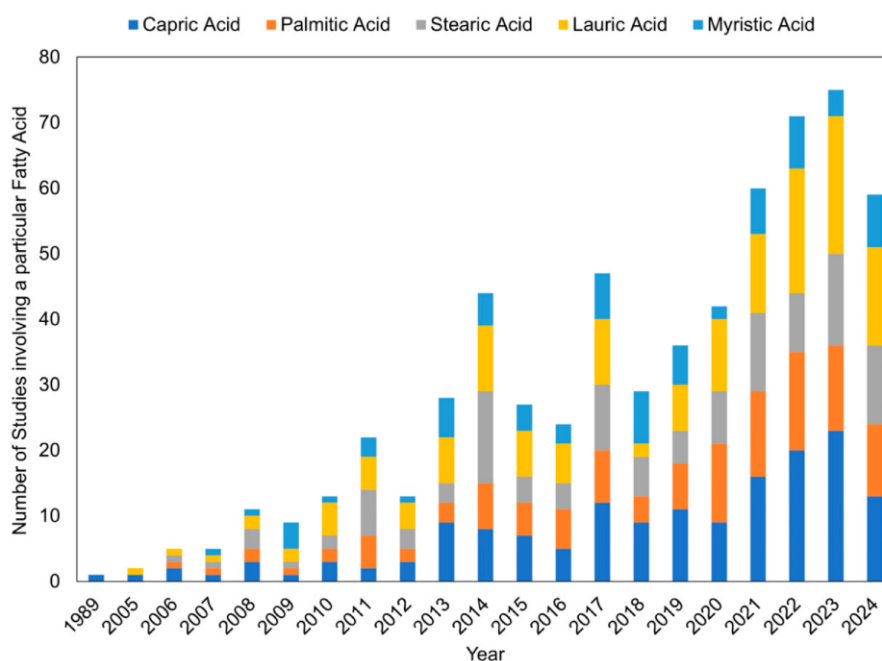


Figure 3. Recent research trends on key fatty acids for TES applications [35].

1.3 Inorganic PCMs

PCMs are broadly classified into two categories: organic materials and inorganic materials. Organic PCMs, such as paraffin and alkanes, are one group, while inorganic PCMs include salts, salt hydrates, metals, and alloys (see **Figure 4**).

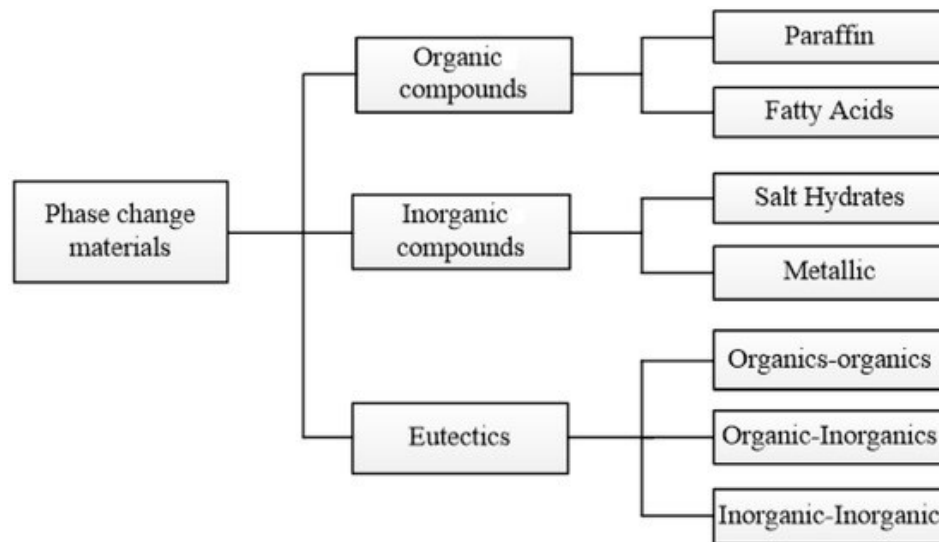


Figure 4. Classification of phase change materials [36].

Farid et al. provided a comparative analysis of properties between sensible energy storage using rock and water, and latent heat energy storage with organic and inorganic phase change materials, as summarized in **Table 3**. The comparison highlights that latent heat storage generally offers superior benefits over sensible heat storage, particularly in terms of storage mass and density [18].

Table 3. Comparison between sensible heat storage and latent heat storage [18].

Property	Sensible Storage		Latent Storage	
	Rock	Water	Organic PCM	Inorganic PCM
Density, kg/m ³	2240	1000	800	1600
Specific heat, kJ/kg	1	4.2	2	2
Latent heat, kJ/kg	-	-	190	230
Latent heat, kJ/m ³	-	-	152	368
Storage mass for 106 J.kg	67.000	16.000	5300	4350
Storage volume for 106 J.m ³	30	16	6.6	2.7
Relative storage mass	15	4	1.25	1
Relative storage volume	11	6	2.5	1

In general, inorganic phase change materials offer approximately twice the heat storage capacity per unit volume compared to organic materials, as shown in the comparison in **Table 3**. These materials also feature higher thermal conductivity, operate at higher temperatures, and are more cost-effective than organic phase change materials [37]. Conversely, inorganic PCMs can be corrosive to metals, which results in a reduced system lifespan and increased costs [38]. Inorganic PCMs (salts and salt hydrates) may experience phase segregation and supercooling, reducing energy storage capacity. However, metals and alloys avoid these issues, making them suitable for high-temperature applications [18].

1.4 Eutectic PCMs

Eutectic PCMs are created by combining organic and inorganic materials, resulting in a mixture with a different transition temperature than the individual components. These mixtures offer advantages such as a favorable transition temperature, high phase change enthalpy, and uniform phase change behavior. However, they are more expensive and exhibit lower thermophysical properties compared to individual organic or inorganic PCMs [39].

Eutectic PCMs have great thermal properties but often face issues with low thermal conductivity and fluid leakage, limiting their performance. Research has focused on using various materials to enhance their thermal conductivity [40].

Fortunately, by creating binary or ternary eutectic mixtures of fatty acids, their phase change temperature can be adjusted to suit a wider range of applications. Ke [41] developed a series of binary and multi-component fatty acid eutectics by combining five different fatty acids including CA, LA, MA, PA, and SA. This study demonstrated that the potential applications of individual fatty acids can be expanded by broadening the selectable phase change temperature range of fatty acid eutectics [42].

2 CONDUCTIVE ENHANCEMENT ON PCMS

The heavy dependence on non-renewable fossil fuels has resulted in significant energy and environmental issues. Solar thermal energy presents a viable and sustainable alternative by reducing fossil fuel use. Among solar technologies, Direct absorption solar collectors (DASCs) stand out for their simplicity and efficiency. Their performance is primarily influenced by the thermophysical and photo-thermal conversion properties of the working fluid [42].

Latent heat storage fluids (LHSFs) are advanced working fluids created by dispersing PCMs or microencapsulated PCMs (MEPCMs) into a base liquid. These fluids offer:

- Efficient heat collection
- Effective thermal storage
- Enhanced heat transfer

However, PCMs in their raw form are prone to leakage and chemical interaction with the environment. This problem can be resolved by encapsulation, i.e. Microencapsulation provides a core-shell materials, where PCM core is covered by a shell, usually made of organic materials such as PMMA, MF, PS, PU and epoxy resin. While effective at containment, these materials have low thermal conductivity, limiting the energy storage rate [40].

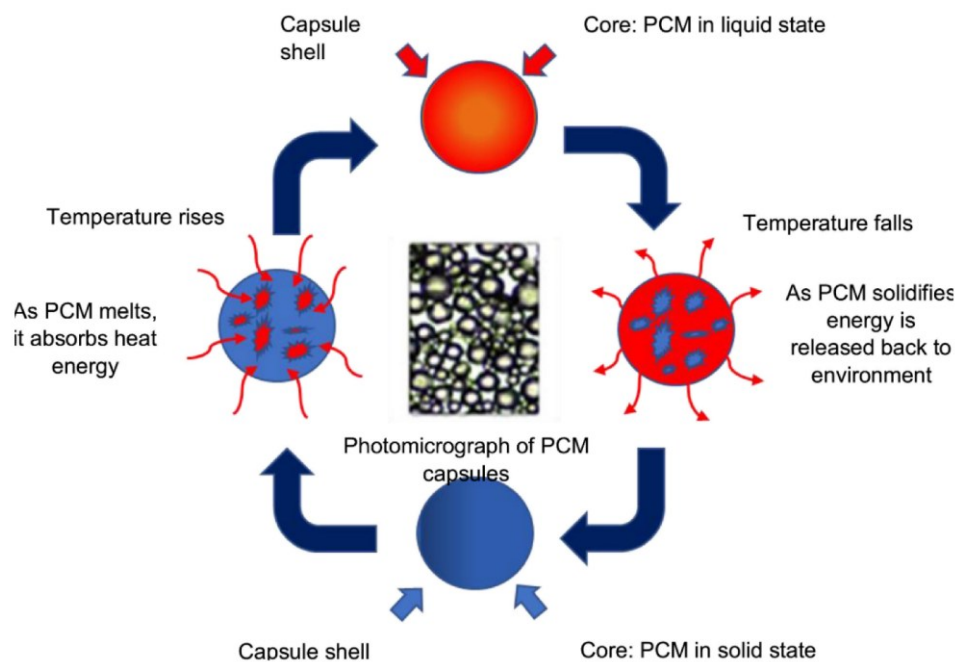


Figure 5. Energy absorption and release cycle in PCM microcapsules (mPCMs) [43].

2.1 Mechanism of Thermal Conductivity

Despite numerous studies in the field of PCMs, research specifically addressing phonon thermal conductivity from the perspective of microscopic mechanisms and material morphology remains limited. Improving the thermal conductivity of PCMs is still a key area of investigation [44]. In composite PCMs, one of the main limitations to thermal conductivity is phonon scattering, which disrupts heat transfer at the microscopic level [40].

Phonons are the primary carriers of heat at the microscopic level. To improve thermal conductivity in composite materials, it is essential to facilitate efficient phonon transport, particularly along the axis of heat conduction. In an ideal scenario, phonons would propagate without interference, allowing for maximum thermal conductivity. Phonon transmission is influenced by three key parameters: phonon velocity, specific heat capacity, and mean free path. These parameters are also impacted by factors such as temperature, atomic mass, material density, and binding energy [40].

The heat transfer process in PCMs, as shown in Figure 5, can be outlined as follows: (a) heat is first absorbed by the surface atoms; (b) these atoms then acquire vibrational energy; (c) the energy is subsequently passed on to adjacent atoms; (d) it spreads throughout the material as vibrational waves; (e) the thermal energy further propagates through the crystal via phonons; and (f) finally, once the heat reaches the opposite side of the material, a portion of it is released into the surrounding environment through conduction or radiation [40].

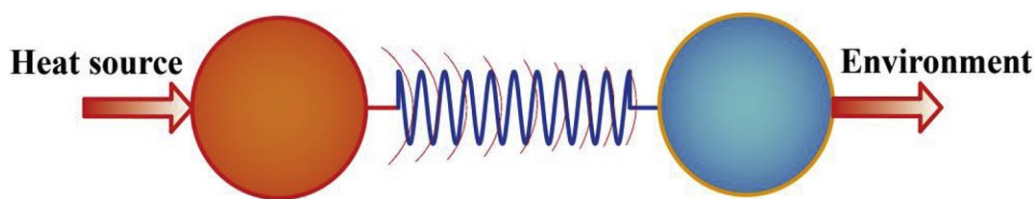


Figure 6. Heat transfer process in crystal heat conduction [40].

2.2 Nano-fillers for PCM Composites

Recent advancements in nano-enhanced phase change materials (NEPCMs) have emerged as promising solutions to overcome existing limitations by incorporating nano-fillers. Highly conductive nano-fillers such as metals, metal foams, metal oxides, nanowires, metal-organic frameworks, and carbon-based materials are particularly effective in enhancing the thermal properties of PCMs, increasing their versatility [45].

NEPCMs can be synthesized using either a one-step or two-step method. The two-step synthesis is often preferred due to its cost-effectiveness, versatility with different NEPCM composites, and scalability for large-scale production. However, the two-step method may cause the agglomeration of nano-fillers, which can reduce the thermal performance of the NEPCMs [46].

To prevent this, surfactants are often employed to reduce the surface tension between the base PCMs and the dispersed nano-fillers, helping to avoid agglomeration [47].

2.3 Carbon-based Fillers

Graphene is highly valued for its unique combination of properties, consisting of a hexagonal carbon lattice. Its exceptional mechanical, thermal, and electrical characteristics make it ideal for applications across diverse fields, including high-performance composites, biomedical technologies, energy storage, catalysis, sensors, and electronic devices. Graphene's versatility has positioned it as a key material in cutting-edge research and development [46].

2.3.1 Graphene nano-platelets

Graphene nanoplatelets (GNPs), typically 5-10 nm in thickness and consisting of 60-100 layers, are commercially available. Their planar structure, resembling carbon nanotubes (CNTs), results in lower thermal contact resistance, enhancing thermal conductivity compared to CNTs and carbon nanofibers (CNFs) [46].

Mehrali et al. [48] highlighted the impressive performance of GNPs as a filler material in form-stable PA composite PCMs, achieving a tenfold increase in the thermal conductivity of PA. GNPs with specific surface areas of 350, 500, and 750 m²/g were found to absorb PA at weight percentages of 78%, 83%, and 92%, respectively, without leakage.

2.3.2 Graphene oxide and reduced graphene oxide

In 1859, Brodie discovered that graphene oxide (GO) is produced by chemically exfoliating graphite flakes with strong oxidizing agents [49]. This process separates graphene layers, resulting in thicker sheets than single-layer graphene.

GO synthesis is complex, with its properties dependent on factors like oxidation time, graphite source, and particle size. GO can be reduced to reduced graphene oxide (RGO),

restoring some of its unique properties [50]. GO has been used to enhance thermal conductivity in PCMs.

2.3.3 Expanded graphite

EG, also called intumescent flake graphite, is a graphite derivative with a partially separated layered structure. Unlike GO, EG retains its original carbon surface without functional modification and is not fully exfoliated. EG is produced by treating graphite with intercalation agents that insert between the graphene layers. When rapidly heated, these agents decompose into gases, forcing the layers apart and creating an expanded structure [51].

2.3.4 Carbon nanotubes

CNTs are nanoscale cylindrical structures that can be visualized as rolled-up sheets of graphene, forming long, tube-like shapes with very high aspect ratios. They are typically categorized into single-walled (SWCNTs) and multi-walled (MWCNTs) types [52].

Known for their extraordinary thermo-mechanical properties, CNTs are among the strongest known fibers, with tensile strengths reaching up to 100 GPa and Young's modulus values approaching 1000 GPa. In addition, they possess excellent thermal and electrical conductivity, comparable to graphite. However, multi-walled CNTs tend to have higher thermal contact resistance compared to other carbon-based materials like GNPs, GO, and thermally reduced graphene (TRG) [53].

2.3.5 Carbon nanofibers

Carbon nanofibers (CNFs), also known as vapor-grown carbon fibers (VGCFs or VGCNFs), are graphene-derived materials with a stacked-cup or cone-like structure, unlike the seamless cylindrical shape of CNTs [54].

While CNTs are known for their exceptional properties, they often come with drawbacks such as poor dispersion, high production costs, and decreased performance after surface modification. CNFs have gained attention as a more practical alternative, offering similar mechanical and thermal characteristics. Their unique structure results in weaker van der Waals interactions, which improves dispersion stability in composites. As a result, CNFs are not only easier to work with but also present a more cost-efficient solution compared to CNTs [55].

2.4 Boron Nitride-based Fillers

A few decades ago, the existence of stable 2D materials was widely doubted due to concerns over their thermodynamic stability. This changed with the discovery of free-standing graphene, which sparked global interest in exploring similar materials [56].

Shortly after, boron nitride (BN) emerged as a graphene-like 2D material. With boron and nitrogen replacing carbon atoms in a hexagonal lattice, BN forms a similar honeycomb structure [57], though the bonding of boron is more complex. BN appears as a soft, white crystal with a bond length of 1.466 Å and interlayer spacing of 3.331 Å, slightly different from graphite. BN also offers high hardness and lubricity [58].

Unlike graphene, which burns in air at high temperatures, BN is chemically stable and flame-resistant, making it more suitable for high-temperature applications [46].

3 ENCAPSULATION

To enhance the properties of PCMs, composite materials can be created by combining two or more pure substances in different configurations, which improves their desirable characteristics. One effective technique for this is PCM encapsulation, where the primary PCM is enclosed within a supporting material. This method not only provides stability but also significantly increases the heat transfer surface area when the PCM is encapsulated in multiple capsules of a specific shape [59; 60].

By using an appropriate encapsulant, issues such as incompatibility between the PCM and its surrounding materials (e.g., containers or heat transfer fluids), as well as concerns like toxicity, corrosiveness, and flammability, can be avoided. In this case, it is the encapsulant, rather than the PCM itself, that comes into direct contact with the environment. Several requirements have been proposed for materials intended to encapsulate PCMs [59], [60; 61], with key considerations including the reactivity between the PCM and the encapsulant, as well as the ability of the encapsulant to accommodate the PCM's volume change during melting [60].

Reducing the capsule size increases the surface area relative to its volume, thereby boosting heat transfer efficiency [62]. Furthermore, microencapsulation results in quicker charging and discharging rates due to the reduced heat transfer distance [63], improved handling of thermal expansion and contraction during phase changes [59], and, in comparison to macroencapsulated PCMs, greater thermal reliability and chemical stability [62].

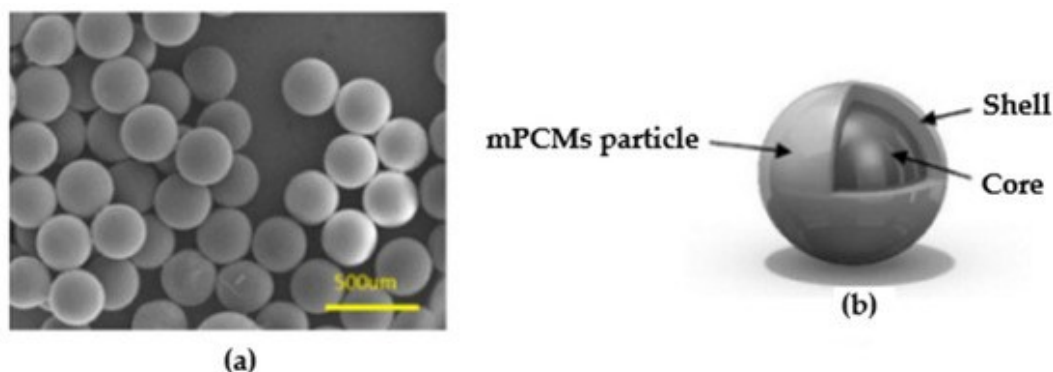


Figure 7. General view of (a) PCM microcapsules and (b) core-shell microcapsules [64].

3.1 Encapsulation Techniques

Recently, PCM encapsulation has been effectively developed to increase the heat transfer area and reduce the interaction of materials with the surrounding environment. This method also helps minimize subcooling and control the volume change during phase transitions. Encapsulation techniques are typically categorized into core-shell and shape-stabilized PCMs (CS-PCMs and SS-PCMs).

A variety of materials, such as acrylics, urea-formaldehyde, silica-based polymers, metals, and carbon composites like graphene and graphite, are used for encapsulating PCMs. These methods significantly improve the thermophysical performance of PCMs [65].

PCM microcapsules (mPCMs) can exhibit various structural morphologies, including simple core-shell configurations, polypore capsules, multilayered core-shell microspheres, and matrix-type capsules, as illustrated in **Figure 8**. The resulting morphology is influenced by the choice of core material, the technique used for shell deposition, and the specific parameters of the synthesis process [66].

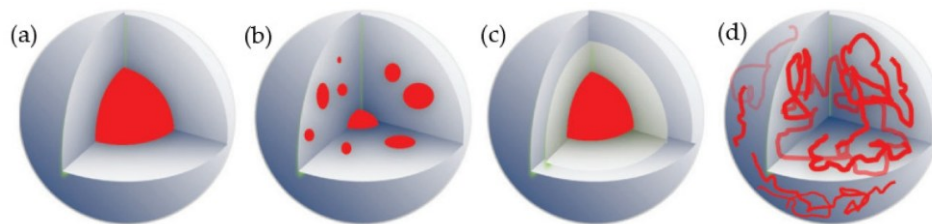


Figure 8. Cross-sectional schematics of four mPCM morphologies - (a) continuous core/shell, (b) polypore capsules, (c) continuous core capsules with more than one layer of shell material, and (d) matrix type capsules [67].

3.1.1 Encapsulation shell materials

The properties of capsules are influenced not only by PCMs but also by the shell materials used. Therefore, selecting appropriate shell materials is crucial to meet the specific requirements of different applications. Like PCMs, shell materials can be classified into three categories: organic, inorganic, and organic-inorganic hybrid materials [68].

3.2 Physical Encapsulation Methods

Physical encapsulation methods have been widely applied in the microencapsulation of PCMs, offering a straightforward and scalable approach. These techniques are typically divided into physio-chemical and physio-mechanical categories. Commonly used physical

methods include pan coating, air-suspension coating, spray drying, centrifugal extrusion, and vibrational nozzle techniques [69].

3.2.1 Spray drying

It is important to note that one of the most used physical methods for encapsulating PCMs is spray-drying. The spray-drying process may involve preparing an oil-water emulsion that contains both PCMs and shell materials. The selection of these materials depends on their compatibility and how they might react with each other. The next step involves atomizing the emulsion and spraying it into a drying chamber. Following this, the droplets are dried, typically by passing a stream of hot gas at an appropriate temperature. Finally, the solid particles are separated from the air stream using a cyclone [70].

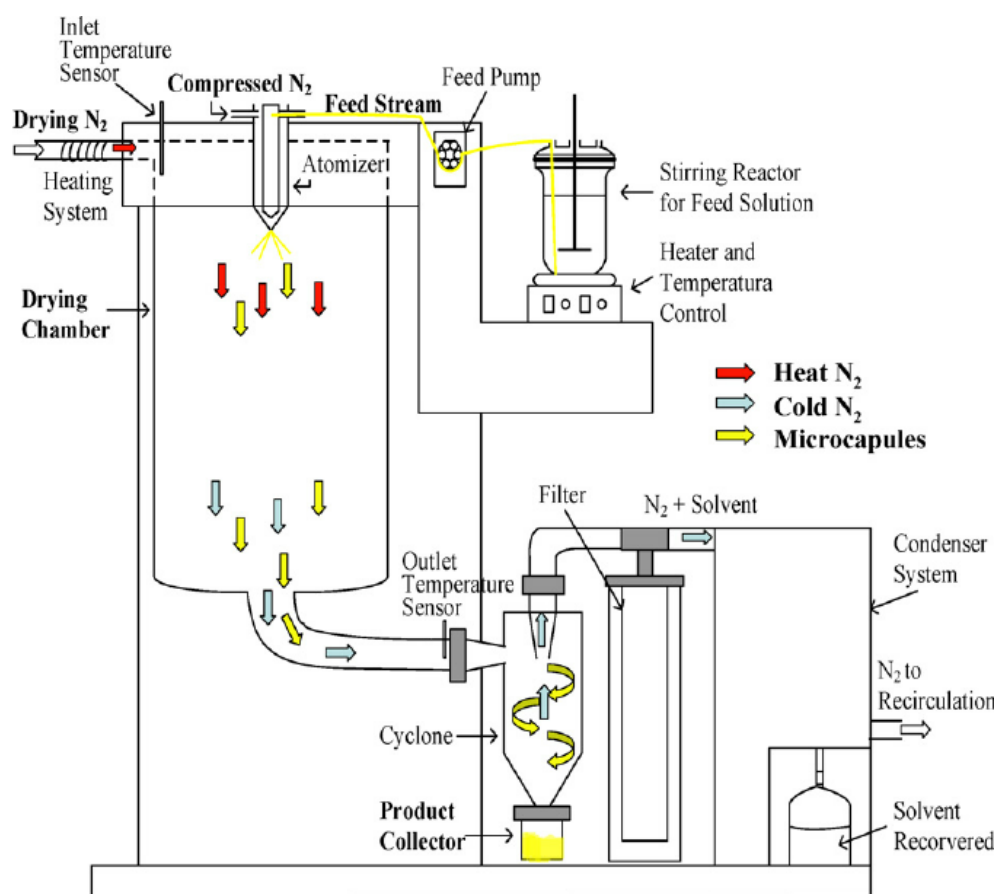


Figure 9. Equipment layout for spray drying process in mPCM manufacturing [71].

3.2.2 Solvent evaporation

Solvent evaporation is a microencapsulation method used for heat-sensitive PCMs. It involves evaporating a low-boiling solvent with heat, which does not affect the PCMs but allows shell materials to form on their surface. The process begins by mixing an aqueous

phase with an emulsifier and an oil phase containing a polymer as the shell material. The core materials and solvent are combined to create an emulsion. Through heating and reduced pressure, the solvent evaporates, causing the polymer to separate and form microcapsules around the core. The final step involves washing and drying the microcapsules [70].

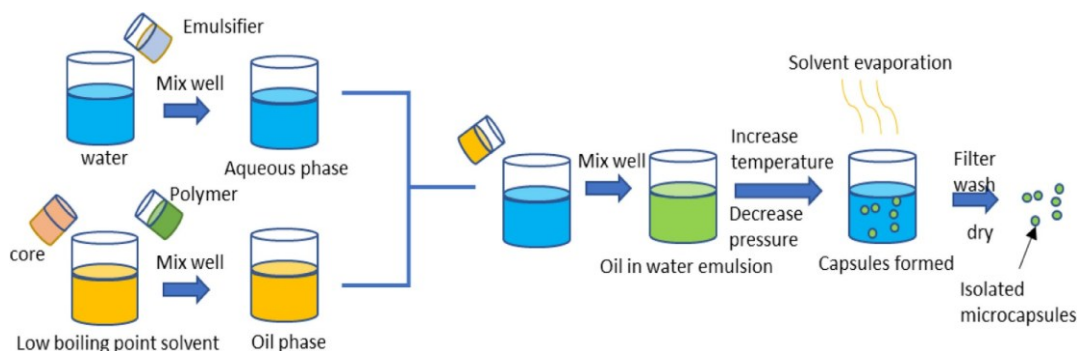


Figure 10. The process and mechanism of solvent evaporation [70].

3.2.3 Centrifugal extrusion

In this method, the core material in its liquid phase flows through an inner tube, while the shell material flows through an outer annular tube surrounding the inner tube. Since the core and shell materials are immiscible, vibration and rotation are used to force them through the nozzle together. This results in the formation of spherical droplets, which are then solidified in a bath using either heat or a chemical reaction, depending on the shell material [72].

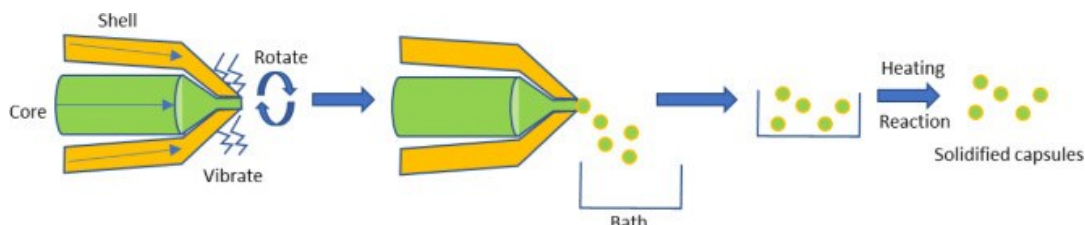


Figure 11. Process flow of centrifugal extrusion for microencapsulation [70].

3.2.4 Pan coating

The pan coating technique is commonly used in the pharmaceutical industry to coat small solid particles or tablets with shell materials. The core material is coated either by spraying the coating onto it or by mixing both materials from the beginning. The spraying method is more energy-efficient and time saving [73]. After heating and cooling, the coating solidifies, encapsulating the core and improving its properties. It is essential that the core material has a higher melting point than the coating to prevent it from melting and losing shape during

the process. Due to these limitations and the inability to produce micro or nano-sized capsules, this method has been less widely studied [70].

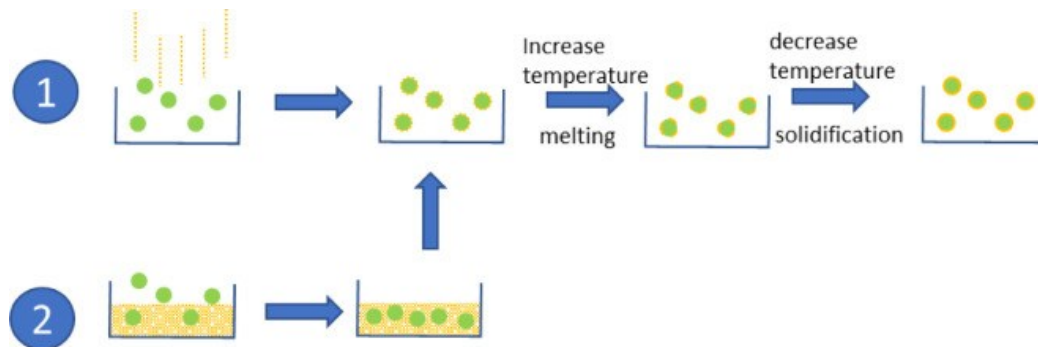


Figure 12. Representation of the pan coating method [70].

3.2.5 Air suspension coating

Air suspension coating offers more flexibility and improved control over shell thickness and closure compared to the pan-coating technique. This is achieved by increasing the number of times the core material passes through the coating zone, resulting in enhanced coating coverage [70].

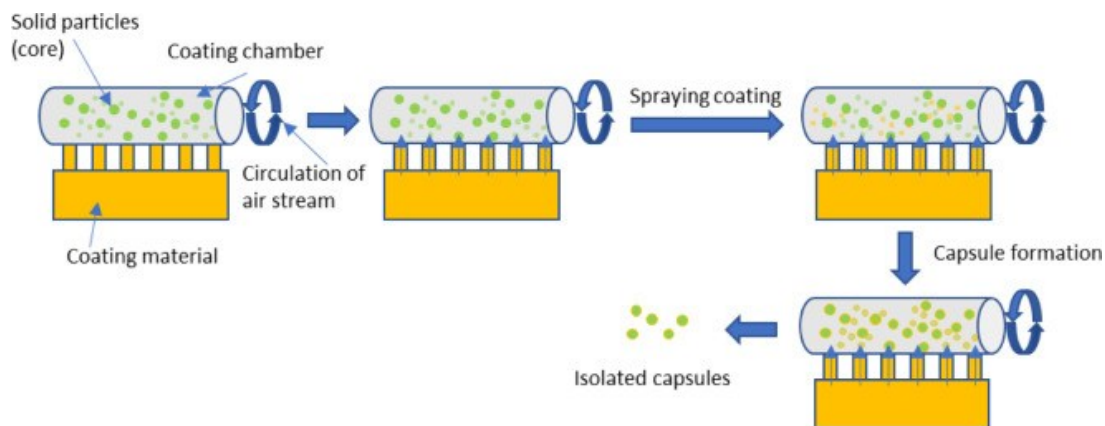


Figure 13. The process of air suspension technique [70].

3.3 Chemical Encapsulation Methods

Chemical encapsulation is commonly used to produce small, uniform PCM capsules with precise shell control. Techniques include in-situ, interfacial, suspension, and emulsion polymerization [74].

The choice of method depends on the compatibility of shell and core materials, the PCM's nature (hydrophobic or hydrophilic), and the intended release mechanism. Chemical encapsulation offers advantages such as high efficiency, uniform shell formation, and the

ability to produce nano capsules unlike physical methods, which are limited to sizes above 100 μm [69].

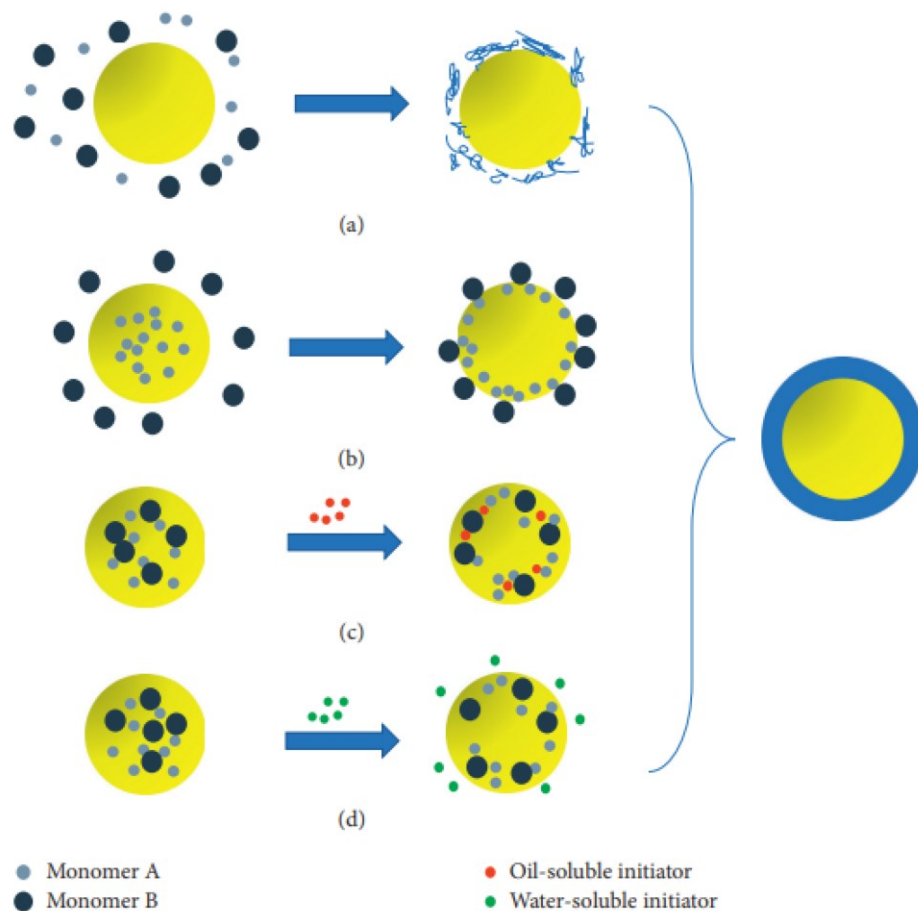


Figure 14. Schematic diagrams of mPCMs formation using: (a) in situ polymerization, (b) interfacial polymerization, (c) suspension polymerization, and (d) emulsion polymerization [75].

3.3.1 In-situ polymerization

In-situ polymerization is based on the polymerization of monomers directly on the surface of the core material. The process begins by preparing an oil-in-water emulsion, where the oil phase contains the core material, and the aqueous phase includes a suitable emulsifier and water-soluble shell material (monomers or pre-polymers). Polymerization is then initiated, often through pH adjustment, causing the monomers to form a water-insoluble shell. The resulting microcapsules are then filtered, washed, and dried [70].

When the pH of the system is lowered, polycondensation begins, resulting in the formation of cross-linked urea-formaldehyde (UF) or melamine-formaldehyde (MF) resins [66]. As the resin reaches a high molecular weight, it becomes insoluble in the aqueous phase, causing it to precipitate and accumulate at the oil-water interface of the droplets. This

process leads to the hardening of the resin and the formation of microcapsule shells, as shown in **Figure 15**.

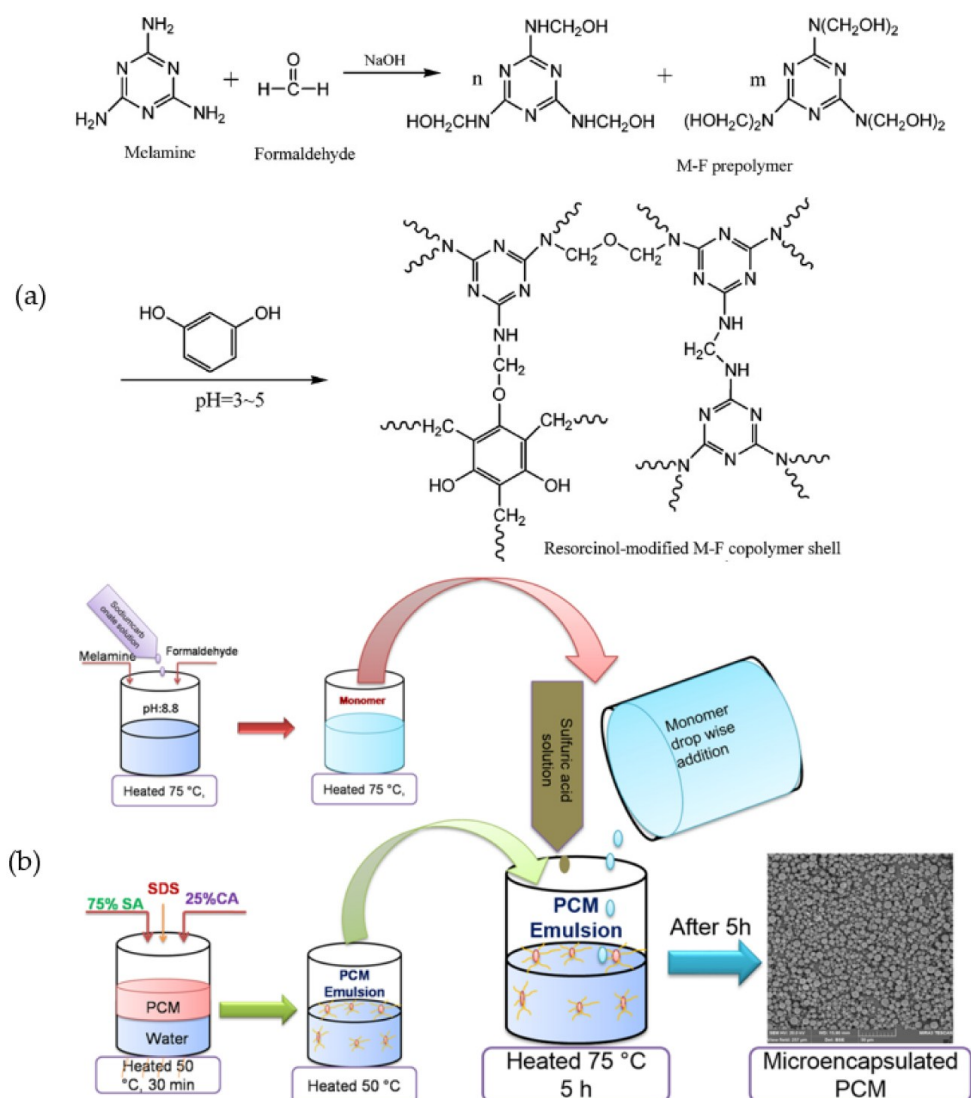


Figure 15. (a) Polymerization reaction of MF prepolymer and (b) stepwise schematic of mPCM preparation using fatty acid eutectic mixture as core and MF shell via in-situ polymerization [76].

3.3.2 Interfacial polymerization

Interfacial polymerization involves dissolving hydrophilic monomers in the aqueous phase and hydrophobic monomers in the oil phase (core). The emulsifier facilitates the dispersion of the oil phase containing the hydrophobic monomers in the aqueous phase. Polymerization is triggered by temperature and pH adjustments when the hydrophilic monomers are added. The resulting microcapsules are then separated, washed, and dried [77].

This method involves forming a polymer shell by rapidly polymerizing monomers at the surface of droplets containing core material. The droplets are created by emulsifying an organic phase with core materials and oil-soluble monomers (typically isocyanate or acid chloride) in an aqueous phase [66]. Adding a water-soluble monomer triggers a rapid polymerization at the droplet interface, forming the shell, as shown in **Figure 16**.

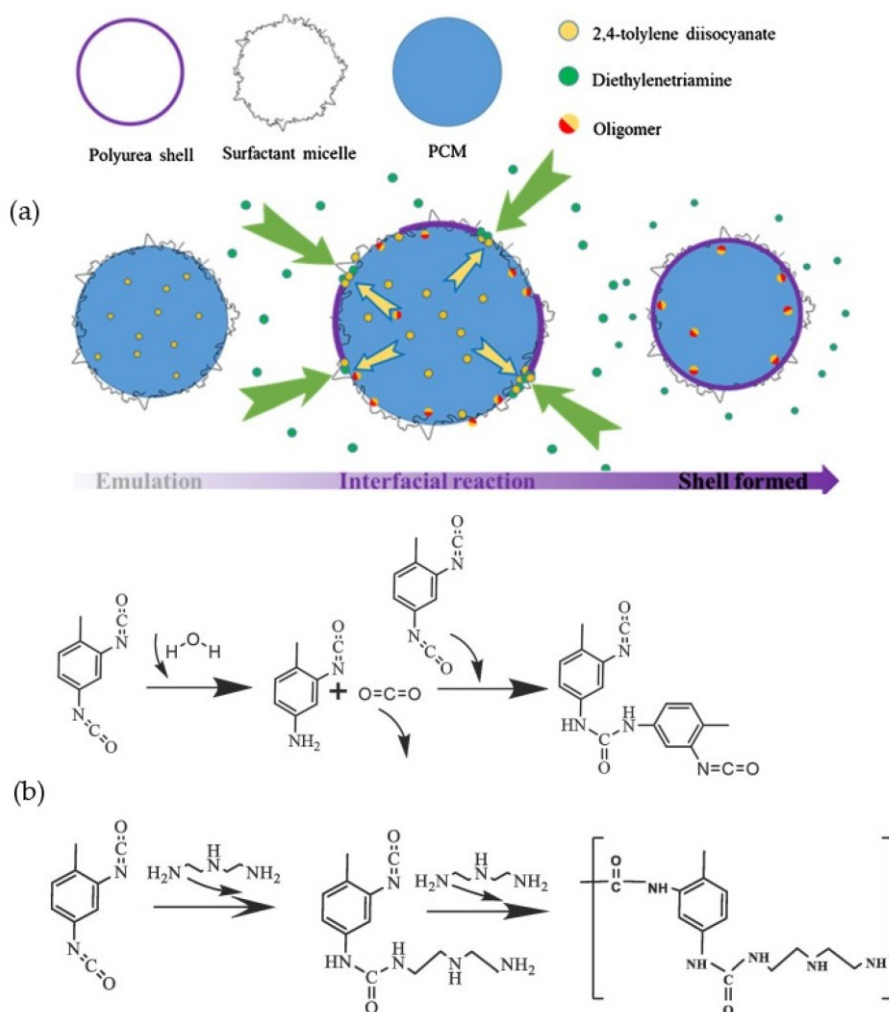


Figure 16. (a) Schematic diagram of mPCM formation via interfacial polymerization and (b) reaction mechanisms involved in interfacial polymerization [78].

3.3.3 Suspension polymerization

Suspension polymerization is a popular method due to its eco-friendliness, affordability, and efficiency. The process begins by preparing two phases: a continuous aqueous phase that contains water and an emulsifier, and a discontinuous oil phase with the core material and oil-soluble monomers. These phases are then mixed at high stirring speeds to form an oil-in-water emulsion. Polymerization is triggered by adjusting the temperature or pH, which causes the monomers in the oil droplets to react at the interface. As a result of the

concentration gradient, monomers move toward the interface and react continuously. Encapsulation efficiency is influenced by the interactions between components like monomers, polymers, PCMs, and initiators. The final morphology is determined by factors such as mobility, compatibility, hydrophobicity, and the core-to-shell ratio [70].

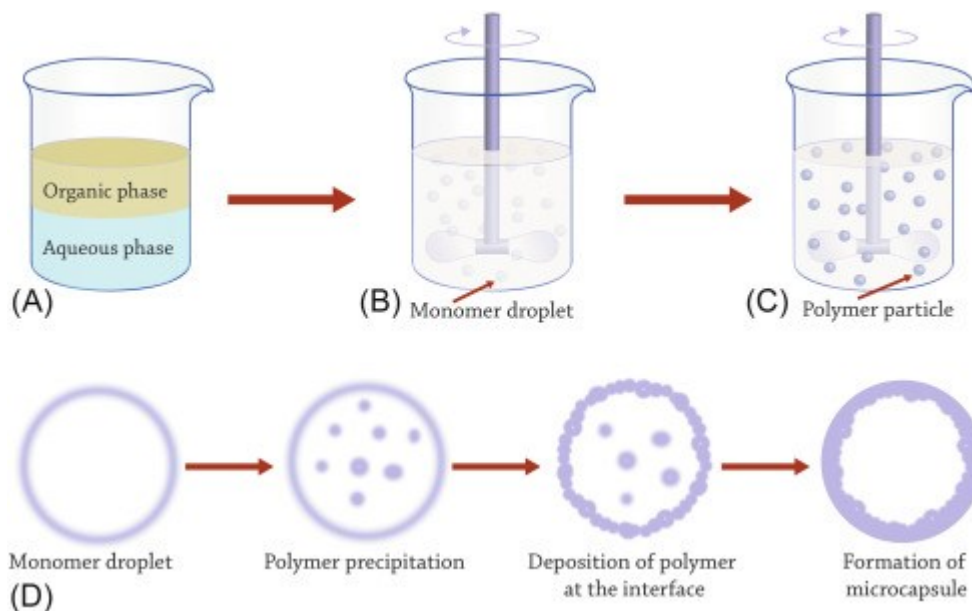


Figure 17. Suspension polymerization: (a) dispersion agent dissolved in water forms the aqueous phase, which is then mixed with the organic phase to create a suspension; (b and c) polymerization occurs in small droplets, producing homogeneous nano/microparticles; (d) molecular-level polymerization [79].

3.3.4 Emulsion polymerization

Emulsion polymerization involves polymerization within the aqueous phase using a water-soluble initiator, in contrast to suspension polymerization, which uses an oil-soluble initiator. The oil phase, containing PCMs and monomers, is mixed with the aqueous phase, which includes water, a surfactant, and the initiator [70]. When the surfactant concentration exceeds a certain threshold, micelles form, typically in spherical shapes, and absorb the monomers. Polymerization occurs inside the micelles, leading to the formation of microcapsules. After filtering, washing, and drying, microcapsules are collected. Factors such as monomer concentration, surfactant level, polymerization temperature, and initiator concentration influence the final particle size [80].

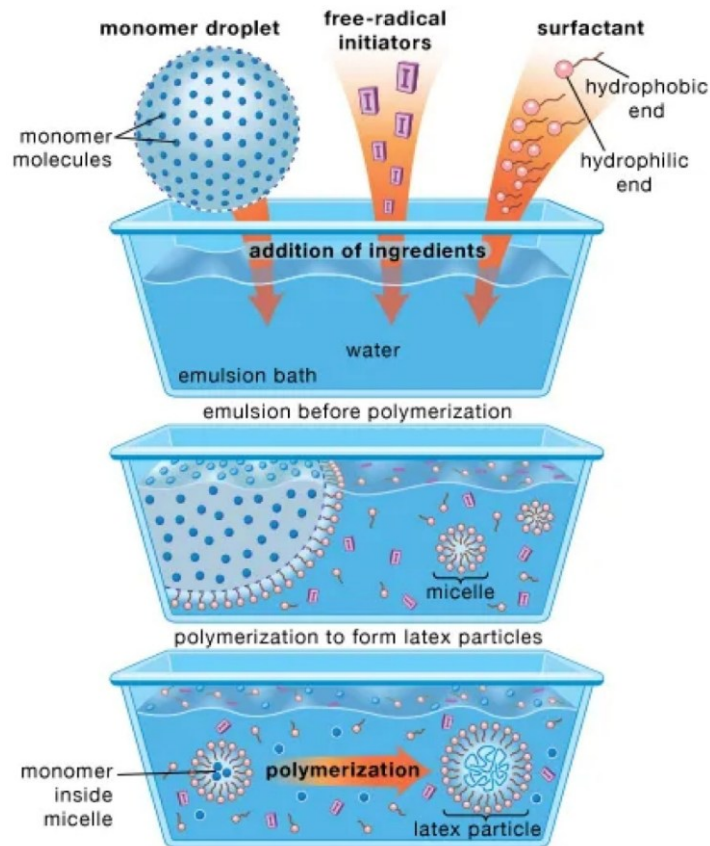


Figure 18. Schematic diagram of the emulsion polymerization [66].

3.4 Physical and Chemical Combined Encapsulation Methods

Physio-chemical encapsulation is a hybrid technique that merges physical processing with chemical reactions to encapsulate PCMs. Compared to purely physical methods, it provides enhanced control over capsule formation and is suitable for applications requiring moderate precision and stability. This method typically involves physical actions such as mixing, emulsification, or agitation, combined with chemical steps like polymer crosslinking or precipitation. The result is a stable shell formed around the PCM core through both mechanical dispersion and chemical bonding [81].

3.4.1 Ionic gelation

The ionic gelation method is commonly used in the pharmaceutical and food industries for drug delivery and nanoparticle synthesis [82]. Despite its widespread use in drug delivery and nanoparticle synthesis, the ionic gelation method is rarely applied in the field of thermal energy storage for encapsulating PCMs. In this process, the core material is first dissolved in an appropriate solvent. A polyelectrolyte solution is then added to form an emulsion, under controlled stirring conditions. Hydrogels are formed from the ionic gelation process

when the emulsion is introduced into a solution containing multivalent cations such as Ca^{2+} , Ba^{2+} , and Al^{3+} [70].

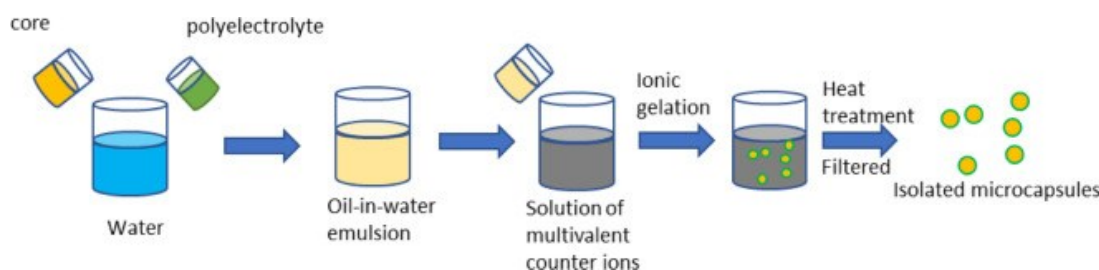


Figure 19. The general process of ionic gelation [70].

3.4.2 Coacervation

Coacervation is a process in which two liquid phases form through electrostatic and hydrophilic hydrogen bonding interactions between two polymers in an aqueous solution. This phase separation occurs after modifying conditions such as pH, temperature, and ionic strength. These interactions are influenced by factors like the molecular weight of the biopolymer, pH, ionic strength, and other conditions [83].

Coacervation can be classified into simple and complex types, both of which involve the same mechanism of microcapsule formation but differ in phase separation due to the distinct polymer systems used. In complex coacervation, phase separation occurs through the complexation of oppositely charged proteins or polyelectrolytes. In contrast, simple coacervation relies on desolvation agents to achieve phase separation. Regarding particle size, complex coacervation typically results in smaller particles [70].

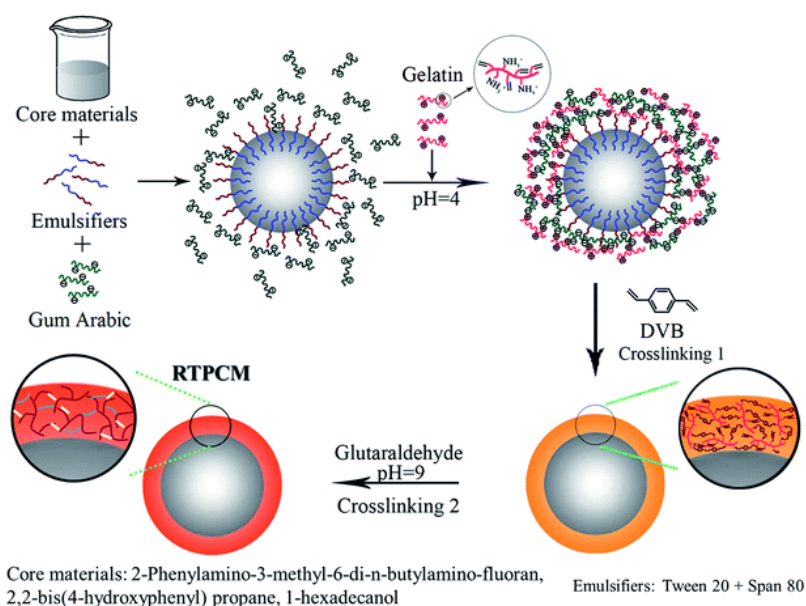


Figure 20. mPCM synthesis via coacervation-phase separation [84].

4 APPLICATIONS

Recently, there has been a significant increase in the cooling demand within the building sector, particularly in developing countries. This rise can be attributed to several factors:

- a) the growing need for comfort among building occupants,
- b) the increased internal heat gains within buildings,
- c) the effects of the urban heat island phenomenon in densely populated cities, and
- d) the decreasing cost of cooling equipment, [87; 88; 89].

In space cooling, the primary goal is to maintain a low temperature, specifically preventing it from rising above a predefined threshold. This can be achieved through three main strategies: reducing heat input, minimizing temperature fluctuations, and enhancing heat rejection.

To meet cooling demands, PCM can be incorporated into buildings through either passive or active systems. Passive systems operate without the need for mechanical equipment or additional energy, relying solely on temperature fluctuations to charge or discharge heat when the air temperature surpasses the PCM's melting point. Cooling is achieved through natural ventilation, with external air providing the necessary cooling. Passive systems are simple to implement and can be seamlessly integrated into the building envelope, including walls, roofs, and floors [88].

In contrast, active systems require mechanical equipment to facilitate the charging or discharging of thermal energy in PCM. In such systems, PCM can be incorporated into storage units, heating, ventilation and air conditioning (HVAC) systems, or utilized as a heat-cold storage tank in solar cooling applications.

4.1 Free Cooling

In free cooling systems, a storage unit is used to store cold energy, which is released when needed by circulating room air through it. Unlike natural night ventilation, which uses the building's thermal mass, free cooling relies on mechanical equipment like fans to charge or discharge heat, improving cooling performance. The effectiveness of PCM-based free cooling depends on a diurnal temperature range of 12-15 °C [89]. If this range is narrow, careful design, including the choice of PCM and its encapsulation is crucial [90].

The PCM-based free cooling system operates in two modes:

- **Solidification:** At night, cool outdoor air passes over the storage unit, causing the PCM to solidify by absorbing heat.
- **Melting:** During the day, as indoor temperatures rise, warm air passes through the storage unit, absorbing heat from the solidified PCM and cooling the room air before it circulates back into the building.

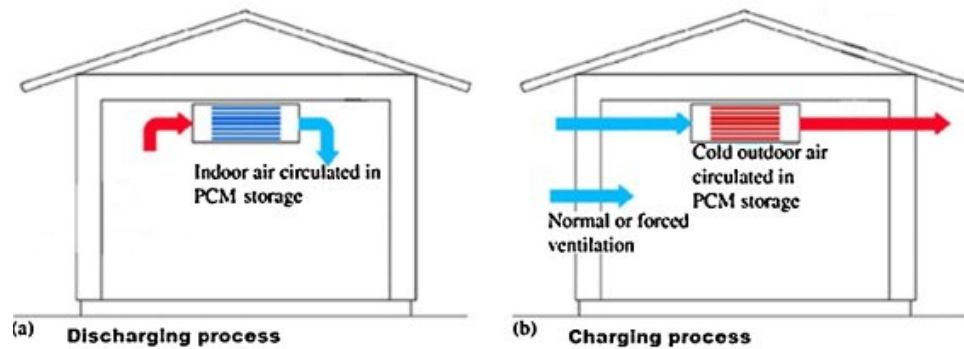


Figure 22. Principle of free cooling system operation [91].

4.2 Solar Cooling Systems with PCM

Recently, solar cooling systems, including adsorption and absorption cooling, have been explored as alternatives to traditional air conditioning. Solar-powered absorption cooling systems can maintain comfortable indoor conditions during the summer while minimizing primary energy use. These systems can reduce cooling demands in hot climates, lower peak electricity consumption, and decrease environmental pollution [92]. Additionally, integrating PCM with solar absorption cooling systems helps meet cooling needs when solar energy is not available [88].

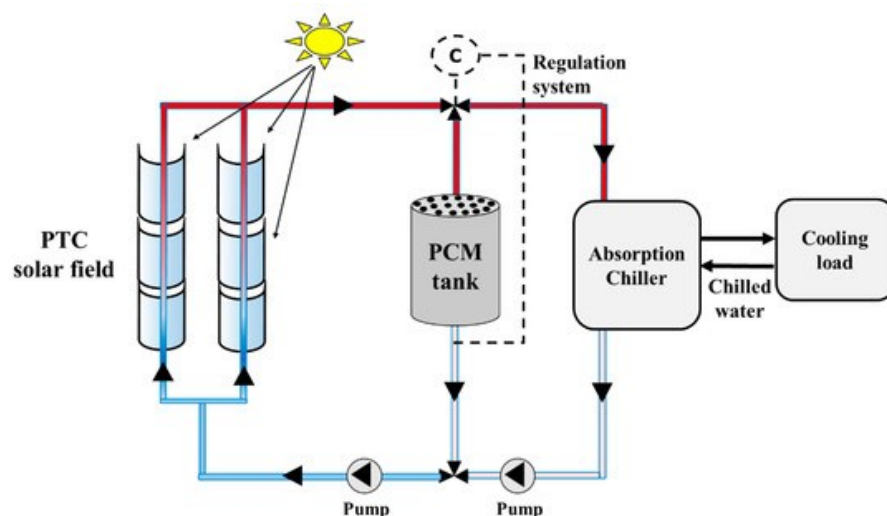


Figure 23. Schema of the solar power system during the charging period [93].

4.3 PCM-air Conditioning Systems

The performance of air conditioning systems is affected by changing weather conditions and the varying needs of homes, businesses, and industrial facilities. These fluctuations cause electricity demand to rise and fall throughout the day, often peaking during periods of high usage. By integrating PCM into AC systems, it's possible to reduce the overall cooling load, which can allow for the use of smaller, more energy-efficient units. Fang et al. [94] evaluated an AC system using a packed bed of PCM-filled spherical capsules. Their study focused on factors such as cooling storage capacity, system pressures, coefficient of performance (COP), and coolant temperatures during charging and discharging. The results showed improved performance with the use of PCM [88]. **Figure 24** shows the experimental system investigated.

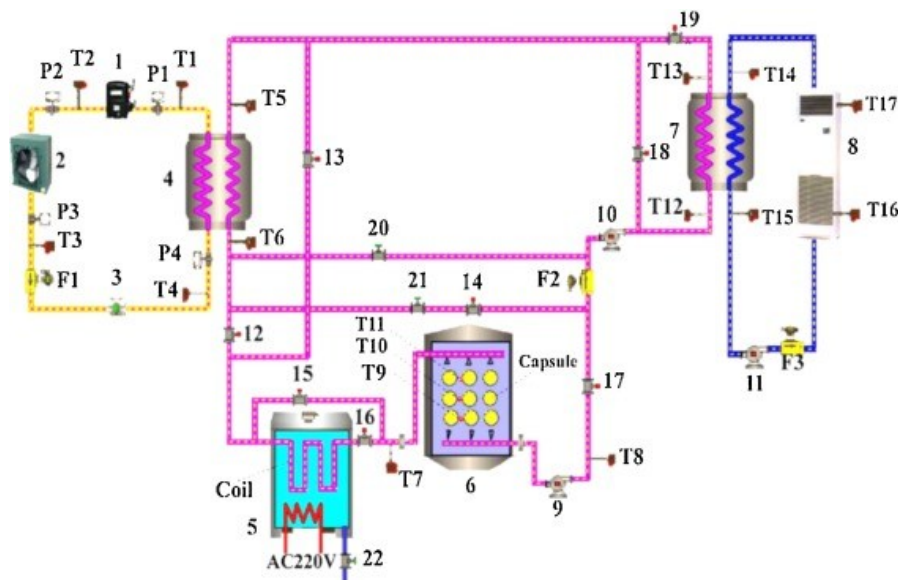


Figure 24. Diagram of the AC test system with PCM [94].

4.4 Evaporative and Radiative Cooling Systems

Direct evaporative cooling cools air by allowing water to evaporate, absorbing heat in the process. While this also increases humidity, it works well in arid climates. Indirect evaporative cooling separates air and water to avoid humidity rise, making it better for moist environments. This system was applied in the Darmstadt house 2009 [95]. Night radiative cooling, which relies on releasing heat through radiation, offers another passive solution [88].

Ansuini et al. [96] developed radiant floor panels with granulated PCM for heating and cooling. The panels were effective in summer but underperformed in winter due to high

resistance between pipes and melted PCM. To improve performance, a steel matrix was added to reduce thermal resistance. After optimization, cooling water requirements were reduced by 25% in summer, with no effect in winter, and a 3.5°C reduction in floor temperature peak during mid-season. The system helps maintain comfortable room temperatures without extra energy.

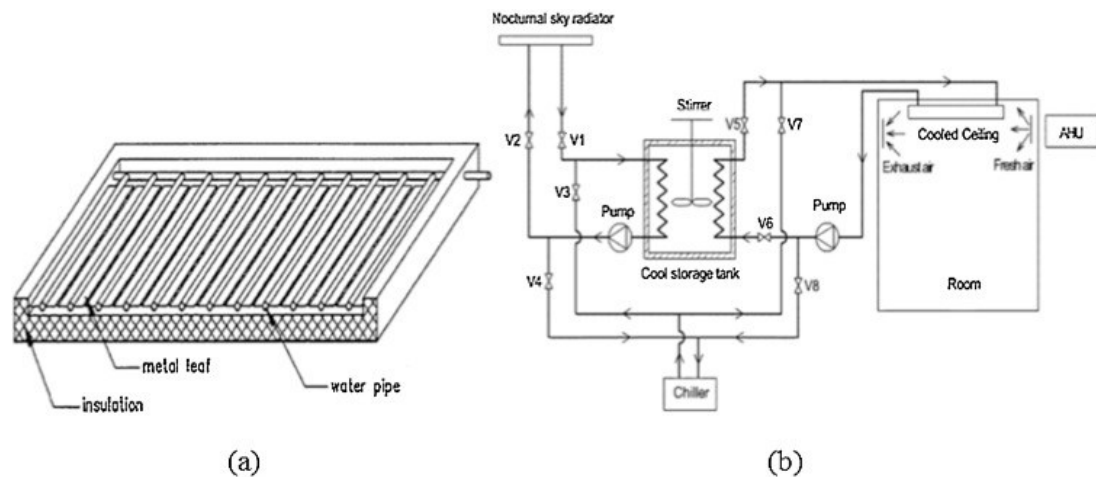


Figure 25. (a) Construction of the nocturnal sky radiator, (b) schematic diagram of the hybrid system [97].

4.5 PCM in Building Envelopes

PCM has typically been used as a separate storage unit in active systems, requiring dedicated space, which can be a limitation. As an alternative, PCM can be integrated into building envelopes like walls, roofs, and floors, enhancing both passive and active systems. This integration has become increasingly popular in the last decade.

4.5.1 PCM passive system applications in the building envelope

Some authors [95] categorize passive PCM applications in building envelopes into two main types:

- **PCM Integrated into Materials:** PCM is incorporated into construction materials like plaster, gypsum, and concrete. These materials reduce peak thermal loads in buildings. For example, microencapsulated PCM in drywall panels was tested in Germany 2009 to reduce overheating and improve thermal stability, with a 25% reduction in cooling needs in summer [98].
- **PCM as a Component:** PCM can also be used as a component in systems such as blinds or suspended ceilings. For example, PCM-integrated blinds delay temperature

rise and improve thermal comfort, reducing cooling demand by 2K in summer. Additionally, PCM panels in ceilings and floors, like the DELTA®COOL system, are effective in both summer and winter for reducing temperature fluctuations [95].

4.5.2 PCM active system applications in the building envelope

Unlike passive systems where PCM is integrated into building materials, active PCM systems enhance heat transfer by replacing free convection with forced convection. In these systems, PCM solidification is achieved with minimal energy consumption, aided by small fans.

Active Systems with Air as Heat Transfer Fluid

- **Ceiling Integrated Systems:** In suspended ceilings, small fans direct air over PCM stored in channels. During the day, warm air is cooled by the PCM, which absorbs heat. At night, cold outside air circulates through the system to discharge the heat. An example of this system is the Swedish "Cool Deck" system, which uses salt hydrate PCM (C24) for cooling [95].
- **Wall Integrated Systems:** In this system, PCM-filled bags are embedded within the walls, similar to the ceiling system. A fan circulates air, and optional external vents allow cold night air to aid in heat absorption. This design ensures comfortable air flow while improving cooling efficiency [99].
- **Floor Integrated Systems:** PCM can be installed under floorboards, where it cools warm air during the day. At night, cold air circulates through the floor, cooling the PCM and discharging the stored heat back outside [95], [99].

Active Systems with Liquid as Heat Transfer Fluid

- **PCM-Plaster with Capillary Sheets:** This system integrates capillary sheets with PCM plaster applied to walls. The capillary sheets act as heat exchangers, improving heat transfer and allowing for more efficient thermal activation of concrete walls [99].
- **Cooling Ceiling with PCM Plasterboard:** This system uses PCM plasterboard panels suspended from the ceiling to regulate room temperature. Cooling air is circulated through the system to absorb heat, which is then released at night [95].

These active PCM systems improve thermal management by using both air and liquid as heat transfer fluids, offering significant energy savings and enhancing indoor comfort.

4.5.3 Ventilated facades principles and applications

Ventilated facades (VF) are essential for reducing a building's energy demand. Integrating PCM into either the outer layer or air cavity of VFs can enhance energy efficiency [100]. VF systems serve as passive cooling solutions by preventing overheating and reducing HVAC reliance. VFs consist of a second skin placed in front of the building, creating a ventilated air cavity, which can be mechanically or naturally ventilated to improve thermal performance [101].

Operational Principles:

- **PCM Solidification:** At night, when outdoor temperatures drop below the PCM's phase change temperature, PCM solidifies with air flowing into the cavity. Mechanical ventilation may be used to improve solidification.
- **PCM Melting:** During the day, PCM absorbs heat from the indoor air, providing cooling.
- **Overheating Prevention:** Natural convection circulates air from outdoors to prevent overheating in the cavity.
- **Free Cooling:** At night, when outdoor temperatures are lower than indoor settings, the system allows for passive cooling.

Studies have shown that VF systems with PCM offer benefits like free cooling, cold storage, and solar radiation protection, with cooling supply reaching up to 150 MJ/day under optimal conditions. Artificial intelligence-based control strategies can further enhance system performance [102].

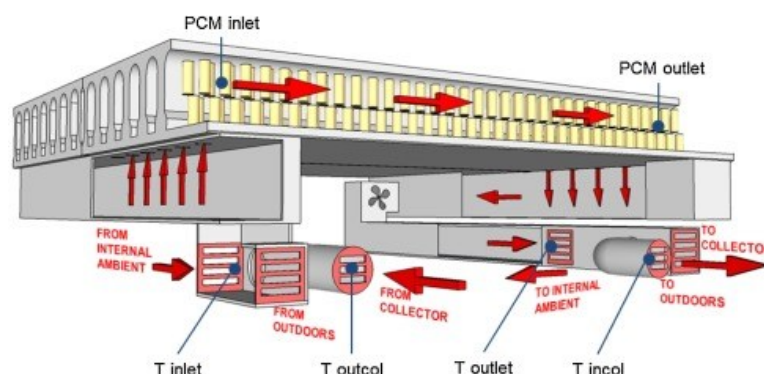


Figure 26. 3D schematic of the active slab system [103].

4.6 Comprehensive Overview of PCM in Building Envelopes

PCM can be used in both passive and active building systems. Passive systems are energy-efficient and easy to install but depend on outdoor temperatures. If night temperatures don't drop enough, the PCM won't fully solidify, limiting performance. Active systems, which utilize mechanical ventilation to improve heat transfer, are more efficient but require energy and complex components like fans and pumps [104].

While passive systems rely on natural conditions, active systems offer better control over the charge/discharge process. PCM materials, like mats and boards, are becoming easier to integrate into both system types. For heating, solar direct gain is effective, but the type of flooring material affects heat transfer. For cooling, night ventilation and solar protection are key, especially in regions with large day-night temperature swings, improving comfort and reducing energy use [105].

4.6.1 Factors affecting PCM selection

Incorporating PCM into buildings enhances thermal energy storage, helping to minimize indoor temperature fluctuations and reduce energy consumption. Several factors influence the efficiency of PCM in buildings:

1. **Outdoor Climate:** External weather plays a major role.
2. **PCM Type:** Melting point and properties.
3. **Encapsulation:** PCM containment method.
4. **Quantity & Placement:** Volume and location of PCM.
5. **System Type:** Active vs. passive systems.
6. **Building Design:** Orientation, internal gains, and materials.
7. **Real-Life Factors:** Heating/cooling setpoints and occupancy.
8. **Solar Gains:** Effect of sunlight on PCM performance.
9. **Cost:** Investment and tariff structure.

Using building simulation and optimization tools can help identify the ideal PCM configuration for each climate and application, improving building design and HVAC system performance [106].

4.6.2 Climatic conditions

Climatic conditions are crucial for PCM performance, as they affect outdoor temperature and energy needs. The Köppen-Geiger classification divides climates into five zones, each with specific energy requirements. PCM performs best in climates with large temperature swings. For example, in hot Mediterranean climates like Seville, PCM can reduce energy consumption by 62%, while in colder climates, PCM primarily reduces heating demand. PCM is most effective when the outdoor temperature range is between 12°C and 15°C [107].

4.6.3 Melting temperature of PCM

The melting temperature of PCM is crucial for its performance. If it is too low, it may not maintain comfortable temperatures at night, if it is too high, it limits solar heat storage. The optimal melting temperature typically ranges from 18 °C to 28 °C. For cooling, temperatures up to 21 °C work best, while 29-60 °C is ideal for hot water applications. PCM performance varies by climate, lower melting points are suited for cooler climates, while higher ones are better for warmer regions [108].

4.6.4 PCM location, surface area and thickness

PCM placement and thickness affect energy savings. For heating, placing PCM in the floor is effective, while wallboards are better for cooling. Increasing surface area improves heat transfer and PCM efficiency. However, thicker layers don't always yield better results. Optimizing PCM volume ensures it melts and solidifies effectively during the temperature cycle. In summary, PCM placement and dimensions must be optimized for maximum energy efficiency [109].

4.6.5 HVAC controls

Two types of studies can be conducted based on the indoor microclimate [88]:

- **Without HVAC (naturally ventilated building):** This examines how PCM affects temperature fluctuations in an indoor space with free-running temperatures, focusing on its potential to reduce temperature peaks. Hourly temperature data is required.
- **With HVAC (air-conditioned building):** This study calculates energy consumption and savings, where the indoor temperature is controlled, and set points are scheduled.

II PRACTICAL PART

5 MAIN AIMS OF THE BACHELOR THESIS

The primary aim of this thesis is to synthesize and optimize wax-based microcapsules for passive thermal regulation in buildings. These capsules are intended to store and release thermal energy through the phase transition of wax, contributing to energy efficiency in building environments. The work focuses on achieving stable capsule formation with high phase transition enthalpy and improved thermal conductivity. To meet these goals, the thesis is structured to fulfil specific aims:

- Optimize PMMA encapsulation to prevent wax leakage.
- Improve thermal conductivity using conducting additives.
- Study how synthesis parameters affect thermal properties and enthalpy.
- Characterize microcapsules using:
 - a) **Differential Scanning Calorimetry (DSC)** to measure phase transition temperature and enthalpy.
 - b) **Thermogravimetric Analysis (TGA)** to assess thermal stability and decomposition behavior.
 - c) **Scanning Electron Microscopy (SEM)** to examine surface morphology and capsule structure.
 - d) **Thermal Conductivity Testing** to analyze improvements in thermal conductivity from conductive additives.
 - e) **Stability of Capsules**

6 EXPERIMENTAL PART

The experimental part describes preparation of the encapsulated PCM systems and its further characterization and evaluation towards intended applications.

6.1 Laboratory Equipment

Three-neck round-bottom flask, magnetic stirrer with heating plate, mechanical overhead stirrer, glass stopper and plastic stopper, laboratory stand and clamps, nitrogen gas supply with flow regulator, thermometer, parafilm sealing film, laboratory-grade, measuring cylinders and volumetric flasks, laboratory balance, pipettes, burettes, watch glass, funnel for adding solids/liquids, laboratory glassware (beakers, flasks, stirring rods, etc.).

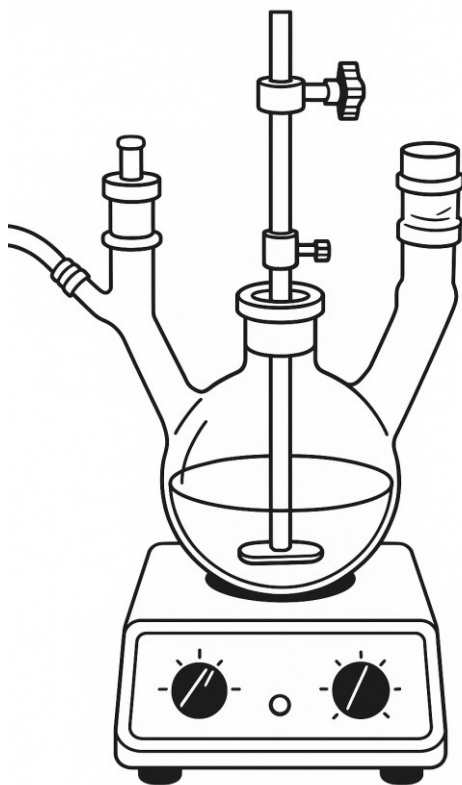


Figure 27. Schematic diagram of the laboratory apparatus used for polymerization.

6.2 Materials

Polyvinylpyrrolidone (PVP, average $M_w \sim 55,000$) (Sigma-Aldrich, Germany), Methyl methacrylate (MMA, 99%) (Sigma-Aldrich, Germany), Benzoyl peroxide (BPO, 75%) (Sigma-Aldrich, Germany), Wax (RT28HC) (Rubitherm Technologies, Germany), Expanded graphite (EG, < 20, synthetic) (Sigma-Aldrich, Germany), Nitrogen gas (N_2 , 5.0 grade) (own production), Distilled water (H_2O , ultrapure, 25 μS) (own production).

6.3 Characterization Techniques

Dispensing machine (Era Pump Systems NE-1000 Programmable Single Syringe Pump) facilitated the sample preparation. Analytical balance (KERN ABS-N) with a precision of 0.001 mg, was used for accurate weighing of the samples. Scanning electron microscope (Phenom Pro) allowed for image acquisition with the following parameters: voltage 5 kV (default), resolution: < 8 nm (SED).

Prior to imaging, each sample was coated with a thin layer of metal using a sputter coater (Quorum Polaron Emitech SC7620 Mini Sputter Coater) operated at 18 mA for 75 seconds, the pressure was automatically regulated by the device. Before SEM analysis, the samples were dried in an oven at 60 °C for 72 hours. The goal was to evaluate the morphology and surface texture of the prepared capsules and to observe how the presence of EG particles influenced their structure.

Differential scanning calorimeter (Perkin Elmer Pyris 1 DSC) was used to measure melting/crystallization temperatures and enthalpies. The program applied a two-cycle heating and cooling process from -10°C to 80°C at a heating rate of 10 K/min under a nitrogen atmosphere 20 ml/min. Sample weights ranged from 5-6 mg.

Thermogravimetric analyzer (TGA Q500), equipped with a TGA heat exchanger. The temperature ranged from 25°C to 800°C at 10°C/min under nitrogen purge flow 40/60 ml/min. Platinum pans were used with sample weights between 5-10 mg. Thermal conductivity analyzer (C-Therm TCi) was used for measuring thermal conductivity.

6.4 Polymerization of Wax Capsules

PVP, MMA, BPO, RT28HC and distilled water are present in all mixtures, while the EG particles were mixed only to 40 % of reactions. Six wax capsules were prepared without the addition of EG and four were prepared with EG (5g). Once polymerization was complete, the entire reaction mixture was filtered through a Büchner funnel using filter paper under reduced pressure. The solid product was then dried. The product was divided into two portions: approximately 1-2 grams were left to air-dry, covered with aluminum foil to prevent dust contamination (these samples were labeled JVA), while the remaining material was dried in an oven at 60°C (these samples were labeled JVO).

For samples JV1, JV2, JV3, JV4, JV5 and JV8, which did not contain EG, the preparation was as follows: PVP (1,5g) was dissolved in 150 ml of distilled water and stirred

for 15 minutes while purged with nitrogen for 15 minutes to eliminate oxygen, injected into heat resistant plastic mold fixed by bulldog clips and sealed off by paraffin film. BPO and RT28HC were added simultaneously, followed by another 15 minutes of stirring. MMA was then added, and the mixture was polymerized under conditions shown in **Table 4**.

Sample number JV8 was the only sample without EG, which was added dropwise using a dispensing machine for 3 hours and total polymerization carried out for an additional 3 hours.

Table 4. Samples JV1, JV2, JV3, JV4, JV5 and JV8 without EG.

Samples	JV1	JV2	JV3	JV4	JV5	JV8
Rotation speed [rpm]	700	300	500	700	700	700
Temperature [°C]	70	70	70	50	60	70
Distilled water [ml]	150	150	150	150	150	150
MMA [ml]	17	17	17	17	17	17
PVP [g]	1.5250	1.5074	1.5071	1.5042	1.5058	1.5068
BPO [g]	0.2564	0.2556	0.2562	0.2604	0.2563	0.2567
RT28HC [g]	16.3025	16.2682	16.2872	16.2691	16.2508	16.2594

Each sample underwent two phases. In the first phase, which occurred prior to polymerization, the sample was mixed for a specified period. Once MMA was added to the mixture, the second phase-polymerization began. During this phase, the duration of polymerization was set according to the parameters outlined in **Table 4**. These details can be found in **Table 5**, which also includes the final weight of each sample after drying.

Table 5. Samples JV1, JV2, JV3, JV4, JV5 and JV8 polymerization duration and evaluation of stability through weight loss.

Samples	JV1	JV2	JV3	JV4	JV5	JV8
Time (h)	3	3	3	5	4	6
Weight (g)	20.4784	18.8873	16.7481	15.8881	8.813	14.9587

The highest product yields were obtained from samples JV1, JV2, JV3, JV4 and JV8. However, in the case of sample 5, the mixture likely did not undergo sufficient polymerization, resulting in significant losses, most of the wax either evaporated or was not encapsulated at all.

For the EG-containing samples, the procedure varied: for sample JV6, EG was mixed with distilled water and PVP during the first phase, while the process remained the same as for the other samples. For samples JV7, JV9 and JV10, EG was mixed with MMA. In sample JV7, graphite was added manually, slowly, after the addition of RT28HC, whereas in samples JV9 and JV10, graphite was added using the drop dispensing machine in the same manner as for sample JV8, which did not contain EG.

Table 6. Samples JV6, JV7, JV9 and JV10 with EG.

Samples	JV6	JV7	JV9	JV10
Rotation speed [rpm]	700	700	700	700
Temperature [°C]	70	70	70	50
Distilled water [ml]	150	150	150	150
MMA [ml]	17	17	17	17
PVP [g]	1.5011	1.5029	1.5014	1.5096
BPO [g]	0.2553	0.2589	0.2560	0.2599
RT28HC [g]	16.2557	16.2663	16.2568	16.2648
Graphite [g]	4.9968	5.0051	5.0034	5.0021

As in the previous case, the duration of the polymerization process can be observed. For samples JV9 and JV10, a dropwise dispersing machine was used to gradually dispense the MMA-EG mixture over a period of 3 hours, making this phase relatively time-consuming. Similarly, for sample JV8, the polymerization process extended to a total duration of 6 hours.

Table 7. Samples JV6, JV7, JV9 and JV10 polymerization duration and evaluation of stability through weight loss.

Samples	JV6	JV7	JV9	JV1
Time (h)	5	5	6	6
Weight (g)	3.568	13.0524	5.5715	11.3545

Consistent with the behavior observed in the sample without the addition of EG, sample JV6 showed a considerable material loss. These results indicate that MMA failed to effectively encapsulate the wax, thereby preventing the polymerization process.

7 RESULTS AND DISCUSSION

7.1 Fabrication of Capsules

According to **Tables 4-7**, wax capsules were fabricated using different formulations and processing conditions, with a focus on the role of composition and the presence of EG in the final product. The variations included differences in stirring speed, reaction temperature, and the method and timing of component addition. In case of four individual samples, EG was added to evaluate its influence on the capsule structure, final yield and overall performance.

Most of the samples without EG (JV1, JV2, JV3, JV4 and JV8) showed successful polymerization and solid product formation, with dry weights typically around 15–20 g. These capsules were stable and suitable for further analysis. However, sample JV5, despite following a similar approach, showed a much lower dry weight, which indicates possible loss of wax or incomplete polymerization, likely due to suboptimal reaction conditions. Sample JV8 used a different strategy involving gradual addition of MMA, which may have affected polymer distribution and reduced the final yield.

The EG-containing samples JV6, JV7, JV 9, and JV10 presented more challenges. The lack of polymerization in these materials resulted in low yield (especially in sample JV6), and the results reflected this. This behavior is likely related to the presence of EG on the interface between water and MMA since the hydrophobicity of EG prevents proper polymerization. For example, the low yield in sample JV6 suggests that wax was not effectively captured by MMA and thus polymerization could not be performed. On the other hand, in the case of sample JV7, the reaction was more successful, due to the fabrication process for sample JV6, where EG was mixed in powder form directly into the water and PVP. In contrast, in case of sample JV7, EG was added to MMA and gradually dripped manually over a period of JV10 minutes, improving the reaction. For samples JV9 and JV10, EG was mixed into MMA and dispensed using a dispensing machine over a period of 3 hours. However, most of the EG particles settled at the bottom of the syringe due to the extended duration of the dosing process.

7.2 Morphology of Capsules

In general, successful encapsulation is expected to result in distinct, well-formed capsule structures. As visible in **Figures 28-37**, the morphology of all tested samples was largely irregular, with fragmented and non-uniform structures. Instead of precisely spherical or

continuous capsule shapes, the material is of relatively wide size distribution. However, in case of intended application, and as is confirmed further in the study, prepared capsules have very good performance even though the SEM images do not prove uniformity. This was particularly evident in samples containing EG, such as JVO6 and JVO7 or JVO10, where the structure appeared even more disrupted. Non-EG samples, i.e. JVO1 or JVO4, showed slightly more uniform textures, but still lacked any morphological features typical of encapsulated systems. These results align with prior observations from the fabrication phase, where part of wax was lost or unretained, indicating that encapsulation did not proceed perfectly under the given conditions. In conclusion, SEM analysis confirmed that the synthesis process produced structurally non-uniform system with various sizes and shapes, those strongly depends on the various formulations and specific reaction conditions.

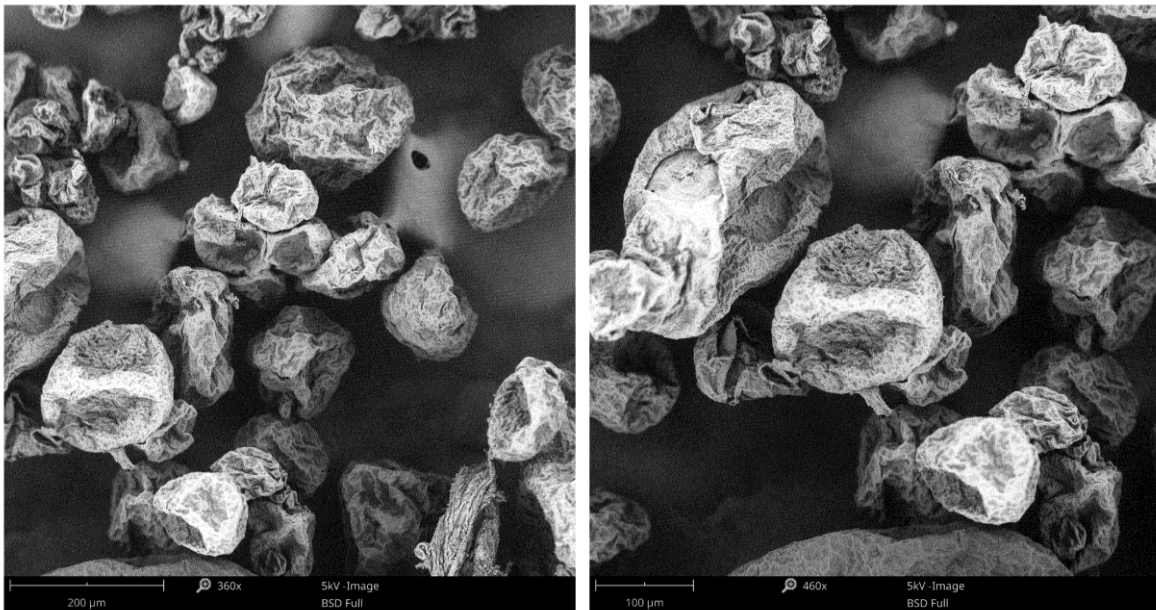


Figure 28. SEM image of the Sample JVO1 without addition of EG.

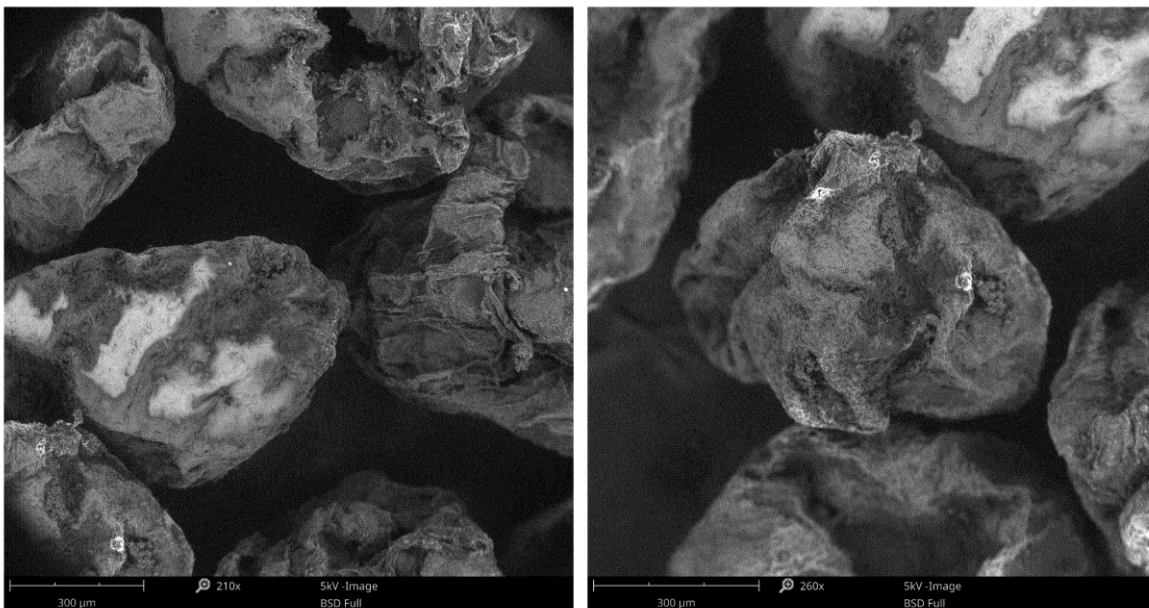


Figure 29. SEM image of the Sample JVO2 without addition of EG.

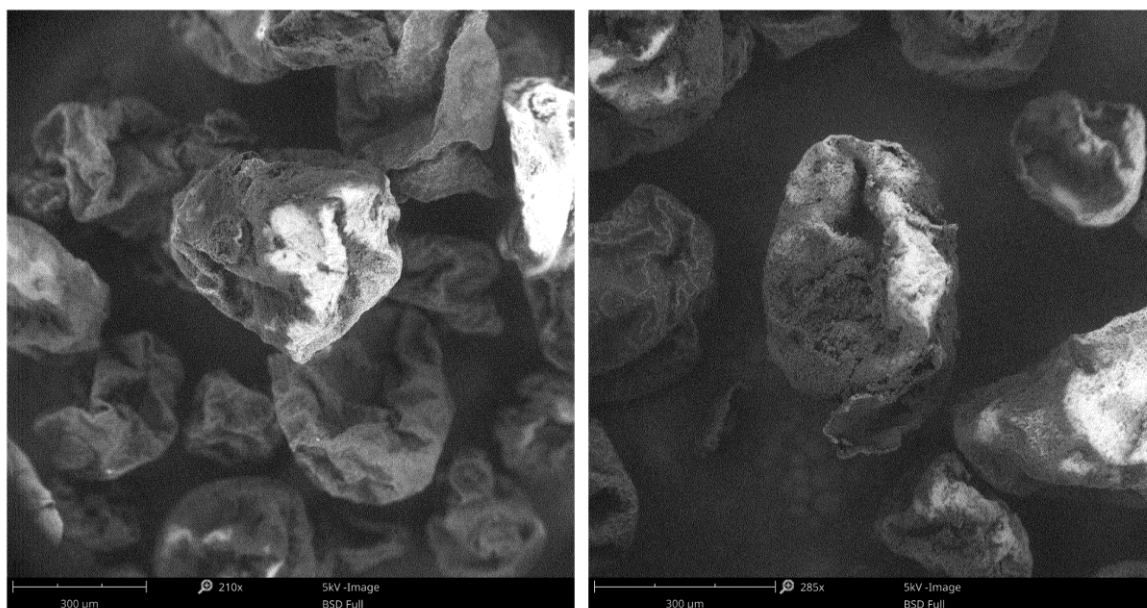


Figure 30. SEM image of the Sample JVO3 without addition of EG.

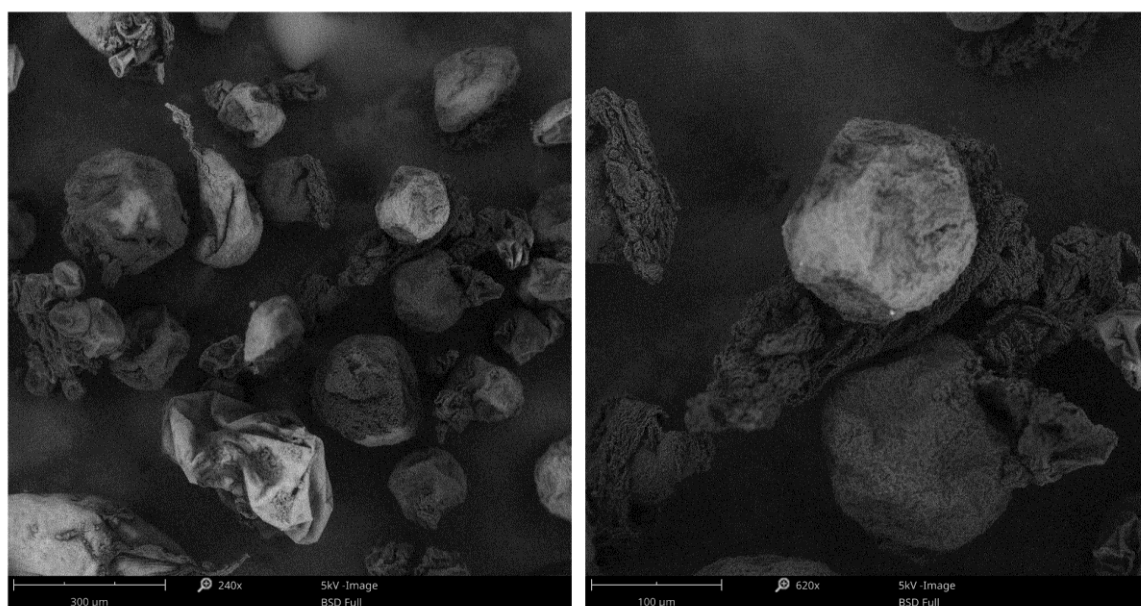


Figure 31. SEM image of the Sample JVO4 without addition of EG.

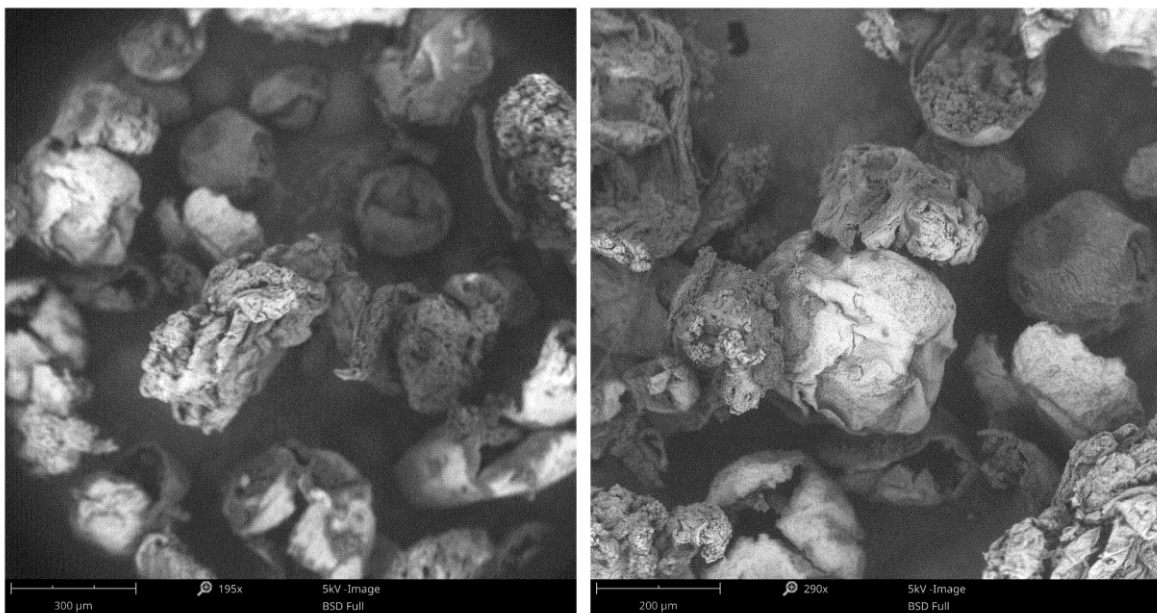


Figure 32. SEM image of the Sample JVO5 without addition of EG.

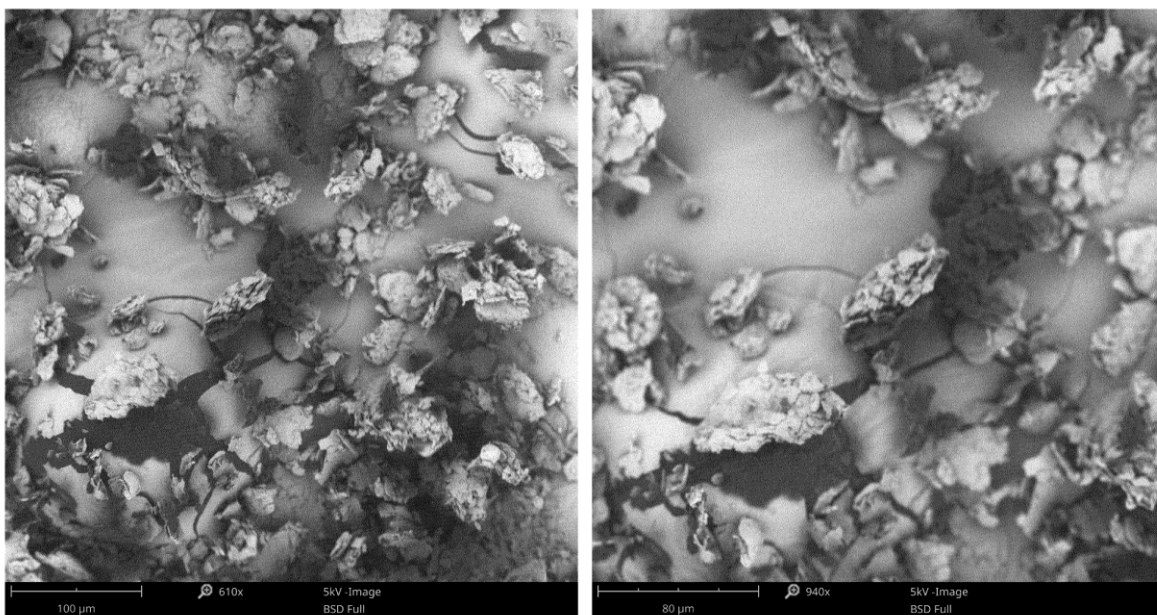


Figure 33. SEM image of the Sample JVO6 with EG.

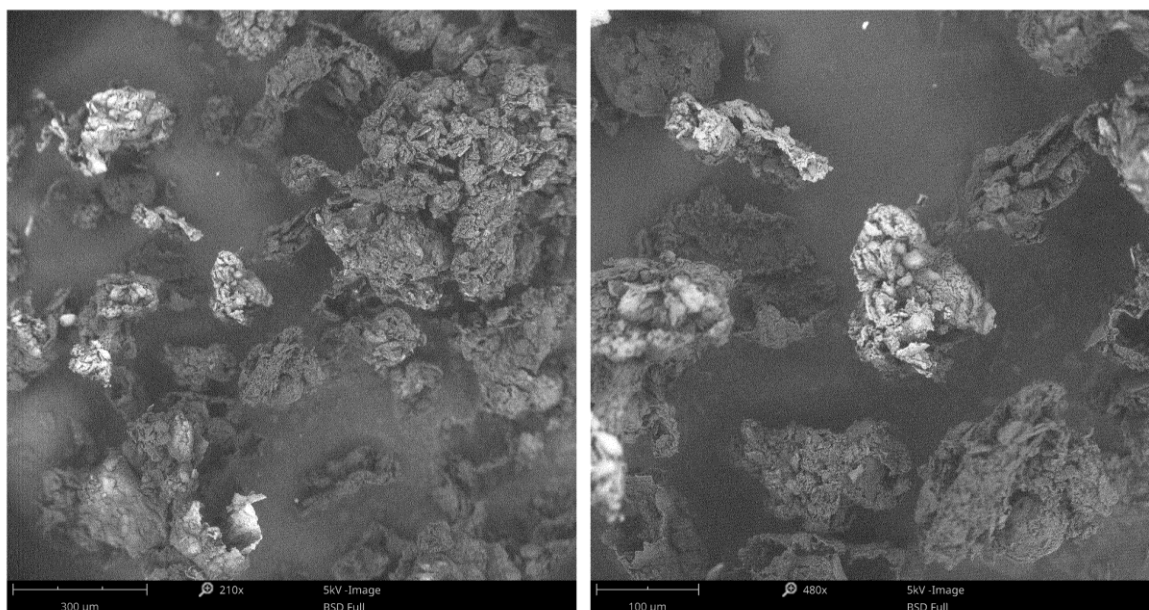


Figure 34. SEM image of the Sample JVO7 with EG.

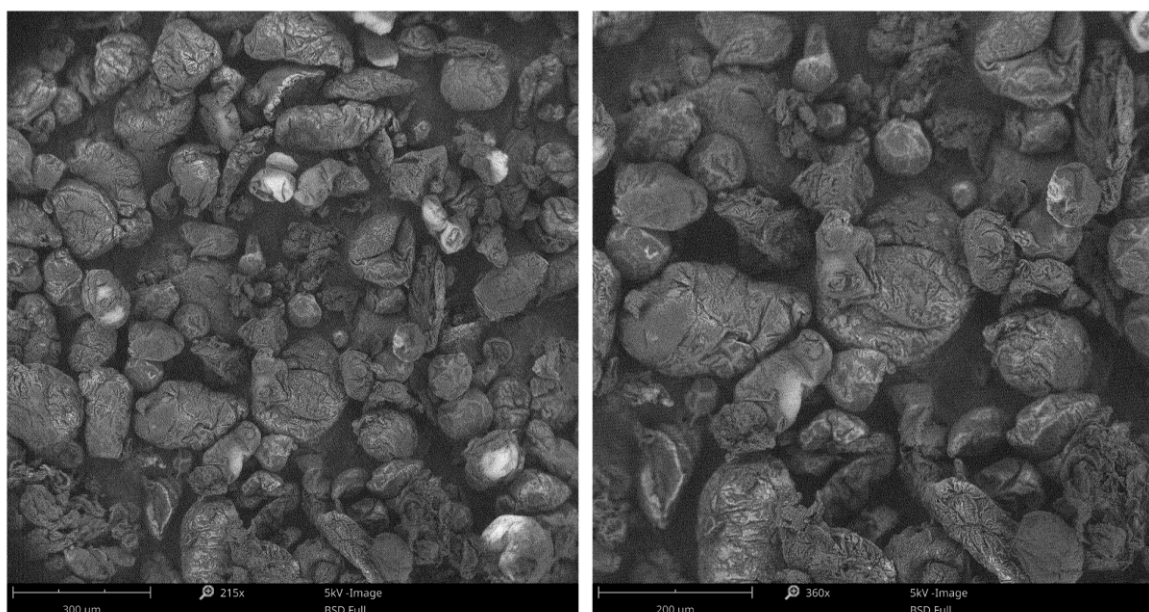


Figure 35. SEM image of the Sample JVO8 without addition of EG.

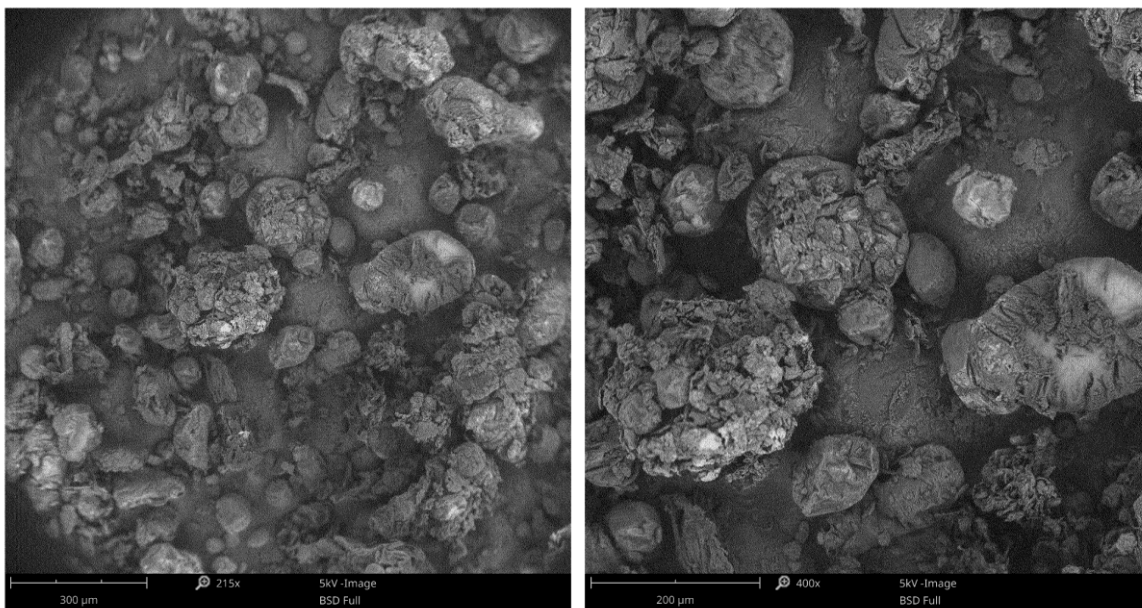


Figure 36. SEM image of the Sample JVO9 with EG.

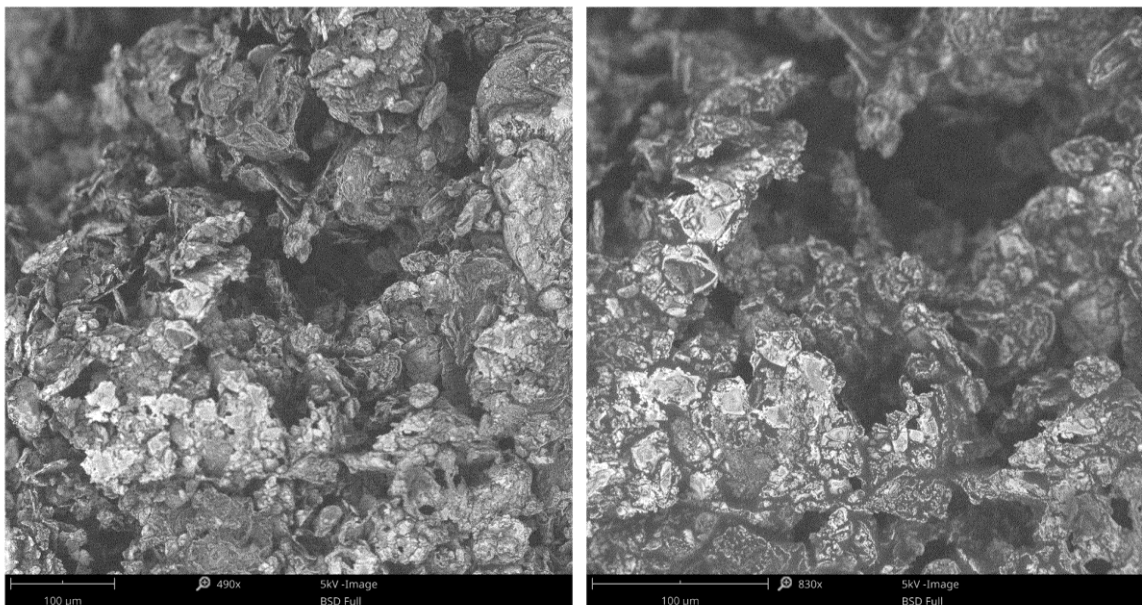


Figure 37. SEM image of the Sample JVO10 with EG.

7.3 TGA

This analysis was performed to assess the thermal stability and composition of the samples, focusing on the content of wax and the effects of EG and drying methods. The weight loss curves for the samples are shown in **Figures 38-41**.

Samples without EG, such as the air-dried group JVA1-JVA5 and JVA8, exhibited significant weight loss between 150 and 400 °C, corresponding to the decomposition of paraffin wax and unreacted monomers. For example, sample JVA8 showed the highest weight loss, which aligns with its large melting and crystallization enthalpies measured by DSC, $\Delta H_m = -225.70$ J/g and $\Delta H_c = 237.53$ J/g, indicating a substantial amount of free wax. In contrast, JVA5 showed lower weight loss and enthalpy values, suggesting more complete polymerization or greater loss of wax during drying.

Oven-dried samples without EG, JVO1-JVO5 and JVO8 generally exhibited lower weight loss, indicating that the drying process facilitated the removal of volatile wax components and possibly also partially wax itself.

Samples containing EG showed notably less weight loss. Oven-dried samples like JVO6 and JVO9 retained a larger residual mass at 800 °C, reflecting the thermal stability of graphite and possibly better wax encapsulation. For instance, JVO6 showed minimal degradation, which could be due to very low organic content and absence of the polymer and wax as well. Air-dried EG samples such as JVA10 displayed higher enthalpies and more weight loss than oven-dried ones, indicating that air drying helps retain wax, though EG still contributes to improved thermal stability.

Overall, TGA results correlate well with DSC data: higher weight losses correspond to higher enthalpy values, confirming the presence of unpolymerized wax. The inclusion of EG and drying methods significantly influence both thermal stability and wax retention in the samples.

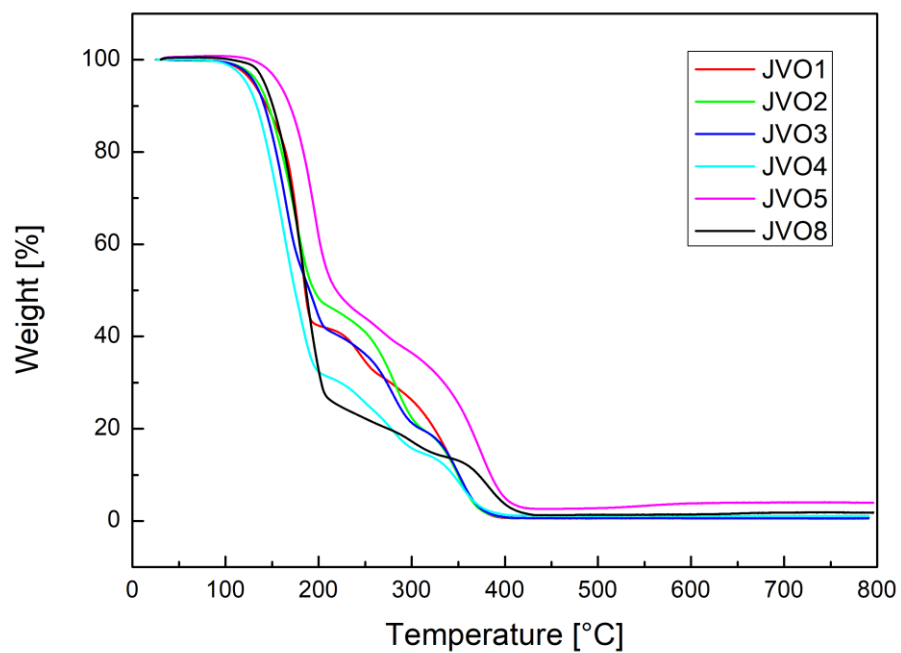


Figure 38. Weight vs. Temperature for samples JVO1, JVO2, JVO3, JVO4, JVO5 and JVO8 without EG, dried in an oven.

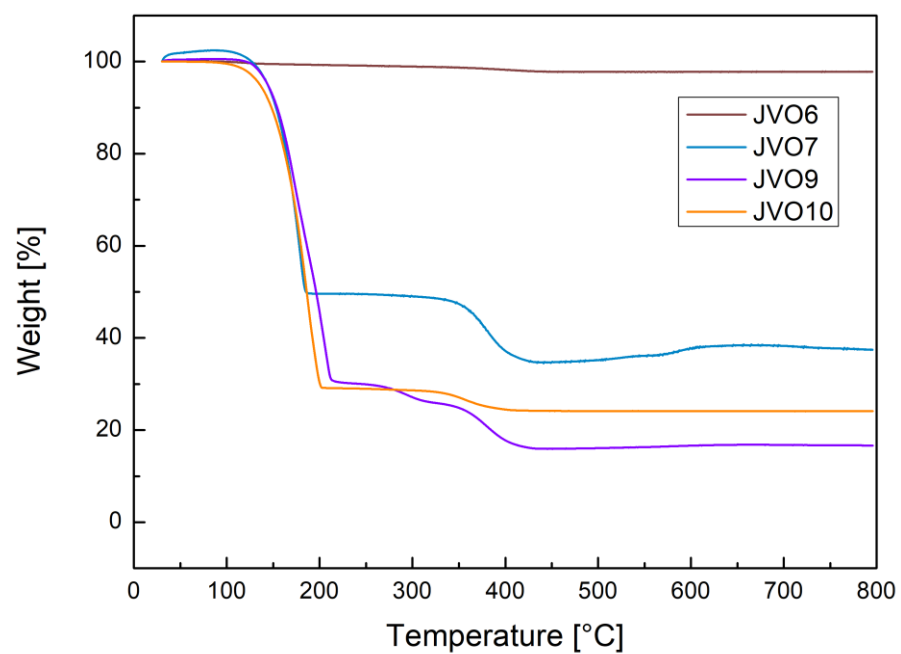


Figure 39. Weight vs Temperature for samples JVO6, JVO7, JVO9 and JVO10 with EG, dried in an oven.

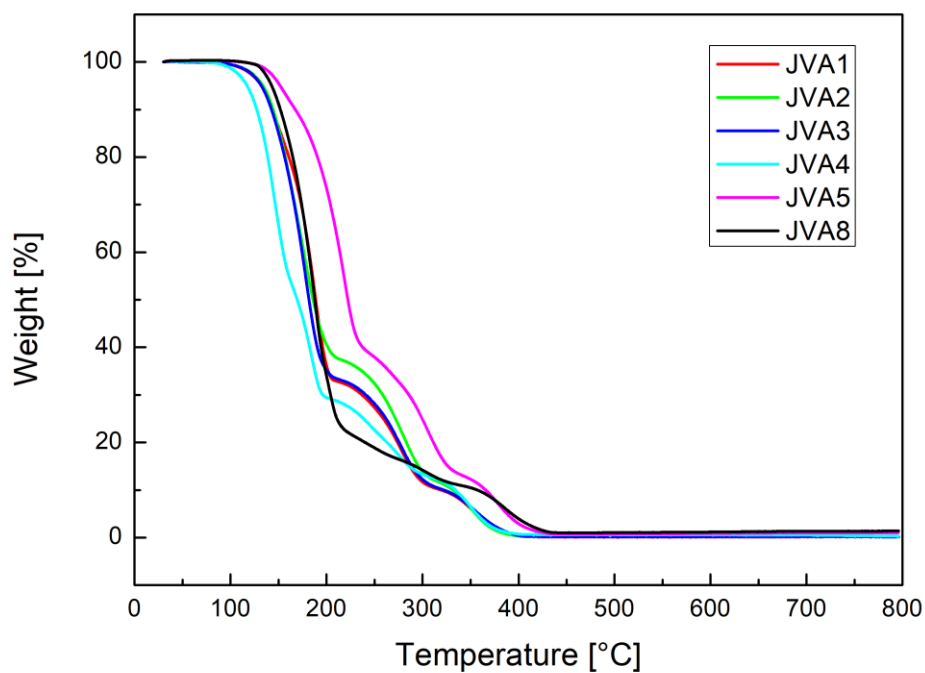


Figure 40. Weight vs. Temperature for samples JVA1, JVA2, JVA3, JVA4, JVA5 and JVA8 without EG, air-dried under aluminum foil.

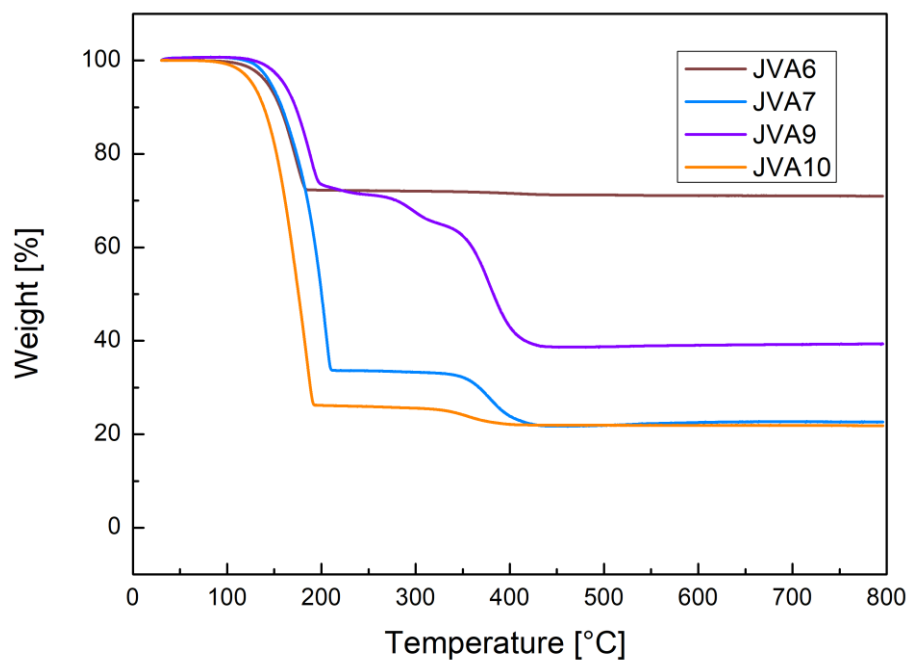


Figure 41. Weight vs. Temperature for samples JVA6, JVA7, JVA9 and JVA10 with EG, air-dried under aluminum foil.

7.4 DSC

The measured values of melting temperature (T_m), crystallization temperature (T_c), melting enthalpy (ΔH_m), and crystallization enthalpy (ΔH_c) are summarized in **Tables 8-11**. The samples were divided into four groups based on the presence of EG and the drying method (air-dried under aluminum foil vs. oven-dried).

JVA samples without EG (**Table 8**) showed relatively high values of both melting and crystallization enthalpy, with the highest recorded in sample JVA8, $\Delta H_m = -225.70$ J/g and $\Delta H_c = 237.53$ J/g. The melting temperatures mostly ranged from 31-34 °C. These results indicate a high proportion of non-encapsulated wax phase in the matrix. Sample JVA5 exhibited lower enthalpy values, possibly due to less sufficient encapsulation, however also with less amount of non-encapsulated wax.

JVA samples with EG (**Table 9**) generally exhibited lower enthalpy values compared to the EG-free samples, except for samples JVA9 and JVA10, which still showed relatively high values $\Delta H_m = -188.35$ and -204.20 J/g. The presence of EG may restrict the mobility of the wax, thereby partially reducing the amount of released heat during the phase change, or it may influence the polymerization process. Interestingly, some EG-containing samples had higher T_c values than their EG-free counterparts, which could be related to improved heat transfer due to EG's high thermal conductivity.

JVO samples without EG (**Table 10**) had lower ΔH_m and ΔH_c values compared to their JVA counterparts, likely due to the oven drying process, which may have accelerated the evaporation of non-encapsulated wax.

JVO samples with EG (**Table 11**) generally showed the lowest enthalpy values, particularly sample JVO9, $\Delta H_m = -62.06$ J/g. The JVO6 sample is a special case, where no polymer shell is present and no wax as well and thus, no data was obtained in this respect. This suggests that the combination of EG and oven drying significantly affects the amount of free wax, either by promoting its removal or by enabling its encapsulation without polymerization. However, sample JVO10 still exhibited relatively high values, indicating some variability within the group.

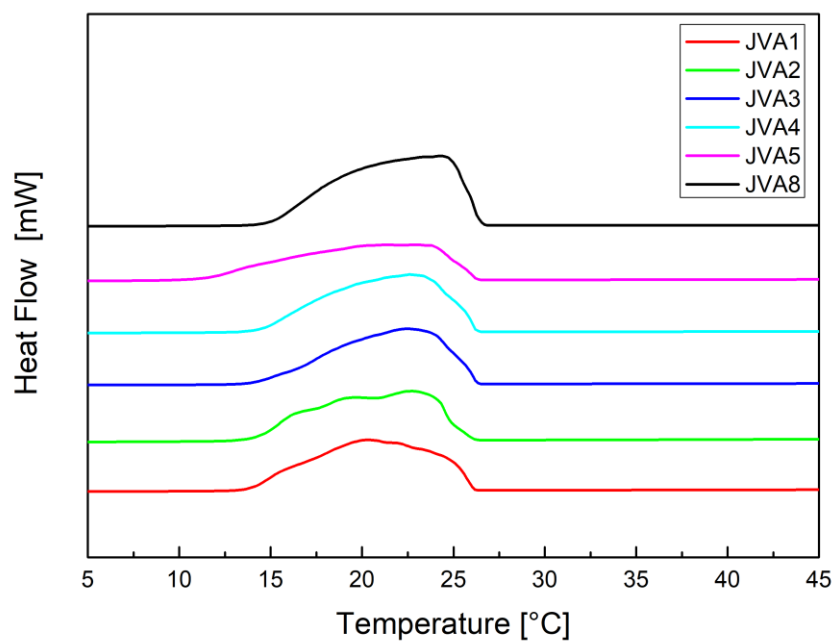


Figure 42. Heat flow vs. Temperature during the first cooling for samples JVA1, JVA2, JVA3, JVA4, JVA5, and JVA8 without EG, air-dried under aluminum foil.

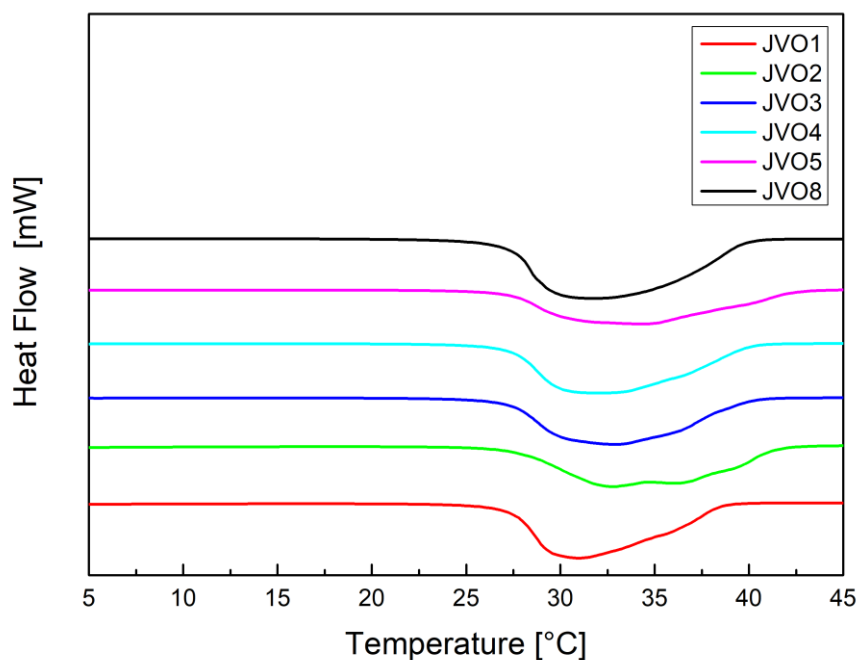


Figure 43. Heat flow vs. Temperature during the first heating for samples JVA1, JVA2, JVA3, JVA4, JVA5, and JVA8 without EG, air-dried under aluminum foil.

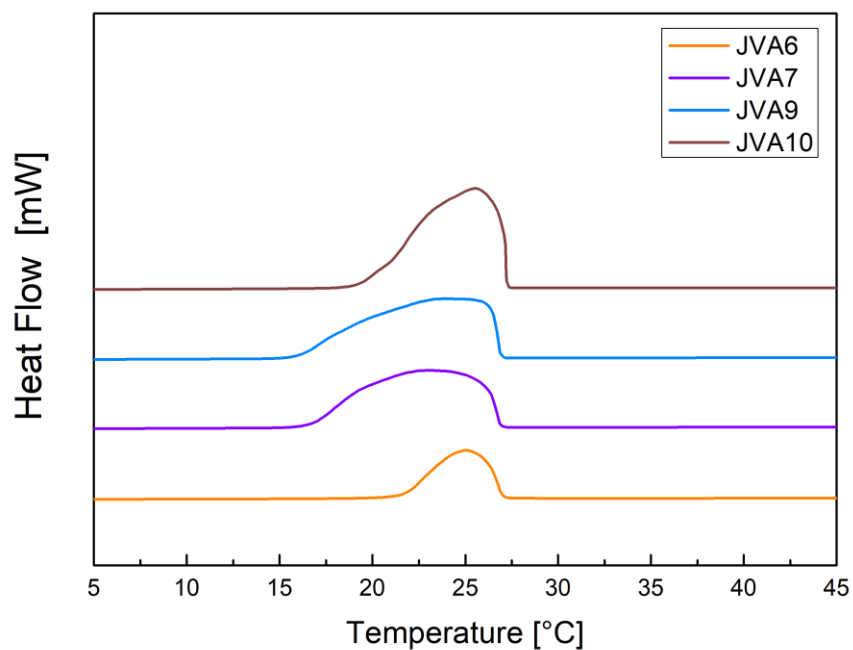


Figure 44. Heat flow vs. Temperature during the first cooling for samples JVA6, JVA7, JVA9 and JVA10 with EG, air-dried under aluminum foil.

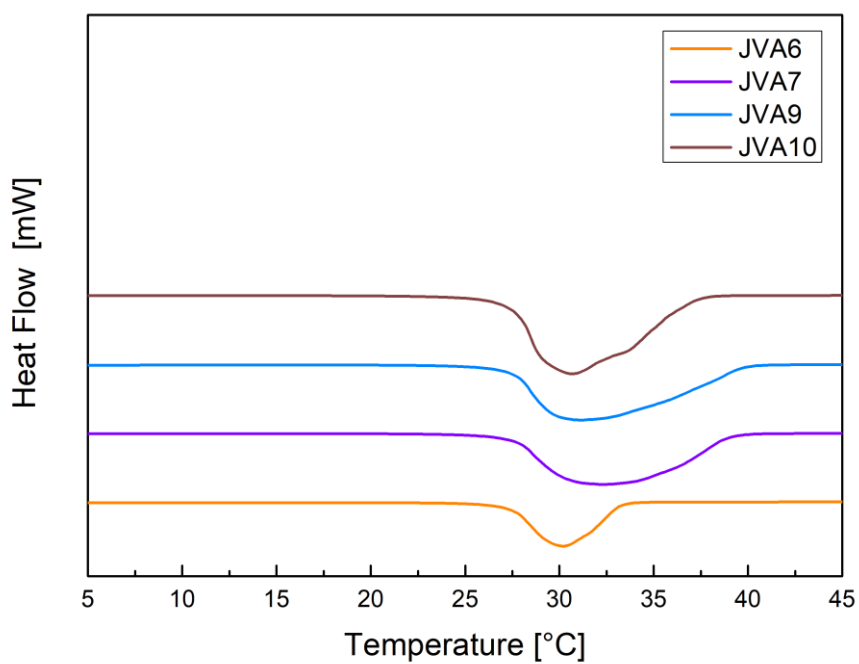


Figure 45. Heat flow vs. Temperature during the first heating for samples JVA6, JVA7, JVA9 and JVA10 with EG, air-dried under aluminum foil.

Table 8. Measured values of ΔH_m , T_m , ΔH_c and T_c of samples JVA1, JVA2, JVA3, JVA4, JVA5 and JVA8 without EG, air-dried under aluminum foil.

Samples	Melting Process		Freezing Process	
	ΔH_m (J/g)	T_m (°C)	ΔH_c (J/g)	T_c (°C)
JVA1	-167.63	31.06	172.79	20.41
JVA2	-163.63	32.82	171.94	22.73
JVA3	-171.82	32.98	178.51	22.57
JVA4	-183.63	31.79	194.12	22.59
JVA5	-148.56	34.35	155.32	21.48
JVA8	-225.70	31.68	237.53	24.38

Table 9. Measured values of ΔH_m , T_m , ΔH_c and T_c of samples JVA6, JVA7, JVA9 and JVA10 with EG, air-dried under aluminum foil.

Samples	Melting Process		Freezing Process	
	ΔH_m (J/g)	T_m (°C)	ΔH_c (J/g)	T_c (°C)
JVA6	-71.31	30.22	71.71	25.14
JVA7	-173.16	32.31	183.89	23.06
JVA9	-188.35	31.09	198.50	23.93
JVA10	-204.20	30.73	214.85	25.58

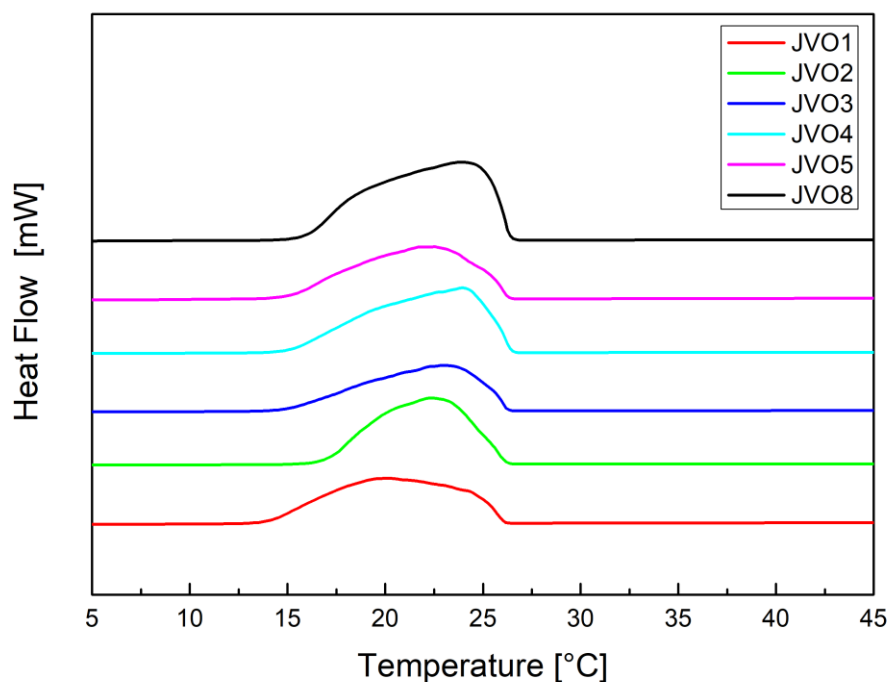


Figure 46. Heat flow vs. Temperature during the first cooling for samples JVO1, JVO2, JVO3, JVO4, JVO5, and JVO8 without EG, dried in an oven.

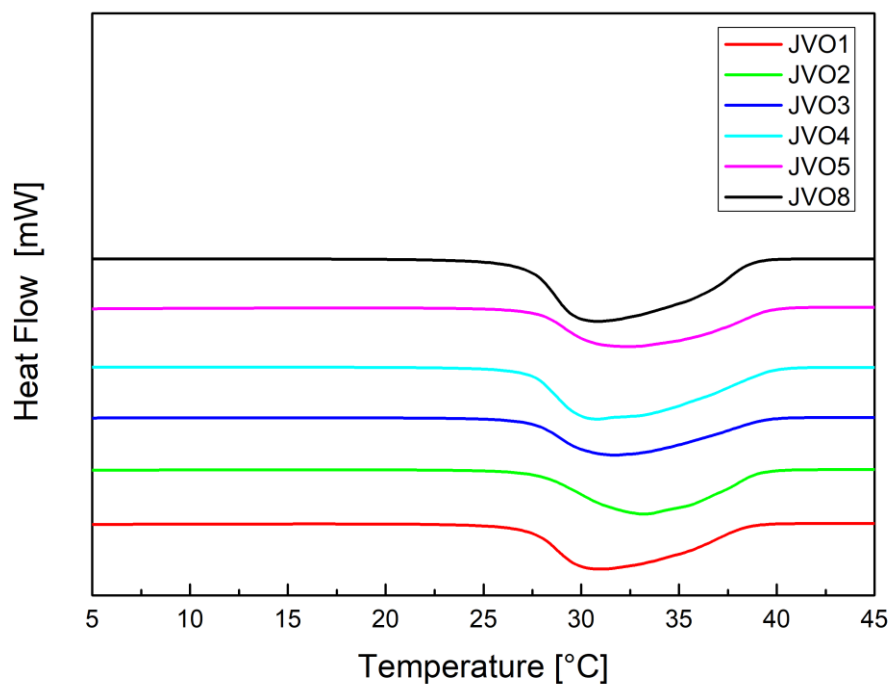


Figure 47. Heat flow vs. Temperature during the first heating for samples JVO1, JVO2, JVO3, JVO4, JVO5, and JVO8 without EG, dried in an oven.

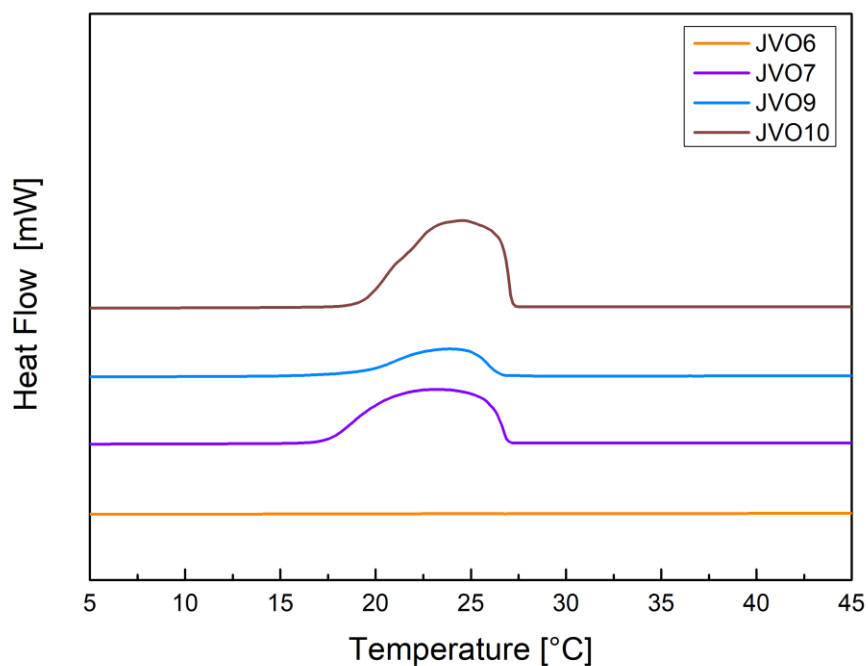


Figure 48. Heat flow vs. Temperature during the first cooling for samples JVO6, JVO7, JVO9 and JVO10 with EG, dried in an oven.

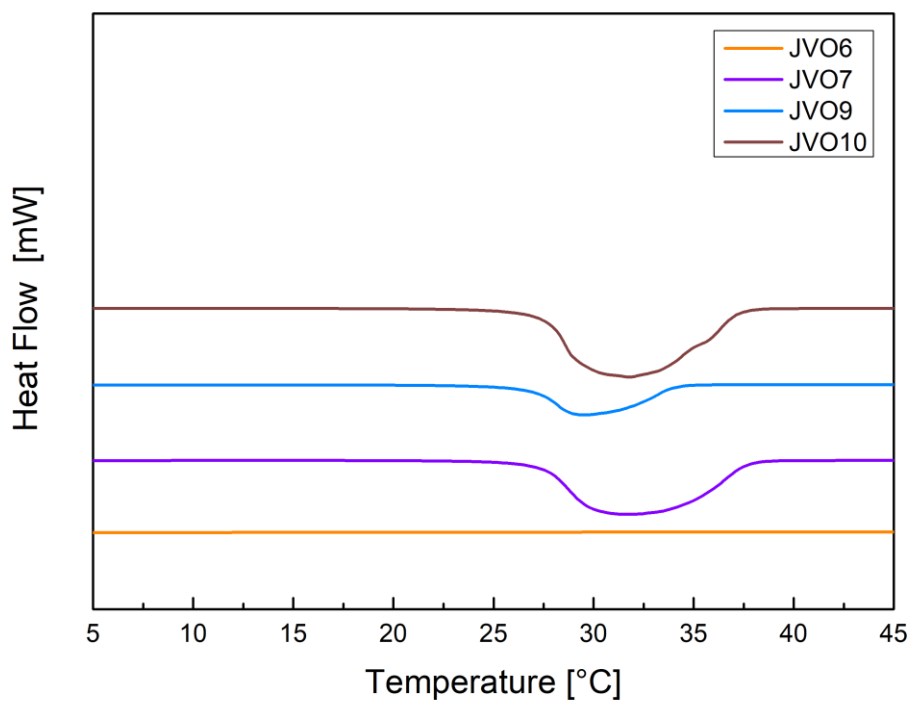


Figure 49. Heat flow vs. Temperature during the first heating for samples JVO6, JVO7, JVO9 and JVO10 with EG, dried in an oven.

Table 10. Measured values of ΔH_m , T_m , ΔH_c and T_c of samples JVO1, JVO2, JVO3, JVO4, JVO5 and JVO8 without EG, dried in an oven.

Samples	Melting Process		Freezing Process	
	ΔH_m (J/g)	T_m (°C)	ΔH_c (J/g)	T_c (°C)
JVO1	-145.17	31.02	153.42	20.28
JVO2	-136.23	33.18	161.18	22.45
JVO3	-123.30	31.72	129.38	22.98
JVO4	-178.33	30.74	185.77	23.98
JVO5	-135.31	32.56	154.07	22.53
JVO8	- 211.04	30.87	231.11	24.04

Table 11. Measured values of ΔH_m , T_m , ΔH_c and T_c of samples JVO6, JVO7, JVO9 and JVO10 with EG, dried in an oven.

Samples	Melting Process		Freezing Process	
	ΔH_m (J/g)	T_m (°C)	ΔH_c (J/g)	T_c (°C)
JVO6	-	-	-	-
JVO7	-158.56	31.79	163.33	23.22
JVO9	-62.06	29.61	62.24	23.88
JVO10	-188.22	31.70	210.77	24.48

7.5 Thermal Heat

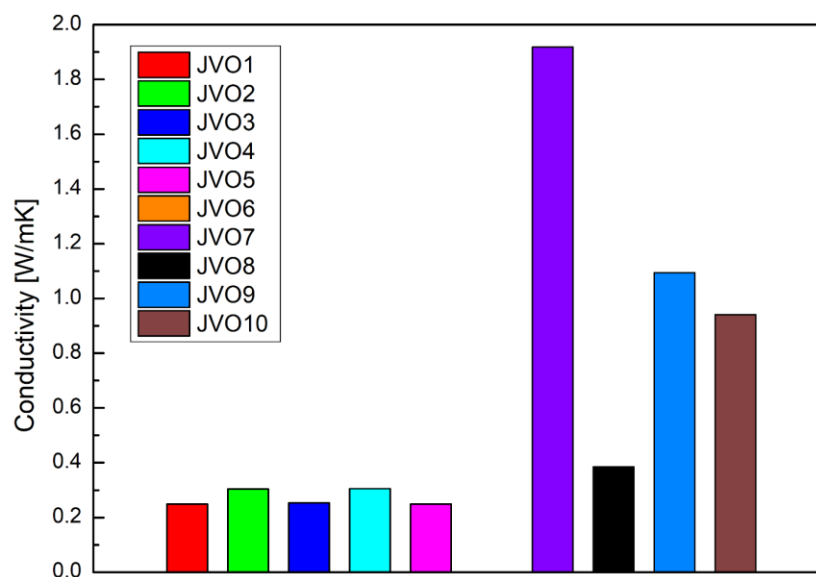


Figure 50. Comparison of thermal conductivity across all samples (JVO1-JVO10).

Figure 50 shows that samples containing EG, specifically JVO7, JVO9, and JVO10, exhibit high thermal conductivity, reaching up to 1.9 W/mK, in the case of JVO7. This enhanced thermal conductivity facilitates faster heat transfer, resulting in a more rapid phase transition and melting of the wax. In contrast, the EG-free samples (JVO1, JVO2, JVO3, JVO4, JVO5, and JVO8) display significantly lower thermal conductivity, ranging between 0.2 and 0.4 W/mK. Sample JVO6 showed no measurable thermal conductivity, the material failed to hold together, as it consisted almost entirely of residual EG with minimal wax content.

7.6 Weight Loss

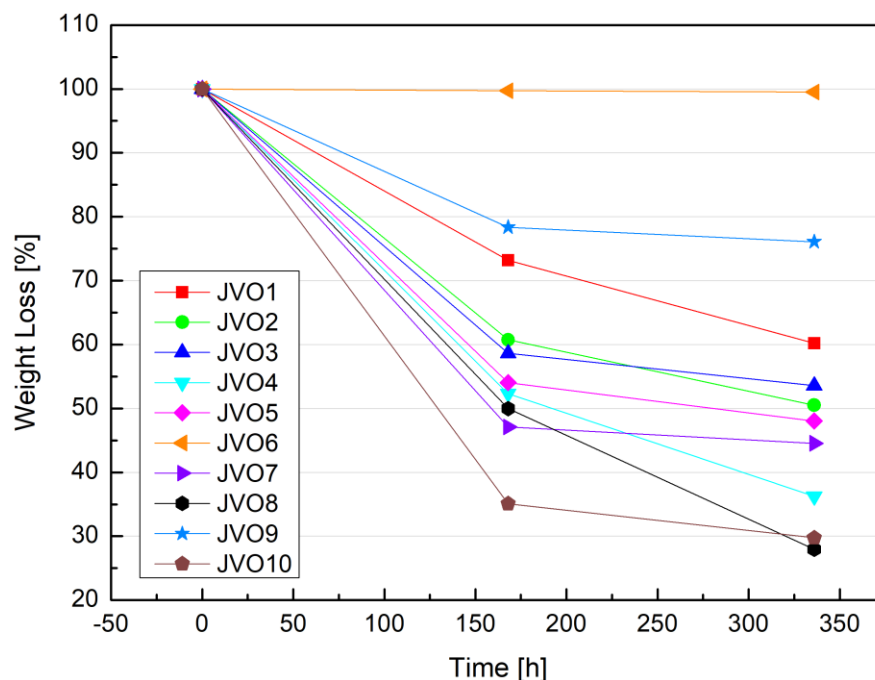


Figure 51. Drying curve, Weight Loss vs. Time for samples (JVO1-JVO10).

At a constant temperature of 60 °C, weight loss was observed over time across all samples, indicating varying degrees of encapsulation efficiency. The JVO10 sample, which included EG, exhibited a weight loss of approximately 70% of its initial mass after one week, while the JVO8 sample without EG reached a slightly higher loss of around 75% after two weeks.

Despite the observed weight loss, several samples demonstrated promising performance. Notably, sample JVO9 retained over 80% of its mass and exhibited a thermal conductivity exceeding 1 W/mK, along with an adjusted latent heat of approximately 40 J/g, values comparable or superior to commercially available materials, which typically offer 40–50 J/g and thermal conductivity around 0.6 W/mK. Similarly, sample JVO7 reached a recalculated final latent heat of about 71 J/g, and JVO10 achieved 54 J/g, confirming that the developed materials hold strong potential for TES applications, especially when considering both thermal conductivity and energy capacity.

CONCLUSION

In the theoretical part, the types of PCMs, their fillers and encapsulation methods were discussed, along with their properties and potential applications in TES systems. In the practical part, the materials used for the encapsulation of RT28HC, were introduced, along with the modified samples containing EG (JVO7, JVO9, JVO10) and those without EG (JVO1, JVO2, JVO3, JVO4, JVO5, JVO8). The preparation method for the wax capsules and the characterization techniques used to analyze the samples were also detailed. Thermal conductivity measurements revealed that the samples containing EG (JVO7, JVO9, JVO10) exhibited significantly higher thermal conductivity, with values reaching up to 1.9 W/mK in the case of JVO7. This high conductivity facilitated faster phase change and resulted in wax melting. In contrast, the samples without EG (JVO1, JVO2, JVO3, JVO4, JVO5, and JVO8) had much lower thermal conductivity, ranging from 0.2 to 0.4 W/mK. The sample JVO6, which did not contain sufficient wax due to poor molding, had near-zero thermal conductivity, making it unsuitable for measurement. DSC analysis showed that the presence of EG significantly influenced the thermal properties of the composites. The samples with EG exhibited faster melting and crystallization transitions compared to the samples without EG. Generally, possessing excellent melting enthalpies ~ 211 J/g for JVO8 and 158 J/g or 186 J/g for JVO7 and JVO10, respectively. TGA provided valuable information about the thermal stability and content of the composites, showing that the presence of EG improved the thermal stability of the encapsulated waxes. Moreover, it is clearly observable, that materials with higher amount of the RT28HC, also showed enhanced values of melting enthalpies. Also, the shell amount can be clearly evaluated where the JVO10 possesses the lowest shell thickness. SEM images confirmed the morphology of the composites, illustrating the dispersion of EG within the polymer matrix and how it affects thermal behavior. Weight loss analysis showed that composites containing EG exhibited faster mass loss rates, likely due to enhanced heat transfer facilitated by the increased thermal conductivity of the EG particles.

From the results of all characterizations, it can be concluded that the addition of EG significantly improves the thermal conductivity of the wax composites, leading to faster phase change and higher efficiency in thermal energy storage. The best-performing composite, JVO7, stands out for its superior thermal conductivity and phase change efficiency. All partial objectives of the study were successfully met, including the characterization of the thermal properties, polymerization behavior, and morphology of the

wax composites. However, further optimization and additional studies are needed to explore the practical applications of these encapsulated PCMs in the various heat energy storage systems.

BIBLIOGRAPHY

- [1] PODARA, C. V.; KARTSONAKIS, I. A. a CHARITIDIS, C. A. Towards Phase Change Materials for Thermal Energy Storage: Classification, Improvements and Applications in the Building Sector. Online. *Applied Sciences*. 2021, roč. 11, č. 4. ISSN 2076-3417. Dostupné z: <https://doi.org/10.3390/app11041490>. [cit. 2025-04-28].
- [2] PASUPATHY, A.; VELRAJ, R. a SEENIRAJ, R. V. Phase change material-based building architecture for thermal management in residential and commercial establishments. Online. *Renewable and Sustainable Energy Reviews*. 2008, roč. 12, č. 1, s. 39-64. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2006.05.010>. [cit. 2025-04-28].
- [3] SARBU, I. a SEBARCHIEVICI, C. A Comprehensive Review of Thermal Energy Storage. Online. *Sustainability*. 2018, roč. 10, č. 1. ISSN 2071-1050. Dostupné z: <https://doi.org/10.3390/su10010191>. [cit. 2025-04-28].
- [4] ITEN, M.; LIU, S. a SHUKLA, A. A review on the air-PCM-TES application for free cooling and heating in the buildings. Online. *Renewable and Sustainable Energy Reviews*. 2016, roč. 61, s. 175-186. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2016.03.007>. [cit. 2025-04-28].
- [5] DIACONU, B. M. Thermal energy savings in buildings with PCM-enhanced envelope: Influence of occupancy pattern and ventilation. Online. *Energy and Buildings*. 2011, roč. 43, č. 1, s. 101-107. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2010.08.019>. [cit. 2025-04-28].
- [6] HASSAN, F.; JAMIL, F.; HUSSAIN, A.; ALI, H. M.; JANJUA, M. M. et al. Recent advancements in latent heat phase change materials and their applications for thermal energy storage and buildings: A state of the art review. Online. *Sustainable Energy Technologies and Assessments*. 2022, roč. 49. ISSN 22131388. Dostupné z: <https://doi.org/10.1016/j.seta.2021.101646>. [cit. 2025-04-28].
- [7] AL-GUNAID, T.; SOBOLČIAK, P.; CHRİAA, I.; KARKRI, M.; MRLIK, M. et al. Phase change materials designed from Tetra Pak waste and paraffin wax as unique thermal energy storage systems. Online. *Journal of Energy Storage*. 2023, roč. 64. ISSN 2352152X. Dostupné z: <https://doi.org/10.1016/j.est.2023.107173>. [cit. 2025-04-28].
- [8] HABIB, M. A. a RAHMAN, M. M. Phase Change Materials for Applications in Building Thermal Energy Storage (Review). Online. *Thermal Engineering*. 2024, roč. 71, č. 8, s. 649-663. ISSN 0040-6015. Dostupné z: <https://doi.org/10.1134/S0040601524700174>. [cit. 2025-04-28].
- [9] MARANI, A. a NEHDI, M. L. Integrating phase change materials in construction materials: Critical review. Online. *Construction and Building Materials*. 2019, roč. 217, s. 36-49. ISSN 09500618. Dostupné z: <https://doi.org/10.1016/j.conbuildmat.2019.05.064>. [cit. 2025-04-28].
- [10] BRAUN, J. E.; MONTGOMERY, K. W. a CHATURVEDI, N. Evaluating the Performance of Building Thermal Mass Control Strategies. Online. *HVAC&R Research*. 2001, roč. 7, č. 4, s. 403-428. ISSN 1078-9669. Dostupné z: <https://doi.org/10.1080/10789669.2001.10391283>. [cit. 2025-04-28].
- [11] ZHANG, Q.; LIU, J.; ZHANG, J.; LIN, L. a SHI, J. A Review of Composite Phase Change Materials Based on Biomass Materials. Online. *Polymers*. 2022, roč. 14, č.

19. ISSN 2073-4360. Dostupné z: <https://doi.org/10.3390/polym14194089>. [cit. 2025-04-28].
- [12] LIU, H.; WANG, X.; WU, D. a JI, S. Morphology-controlled synthesis of microencapsulated phase change materials with TiO₂ shell for thermal energy harvesting and temperature regulation. Online. *Energy*. 2019, roč. 172, s. 599-617. ISSN 03605442. Dostupné z: <https://doi.org/10.1016/j.energy.2019.01.151>. [cit. 2025-04-28].
- [13] JIANG, T.; ZHANG, Y.; OLAYIWOLA, S.; LAU, C.; FAN, M. et al. Biomass-derived porous carbons support in phase change materials for building energy efficiency: a review. Online. *Materials Today Energy*. 2022, roč. 23. ISSN 24686069. Dostupné z: <https://doi.org/10.1016/j.mtener.2021.100905>. [cit. 2025-04-28].
- [14] PARAMESHWARAN, R.; KALAISELVAM, S.; HARIKRISHNAN, S. a ELAYAPERUMAL, A. Sustainable thermal energy storage technologies for buildings: A review. Online. *Renewable and Sustainable Energy Reviews*. 2012, roč. 16, č. 5, s. 2394-2433. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2012.01.058>. [cit. 2025-04-28].
- [15] CAO, Q. a LIU, P. Crystalline-amorphous phase transition of hyperbranched polyurethane phase change materials for energy storage. Online. *Journal of Materials Science*. 2007, roč. 42, č. 14, s. 5661-5665. ISSN 0022-2461. Dostupné z: <https://doi.org/10.1007/s10853-006-0884-z>. [cit. 2025-04-28].
- [16] NALLUSAMY, N.; SAMPATH, S. a VELRAJ, R. Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources. Online. *Renewable Energy*. 2007, roč. 32, č. 7, s. 1206-1227. ISSN 09601481. Dostupné z: <https://doi.org/10.1016/j.renene.2006.04.015>. [cit. 2025-05-01].
- [17] LI, G. Sensible heat thermal storage energy and exergy performance evaluations. Online. *Renewable and Sustainable Energy Reviews*. 2016, roč. 53, s. 897-923. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2015.09.006>. [cit. 2025-05-01].
- [18] MOHAMED, S. A.; AL-SULAIMAN, F. A.; IBRAHIM, N. I.; ZAHIR, M. H.; AL-AHMED, A. et al. A review on current status and challenges of inorganic phase change materials for thermal energy storage systems. Online. *Renewable and Sustainable Energy Reviews*. 2017, roč. 70, s. 1072-1089. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2016.12.012>. [cit. 2025-04-28].
- [19] YE, R.; HUANG, R.; FANG, X. a ZHANG, Z. Simulative optimization on energy saving performance of phase change panels with different phase transition temperatures. Online. *Sustainable Cities and Society*. 2020, roč. 52. ISSN 22106707. Dostupné z: <https://doi.org/10.1016/j.scs.2019.101833>. [cit. 2025-04-28].
- [20] WANG, C.; CHENG, C.; JIN, T. a DONG, H. Water evaporation inspired biomass-based PCM from daisy stem and paraffin for building temperature regulation. Online. *Renewable Energy*. 2022, roč. 194, s. 211-219. ISSN 09601481. Dostupné z: <https://doi.org/10.1016/j.renene.2022.05.107>. [cit. 2025-04-28].
- [21] NAVEEN-KUMAR, G.; VINAYAKA-RAM, V. a PARAMESHWARAN, R. Thermal and structural properties of cement mortar embedded with hybrid nanocomposite based phase change nanocapsules for building application. Online. *Construction and Building Materials*. 2023, roč. 385. ISSN 09500618. Dostupné z: <https://doi.org/10.1016/j.conbuildmat.2023.131481>. [cit. 2025-04-28].
- [22] XU, M.; WANG, A.; XIANG, Y. a NIU, J. Biomass-based porous carbon/graphene self-assembled composite aerogels for high-rate performance supercapacitor. Online.

- Journal of Cleaner Production*. 2021, roč. 315. ISSN 09596526. Dostupné z: <https://doi.org/10.1016/j.jclepro.2021.128110>. [cit. 2025-05-01].
- [23] CHEN, C.; LIU, W.; WANG, H. a PENG, K. Synthesis and performances of novel solid–solid phase change materials with hexahydroxy compounds for thermal energy storage. Online. *Applied Energy*. 2015, roč. 152, s. 198-206. ISSN 03062619. Dostupné z: <https://doi.org/10.1016/j.apenergy.2014.12.004>. [cit. 2025-04-28].
- [24] MA, Y.; SHEN, J.; LI, T.; SHENG, X. a CHEN, Y. A “net-ball” structure fiber membrane with electro-/photo-thermal heating and phase change synchronous temperature regulation capacity via electrospinning. Online. *Solar Energy Materials and Solar Cells*. 2024, roč. 276. ISSN 09270248. Dostupné z: <https://doi.org/10.1016/j.solmat.2024.113078>. [cit. 2025-04-28].
- [25] LACHHEB, M.; YOUNSI, Z.; YOUSSEF, N. a BOUADILA, S. Enhancing building energy efficiency and thermal performance with PCM-Integrated brick walls: A comprehensive review. Online. *Building and Environment*. 2024, roč. 256. ISSN 03601323. Dostupné z: <https://doi.org/10.1016/j.buildenv.2024.111476>. [cit. 2025-04-28].
- [26] RATHORE, P. K. S. a SHUKLA, S. K. Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review. Online. *Energy and Buildings*. 2021, roč. 236. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2021.110799>. [cit. 2025-04-28].
- [27] MOUSAVI, S. M.; KHANMOHAMMADI, F. a RABIENATAJ-DARZI, A. A. Magnetic influence on phase change materials for optimized thermal energy storage: A comprehensive review and prospective insights. Online. *Journal of Energy Storage*. 2024, roč. 89. ISSN 2352152X. Dostupné z: <https://doi.org/10.1016/j.est.2024.111625>. [cit. 2025-04-28].
- [28] SÁNCHEZ-SILVA, L.; RODRÍGUEZ, J. F.; ROMERO, A.; BORREGUERO, A. M.; CARMONA, M. et al. Microencapsulation of PCMs with a styrene-methyl methacrylate copolymer shell by suspension-like polymerisation. Online. *Chemical Engineering Journal*. 2010, roč. 157, č. 1, s. 216-222. ISSN 13858947. Dostupné z: <https://doi.org/10.1016/j.cej.2009.12.013>. [cit. 2025-04-28].
- [29] ABDEALI, G.; BAHRAMIAN, A. R. a ABDOLLAHI, M. Review on Nanostructure Supporting Material Strategies in Shape-stabilized Phase Change Materials. Online. *Journal of Energy Storage*. 2020, roč. 29. ISSN 2352152X. Dostupné z: <https://doi.org/10.1016/j.est.2020.101299>. [cit. 2025-04-28].
- [30] ARSHAD, A.; JABBAL, M. a YAN, Y. Preparation and characteristics evaluation of mono and hybrid nano-enhanced phase change materials (NePCMs) for thermal management of microelectronics. Online. *Energy Conversion and Management*. 2020, roč. 205. ISSN 01968904. Dostupné z: <https://doi.org/10.1016/j.enconman.2019.112444>. [cit. 2025-04-28].
- [31] BHARATHIRAJA, R.; RAMKUMAR, T.; SELVAKUMAR, M. a RADHIKA, N. Thermal characteristics enhancement of Paraffin Wax Phase Change Material (PCM) for thermal storage applications. Online. *Renewable Energy*. 2024, roč. 222. ISSN 09601481. Dostupné z: <https://doi.org/10.1016/j.renene.2024.119986>. [cit. 2025-04-28].
- [32] THANGARAJ, P. a PARIMELAZHAGAN, T. Extraction of Bioactive Compounds. Online. In: *Pharmacological Assays of Plant-Based Natural Products*. Progress in Drug Research. Cham: Springer International Publishing, 2016, s. 11-13. ISBN 978-

- 3-319-26810-1. Dostupné z: https://doi.org/10.1007/978-3-319-26811-8_3. [cit. 2025-04-28].
- [33] MELGOSA, R.; SANZ, M. a BELTRÁN, S. Supercritical CO₂ processing of omega-3 polyunsaturated fatty acids – Towards a biorefinery for fish waste valorization. Online. *The Journal of Supercritical Fluids*. 2021, roč. 169. ISSN 08968446. Dostupné z: <https://doi.org/10.1016/j.supflu.2020.105121>. [cit. 2025-04-28].
- [34] ZHOU, B.; ZHEN, L.; YANG, Y.; MA, W.; FU, Y. et al. Novel composite phase change material of high heat storage and photothermal conversion ability. Online. *Journal of Energy Storage*. 2022, roč. 49. ISSN 2352152X. Dostupné z: <https://doi.org/10.1016/j.est.2022.104101>. [cit. 2025-04-28].
- [35] HERRERA, P.; DE-LA-HOZ-SIEGLER, H. a CLARKE, M. Fatty Acids as Phase Change Materials for Building Applications: Drawbacks and Future Developments. Online. *Energies*. 2024, roč. 17, č. 19. ISSN 1996-1073. Dostupné z: <https://doi.org/10.3390/en17194880>. [cit. 2025-05-01].
- [36] MOFIJUR, M.; MAHLIA, T.; SILITONGA, A.; ONG, H.; SILAKHORI, M. et al. Phase Change Materials (PCM) for Solar Energy Usages and Storage: An Overview. Online. *Energies*. 2019, roč. 12, č. 16. ISSN 1996-1073. Dostupné z: <https://doi.org/10.3390/en12163167>. [cit. 2025-05-01].
- [37] LIU, M.; SAMAN, W. a BRUNO, F. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. Online. *Renewable and Sustainable Energy Reviews*. 2012, roč. 16, č. 4, s. 2118-2132. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2012.01.020>. [cit. 2025-04-28].
- [38] CHEN, C.; WANG, L. a HUANG, Y. Morphology and thermal properties of electrospun fatty acids/polyethylene terephthalate composite fibers as novel form-stable phase change materials. Online. *Solar Energy Materials and Solar Cells*. 2008, roč. 92, č. 11, s. 1382-1387. ISSN 09270248. Dostupné z: <https://doi.org/10.1016/j.solmat.2008.05.013>. [cit. 2025-04-28].
- [39] OLABI, A. G.; WILBERFORCE, T.; ELSAID, K.; SAYED, E. T.; RAMADAN, M. et al. Recent progress on Carbon-based nanomaterial for phase change materials: Prospects and challenges. Online. *Thermal Science and Engineering Progress*. 2021, roč. 23. ISSN 24519049. Dostupné z: <https://doi.org/10.1016/j.tsep.2021.100920>. [cit. 2025-05-01].
- [40] WU, S.; YAN, T.; KUAI, Z. a PAN, W. Thermal conductivity enhancement on phase change materials for thermal energy storage: A review. Online. *Energy Storage Materials*. 2020, roč. 25, s. 251-295. ISSN 24058297. Dostupné z: <https://doi.org/10.1016/j.ensm.2019.10.010>. [cit. 2025-04-28].
- [41] KE, H. Phase diagrams, eutectic mass ratios and thermal energy storage properties of multiple fatty acid eutectics as novel solid-liquid phase change materials for storage and retrieval of thermal energy. Online. *Applied Thermal Engineering*. 2017, roč. 113, s. 1319-1331. ISSN 13594311. Dostupné z: <https://doi.org/10.1016/j.applthermaleng.2016.11.158>. [cit. 2025-04-28].
- [42] LIU, Z.; CHEN, Z. a YU, F. Enhanced thermal conductivity of microencapsulated phase change materials based on graphene oxide and carbon nanotube hybrid filler. Online. *Solar Energy Materials and Solar Cells*. 2019, roč. 192, s. 72-80. ISSN 09270248. Dostupné z: <https://doi.org/10.1016/j.solmat.2018.12.014>. [cit. 2025-05-01].

- [43] ASLFATTAHI, N.; SAIDUR, R.; ARIFUTZZAMAN, A.; SADRI, R.; BIMBO, N. et al. Experimental investigation of energy storage properties and thermal conductivity of a novel organic phase change material/MXene as A new class of nanocomposites. Online. *Journal of Energy Storage*. 2020, roč. 27. ISSN 2352152X. Dostupné z: <https://doi.org/10.1016/j.est.2019.101115>. [cit. 2025-05-11].
- [44] SRIVASTAV, S. K.; SAHU, M. R.; WATANABE, K.; TANIGUCHI, T.; BANERJEE, S. et al. Universal quantized thermal conductance in graphene. Online. *Science Advances*. 2019, roč. 5, č. 7. ISSN 2375-2548. Dostupné z: <https://doi.org/10.1126/sciadv.aaw5798>. [cit. 2025-05-01].
- [45] SAID, Z.; PANDEY, A. K.; TIWARI, A. K.; KALIDASAN, B.; JAMIL, F. et al. Nano-enhanced phase change materials: Fundamentals and applications. Online. *Progress in Energy and Combustion Science*. 2024, roč. 104. ISSN 03601285. Dostupné z: <https://doi.org/10.1016/j.pecs.2024.101162>. [cit. 2025-05-01].
- [46] SHAHID, U. B. a ABDALA, A. A critical review of phase change material composite performance through Figure-of-Merit analysis: Graphene vs Boron Nitride. Online. *Energy Storage Materials*. 2021, roč. 34, s. 365-387. ISSN 24058297. Dostupné z: <https://doi.org/10.1016/j.ensm.2020.10.004>. [cit. 2025-05-01].
- [47] TARIQ, S. L.; ALI, H. M.; AKRAM, M. A.; JANJUA, M. M. a AHMADLOUYDARAB, M. Nanoparticles enhanced phase change materials (NePCMs)-A recent review. Online. *Applied Thermal Engineering*. 2020, roč. 176. ISSN 13594311. Dostupné z: <https://doi.org/10.1016/j.applthermaleng.2020.115305>. [cit. 2025-05-01].
- [48] MEHRALI, M.; LATIBARI, S. T.; MEHRALI, M.; INDRA-MAHLIA, T. M.; CORNELIS-METSELAAR, H. S. et al. Preparation and characterization of palmitic acid/graphene nanoplatelets composite with remarkable thermal conductivity as a novel shape-stabilized phase change material. Online. *Applied Thermal Engineering*. 2013, roč. 61, č. 2, s. 633-640. ISSN 13594311. Dostupné z: <https://doi.org/10.1016/j.applthermaleng.2013.08.035>. [cit. 2025-05-01].
- [49] HUMMERS, W. S. a OFFEMAN, R. E. Preparation of Graphitic Oxide. Online. *Journal of the American Chemical Society*. 1958, roč. 80, č. 6, s. 1339-1339. ISSN 0002-7863. Dostupné z: <https://doi.org/10.1021/ja01539a017>. [cit. 2025-05-01].
- [50] MARCANO, D. C.; KOSYNKIN, D. V.; BERLIN, J. M.; SINITSKII, A.; SUN, Z. et al. Improved Synthesis of Graphene Oxide. Online. *ACS Nano*. 2010, roč. 4, č. 8, s. 4806-4814. ISSN 1936-0851. Dostupné z: <https://doi.org/10.1021/nn1006368>. [cit. 2025-05-01].
- [51] LIU, T.; ZHANG, R.; ZHANG, X.; LIU, K.; LIU, Y. et al. One-step room-temperature preparation of expanded graphite. Online. *Carbon*. 2017, roč. 119, s. 544-547. ISSN 00086223. Dostupné z: <https://doi.org/10.1016/j.carbon.2017.04.076>. [cit. 2025-05-01].
- [52] IJIMA, S. Helical microtubules of graphitic carbon. Online. *Nature*. 1991, roč. 354, č. 6348, s. 56-58. ISSN 0028-0836. Dostupné z: <https://doi.org/10.1038/354056a0>. [cit. 2025-05-01].
- [53] POP, E.; VARSHNEY, V. a ROY, A. K. Thermal properties of graphene: Fundamentals and applications. Online. *MRS Bulletin*. 2012, roč. 37, č. 12, s. 1273-1281. ISSN 0883-7694. Dostupné z: <https://doi.org/10.1557/mrs.2012.203>. [cit. 2025-05-01].
- [54] HAMMEL, E.; TANG, X.; TRAMPERT, M.; SCHMITT, T.; MAUTHNER, K. et al. Carbon nanofibers for composite applications. Online. *Carbon*. 2004, roč. 42, č. 5-6,

- s. 1153-1158. ISSN 00086223. Dostupné z: <https://doi.org/10.1016/j.carbon.2003.12.043>. [cit. 2025-05-01].
- [55] EITAN, A.; JIANG, K.; DUKES, D.; ANDREWS, R. a SCHADLER, L. S. Surface Modification of Multiwalled Carbon Nanotubes: Toward the Tailoring of the Interface in Polymer Composites. Online. *Chemistry of Materials*. 2003, roč. 15, č. 16, s. 3198-3201. ISSN 0897-4756. Dostupné z: <https://doi.org/10.1021/cm020975d>. [cit. 2025-05-01].
- [56] GENG, D. a YANG, H. Y. Recent Advances in Growth of Novel 2D Materials: Beyond Graphene and Transition Metal Dichalcogenides. Online. *Advanced Materials*. 2018, roč. 30, č. 45. ISSN 0935-9648. Dostupné z: <https://doi.org/10.1002/adma.201800865>. [cit. 2025-05-01].
- [57] PAINE, R. T. a NARULA, C. K. Synthetic routes to boron nitride. Online. *Chemical Reviews*. 1990, roč. 90, č. 1, s. 73-91. ISSN 0009-2665. Dostupné z: <https://doi.org/10.1021/cr00099a004>. [cit. 2025-05-01].
- [58] YIN, J.; LI, J.; HANG, Y.; YU, J.; TAI, G. et al. Boron Nitride Nanostructures: Fabrication, Functionalization and Applications. Online. *Small*. 2016, roč. 12, č. 22, s. 2942-2968. ISSN 1613-6810. Dostupné z: <https://doi.org/10.1002/smll.201600053>. [cit. 2025-05-01].
- [59] XU, B.; LI, P. a CHAN, C. Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: A review to recent developments. Online. *Applied Energy*. 2015, roč. 160, s. 286-307. ISSN 03062619. Dostupné z: <https://doi.org/10.1016/j.apenergy.2015.09.016>. [cit. 2025-04-28].
- [60] BELESSIOTIS, G. V.; PAPADOKOSTAKI, K. G.; FAVVAS, E. P.; EFTHIMIADOU, E. K. a KARELLAS, S. Preparation and investigation of distinct and shape stable paraffin/SiO₂ composite PCM nanospheres. Online. *Energy Conversion and Management*. 2018, roč. 168, s. 382-394. ISSN 01968904. Dostupné z: <https://doi.org/10.1016/j.enconman.2018.04.059>. [cit. 2025-04-28].
- [61] NOMURA, T.; OKINAKA, N. a AKIYAMA, T. Technology of Latent Heat Storage for High Temperature Application: A Review. Online. *ISIJ International*. 2010, roč. 50, č. 9, s. 1229-1239. ISSN 0915-1559. Dostupné z: <https://doi.org/10.2355/isijinternational.50.1229>. [cit. 2025-04-28].
- [62] SALUNKHE, P. B. a SHEMBEKAR, P. S. A review on effect of phase change material encapsulation on the thermal performance of a system. Online. *Renewable and Sustainable Energy Reviews*. 2012, roč. 16, č. 8, s. 5603-5616. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2012.05.037>. [cit. 2025-04-28].
- [63] ALAM, T. E.; DHAU, J. S.; GOSWAMI, D. Y. a STEFANAKOS, E. Macroencapsulation and characterization of phase change materials for latent heat thermal energy storage systems. Online. *Applied Energy*. 2015, roč. 154, s. 92-101. ISSN 03062619. Dostupné z: <https://doi.org/10.1016/j.apenergy.2015.04.086>. [cit. 2025-04-28].
- [64] RAN, F.; CHEN, Y.; CONG, R. a FANG, G. Flow and heat transfer characteristics of microencapsulated phase change slurry in thermal energy systems: A review. Online. *Renewable and Sustainable Energy Reviews*. 2020, roč. 134. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2020.110101>. [cit. 2025-05-01].
- [65] MILIÁN, Y. E.; GUTIÉRREZ, A.; GRÁGEDA, M. a USHAK, S. A review on encapsulation techniques for inorganic phase change materials and the influence on their thermophysical properties. Online. *Renewable and Sustainable Energy Reviews*.

- 2017, roč. 73, s. 983-999. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2017.01.159>. [cit. 2025-04-28].
- [66] AL-SHANNAQ, R.; FARID, M. M. a IKUTEGBE, C. A. Methods for the Synthesis of Phase Change Material Microcapsules with Enhanced Thermophysical Properties—A State-of-the-Art Review. Online. *Micro*. 2022, roč. 2, č. 3, s. 426-474. ISSN 2673-8023. Dostupné z: <https://doi.org/10.3390/micro2030028>. [cit. 2025-05-11].
- [67] TROJANOWSKA, A.; NOGALSKA, A.; VALLS, R. G.; GIAMBERINI, M. a TYLKOWSKI, B. Technological solutions for encapsulation. Online. *Physical Sciences Reviews*. 2017, roč. 2, č. 9. ISSN 2365-659X. Dostupné z: <https://doi.org/10.1515/psr-2017-0020>. [cit. 2025-05-11].
- [68] LI, Z.; ZHOU, M.; WU, F.; SHEN, L.; LIN, X. et al. Direct compaction properties of Zingiberis Rhizoma extracted powders coated with various shell materials: Improvements and mechanism analysis. Online. *International Journal of Pharmaceutics*. 2019, roč. 564, s. 10-21. ISSN 03785173. Dostupné z: <https://doi.org/10.1016/j.ijpharm.2019.04.021>. [cit. 2025-04-28].
- [69] MARTINS, I. M.; BARREIRO, M. F.; COELHO, M. a RODRIGUES, A. E. Microencapsulation of essential oils with biodegradable polymeric carriers for cosmetic applications. Online. *Chemical Engineering Journal*. 2014, roč. 245, s. 191-200. ISSN 13858947. Dostupné z: <https://doi.org/10.1016/j.cej.2014.02.024>. [cit. 2025-05-01].
- [70] HUANG, Y.; STONEHOUSE, A. a ABEYKOON, C. Encapsulation methods for phase change materials – A critical review. Online. *International Journal of Heat and Mass Transfer*. 2023, roč. 200. ISSN 00179310. Dostupné z: <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123458>. [cit. 2025-04-28].
- [71] BORREGUERO, A. M.; VALVERDE, J. L.; RODRÍGUEZ, J. F.; BARBER, A. H.; CUBILLO, J. J. et al. Synthesis and characterization of microcapsules containing Rubitherm®RT27 obtained by spray drying. Online. *Chemical Engineering Journal*. 2011, roč. 166, č. 1, s. 384-390. ISSN 13858947. Dostupné z: <https://doi.org/10.1016/j.cej.2010.10.055>. [cit. 2025-05-11].
- [72] GHOSH, S. K. (ed.). *Functional Coatings*. Online. Weinheim: Wiley, 2006. ISBN 9783527312962. Dostupné z: <https://doi.org/10.1002/3527608478>. [cit. 2025-04-28].
- [73] PONCELET, D. Microencapsulation: fundamentals, methods and applications. Online. In: BLITZ, Jonathan P. a GUN'KO, Vladimir M. (ed.). *Surface Chemistry in Biomedical and Environmental Science*. Springer Netherlands, 2006, s. 23-34. ISBN 978-1-4020-4739-8. Dostupné z: https://doi.org/10.1007/1-4020-4741-X_3. [cit. 2025-04-28].
- [74] TYAGI, V. V.; KAUSHIK, S. C.; TYAGI, S. K. a AKIYAMA, T. Development of phase change materials based microencapsulated technology for buildings: A review. Online. *Renewable and Sustainable Energy Reviews*. 2011, roč. 15, č. 2, s. 1373-1391. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2010.10.006>. [cit. 2025-05-01].
- [75] PENG, G.; DOU, G.; HU, Y.; SUN, Y. a CHEN, Z. Phase Change Material (PCM) Microcapsules for Thermal Energy Storage. Online. *Advances in Polymer Technology*. 2020, roč. 2020, s. 1-20. ISSN 0730-6679. Dostupné z: <https://doi.org/10.1155/2020/9490873>. [cit. 2025-05-11].
- [76] B, S.; SINGH, L.; TYAGI, I.; RAWAT, A. a SINHA, S. Microencapsulation of a eutectic PCM using in situ polymerization technique for thermal energy storage.

- Online. *International Journal of Energy Research*. 2020, roč. 44, č. 5, s. 3854-3864. ISSN 0363-907X. Dostupné z: <https://doi.org/10.1002/er.5182>. [cit. 2025-05-11].
- [77] SALAÜN, F.; BEDEK, G.; DEVAUX, E.; DUPONT, D. a GENGEMBRE, L. Microencapsulation of a cooling agent by interfacial polymerization: Influence of the parameters of encapsulation on poly(urethane-urea) microparticles characteristics. Online. *Journal of Membrane Science*. 2011, roč. 370, č. 1-2, s. 23-33. ISSN 03767388. Dostupné z: <https://doi.org/10.1016/j.memsci.2010.11.033>. [cit. 2025-04-28].
- [78] CAI, C.; OUYANG, X.; ZHOU, L.; LIU, G.; WANG, Y. et al. Co-solvent free interfacial polycondensation and properties of polyurea PCM microcapsules with dodecanol dodecanoate as core material. Online. *Solar Energy*. 2020, roč. 199, s. 721-730. ISSN 0038092X. Dostupné z: <https://doi.org/10.1016/j.solener.2020.02.071>. [cit. 2025-05-11].
- [79] SEFAT, F.; FARZI, G. a MOZAFARI, M. *Principles of Biomaterials Encapsulation: Volume One*. Online. Elsevier, 2023. ISBN 9780323859479. Dostupné z: <https://doi.org/10.1016/C2020-0-01661-0>. [cit. 2025-05-11].
- [80] JAMEKHORSHID, A.; SADRAMELI, S.M. a FARID, M. A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium. Online. *Renewable and Sustainable Energy Reviews*. 2014, roč. 31, s. 531-542. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2013.12.033>. [cit. 2025-04-28].
- [81] SIVANATHAN, A.; DOU, Q.; WANG, Y.; LI, Y.; CORKER, J. et al. Phase change materials for building construction: An overview of nano-/micro-encapsulation. Online. *Nanotechnology Reviews*. 2020, roč. 9, č. 1, s. 896-921. ISSN 2191-9097. Dostupné z: <https://doi.org/10.1515/ntrev-2020-0067>. [cit. 2025-05-01].
- [82] LUO, Y.; WANG, T. T.Y.; TENG, Z.; CHEN, P.; SUN, J. et al. Encapsulation of indole-3-carbinol and 3,3'-diindolylmethane in zein/carboxymethyl chitosan nanoparticles with controlled release property and improved stability. Online. *Food Chemistry*. 2013, roč. 139, č. 1-4, s. 224-230. ISSN 03088146. Dostupné z: <https://doi.org/10.1016/j.foodchem.2013.01.113>. [cit. 2025-04-28].
- [83] OZKAN, Gulay; FRANCO, Paola; DE MARCO, Iolanda; XIAO, Jianbo a CAPANOGLU, Esra. A review of microencapsulation methods for food antioxidants: Principles, advantages, drawbacks and applications. Online. *Food Chemistry*. 2019, roč. 272, s. 494-506. ISSN 03088146. Dostupné z: <https://doi.org/10.1016/j.foodchem.2018.07.205>. [cit. 2025-04-28].
- [84] WU, B; SHI, L; ZHANG, Q a WANG, W. J. Microencapsulation of 1-hexadecanol as a phase change material with reversible thermochromic properties. Online. *RSC Advances*. 2017, roč. 7, č. 67, s. 42129-42137. ISSN 2046-2069. Dostupné z: <https://doi.org/10.1039/C7RA06764J>. [cit. 2025-05-11].
- [85] AHMADZADEH, M. A.; CHINI, S. F. a SADEGHI, A. Size and shape tailored sol-gel synthesis and characterization of lanthanum phosphate (LaPO₄) nanoparticles. Online. *Materials & Design*. 2019, roč. 181. ISSN 02641275. Dostupné z: <https://doi.org/10.1016/j.matdes.2019.108058>. [cit. 2025-04-28].
- [86] HE, F.; WANG, X. a WU, D. New approach for sol-gel synthesis of microencapsulated n-octadecane phase change material with silica wall using sodium silicate precursor. Online. *Energy*. 2014, roč. 67, s. 223-233. ISSN 03605442. Dostupné z: <https://doi.org/10.1016/j.energy.2013.11.088>. [cit. 2025-05-11].

- [87] ARTMANN, N.; JENSEN, R. L.; MANZ, H. a HEISELBERG, P. Experimental investigation of heat transfer during night-time ventilation. Online. *Energy and Buildings*. 2010, roč. 42, č. 3, s. 366-374. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2009.10.003>. [cit. 2025-04-28].
- [88] SOUAYFANE, F.; FARDOUN, F. a BIWOLE, P. H. Phase change materials (PCM) for cooling applications in buildings: A review. Online. *Energy and Buildings*. 2016, roč. 129, s. 396-431. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2016.04.006>. [cit. 2025-04-28].
- [89] RAJ, V. A. A. a VELRAJ, R. Review on free cooling of buildings using phase change materials. Online. *Renewable and Sustainable Energy Reviews*. 2010, roč. 14, č. 9, s. 2819-2829. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2010.07.004>. [cit. 2025-04-28].
- [90] ZALBA, B.; MARÍN, J. M.; CABEZA, L. F. a MEHLING, H. Free-cooling of buildings with phase change materials. Online. *International Journal of Refrigeration*. 2004, roč. 27, č. 8, s. 839-849. ISSN 01407007. Dostupné z: <https://doi.org/10.1016/j.ijrefrig.2004.03.015>. [cit. 2025-04-28].
- [91] KAMALI, S. Review of free cooling system using phase change material for building. Online. *Energy and Buildings*. 2014, roč. 80, s. 131-136. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2014.05.021>. [cit. 2025-05-11].
- [92] HENNING, H. M. Solar assisted air conditioning of buildings – an overview. Online. *Applied Thermal Engineering*. 2007, roč. 27, č. 10, s. 1734-1749. ISSN 13594311. Dostupné z: <https://doi.org/10.1016/j.applthermaleng.2006.07.021>. [cit. 2025-04-28].
- [93] AJBAR, A.; LAMRANI, B. a ALI, E. Dynamic Investigation of a Coupled Parabolic Trough Collector–Phase Change Material Tank for Solar Cooling Process in Arid Climates. Online. *Energies*. 2023, roč. 16, č. 10. ISSN 1996-1073. Dostupné z: <https://doi.org/10.3390/en16104235>. [cit. 2025-05-11].
- [94] FANG, G.; WU, S. a LIU, X. Experimental study on cool storage air-conditioning system with spherical capsules packed bed. Online. *Energy and Buildings*. 2010, roč. 42, č. 7, s. 1056-1062. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2010.01.018>. [cit. 2025-04-28].
- [95] RODRIGUEZ-UBINAS, E.; RUIZ-VALERO, L.; VEGA, S. a NEILA, J. Applications of Phase Change Material in highly energy-efficient houses. Online. *Energy and Buildings*. 2012, roč. 50, s. 49-62. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2012.03.018>. [cit. 2025-04-28].
- [96] ANSUINI, R.; LARGHETTI, R.; GIRETTI, A. a LEMMA, M. Radiant floors integrated with PCM for indoor temperature control. Online. *Energy and Buildings*. 2011, roč. 43, č. 11, s. 3019-3026. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2011.07.018>. [cit. 2025-04-28].
- [97] ZHANG, S. a NIU, J. Cooling performance of nocturnal radiative cooling combined with microencapsulated phase change material (MPCM) slurry storage. Online. *Energy and Buildings*. 2012, roč. 54, s. 122-130. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2012.07.041>. [cit. 2025-05-11].
- [98] KOŠNY, J. *PCM-Enhanced Building Components*. Online. Engineering Materials and Processes. Cham: Springer International Publishing, 2015. ISBN 978-3-319-14285-2. Dostupné z: <https://doi.org/10.1007/978-3-319-14286-9>. [cit. 2025-04-28].

- [99] HEINEKAMP, J. F.; VOS, M.; KRUTZSCH, S.; SICK, F.; STRUNZ, K. et al. Integration of Building Inertia Thermal Energy Storage into Smart Grid Control. Online. In: *2020 International Conference on Smart Energy Systems and Technologies (SEST)*. IEEE, 2020, s. 1-6. ISBN 978-1-7281-4701-7. Dostupné z: <https://doi.org/10.1109/SEST48500.2020.9203238>. [cit. 2025-04-28].
- [100] DIARCE, G.; URRESTI, A.; GARCÍA-ROMERO, A.; DELGADO, A.; ERKOREKA, A. et al. Ventilated active façades with PCM. Online. *Applied Energy*. 2013, roč. 109, s. 530-537. ISSN 03062619. Dostupné z: <https://doi.org/10.1016/j.apenergy.2013.01.032>. [cit. 2025-04-28].
- [101] SAFER, N.; WOLOSZYN, M. a ROUX, J. J. Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin facade equipped with a venetian blind. Online. *Solar Energy*. 2005, roč. 79, č. 2, s. 193-203. ISSN 0038092X. Dostupné z: <https://doi.org/10.1016/j.solener.2004.09.016>. [cit. 2025-04-28].
- [102] DE GRACIA, A.; NAVARRO, L.; CASTELL, A. a CABEZA, L. F. Energy performance of a ventilated double skin facade with PCM under different climates. Online. *Energy and Buildings*. 2015, roč. 91, s. 37-42. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2015.01.011>. [cit. 2025-04-28].
- [103] NAVARRO, L.; GRACIA, A. D.; CASTELL, A. a CABEZA, L. F. Experimental study of an active slab with PCM coupled to a solar air collector for heating purposes. Online. *Energy and Buildings*. 2016, roč. 128, s. 12-21. ISSN 03787788. Dostupné z: <https://doi.org/10.1016/j.enbuild.2016.06.069>. [cit. 2025-05-11].
- [104] TAKEDA, S.; NAGANO, K.; MOCHIDA, T. a SHIMAKURA, K. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. Online. *Solar Energy*. 2004, roč. 77, č. 3, s. 329-338. ISSN 0038092X. Dostupné z: <https://doi.org/10.1016/j.solener.2004.04.014>. [cit. 2025-04-28].
- [105] ZHANG, Yinping; ZHOU, Guobing; LIN, Kunping; ZHANG, Qunli a DI, Hongfa. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Online. *Building and Environment*. 2007, roč. 42, č. 6, s. 2197-2209. ISSN 03601323. Dostupné z: <https://doi.org/10.1016/j.buildenv.2006.07.023>. [cit. 2025-04-28].
- [106] ASADI, E.; DA SILVA, M. G.; ANTUNES, C. H. a DIAS, L. A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. Online. *Building and Environment*. 2012, roč. 56, s. 370-378. ISSN 03601323. Dostupné z: <https://doi.org/10.1016/j.buildenv.2012.04.005>. [cit. 2025-04-28].
- [107] ASCIONE, F.; BIANCO, N.; DE-MASI, R. F.; DE'-ROSSI, F. a VANOLI, G. P. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. Online. *Applied Energy*. 2014, roč. 113, s. 990-1007. ISSN 03062619. Dostupné z: <https://doi.org/10.1016/j.apenergy.2013.08.045>. [cit. 2025-04-28].
- [108] NIE, B.; PALACIOS, A.; ZOU, B.; LIU, J; ZHANG, T et al. Review on phase change materials for cold thermal energy storage applications. Online. *Renewable and Sustainable Energy Reviews*. 2020, roč. 134. ISSN 13640321. Dostupné z: <https://doi.org/10.1016/j.rser.2020.110340>. [cit. 2025-04-28].
- [109] ZHOU, D.; ZHAO, C. Y. a TIAN, Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Online. *Applied Energy*. 2012, roč.

92, s. 593-605. ISSN 03062619. Dostupné z:
<https://doi.org/10.1016/j.apenergy.2011.08.025>. [cit. 2025-04-28].

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LIST OF ABBREVIATIONS

PMMA	Polymethyl methacrylate
DSC	Differential scanning calorimetry
TGA	Thermogravimetric analysis
TES	Thermal energy storage
MMA	Methyl methacrylate
EG	Expanded graphite
PCM	Phase change material
SLPCM	Solid-liquid phase change material
SSPCM	Solid-solid phase change material
LGPCM	Liquid-gas phase change material
PEG	Polyethylene glycol
SHS	Sensible heat storage
LHS	Latent heat storage
SA	Stearic acid
LA	Lauric acid
DA	Decanoic acid
CA	Capric acid
MA	Myristic acid
PA	Palmitic acid
DASC	Direct absorption solar collector
LHSF	Latent heat storage fluid
MEPCM	Microencapsulated phase change material
MF	Melamine formaldehyde
PS	Polystyrene
PU	Polyurethane

NEPCM	Nano-enhanced phase change material
GNP	Graphene nanoplate
CNT	Carbon nanotube
CNF	Carbon nanofiber
GO	Graphene oxide
RGO	Reduced graphene oxide
SWCNT	Single-walled carbon nanotubes
MWCNT	Multi-walled carbon nanotubes
TRG	Thermally reduced graphene
VGCNF	Vapor-grown carbon nanofibers
BN	Boron nitride
CS-PCM	Core-shell phase change material
SS-PCM	Shape-stabilized phase change material
mPCM	Microcapsule phase change material
UF	Urea formaldehyde
HVAC	Heating, ventilation and air conditioning
AC	Air conditioning
COP	Coefficient of performance
VF	Ventilated facade
SEM	Scanning electron microscopy
PVP	Polyvinylpyrrolidone
BPO	Benzoyl peroxide
N ₂	Nitrogen gas
H ₂ O	Distilled water
ΔH_m	Melting enthalpy
T _m	Melting temperature

ΔH_c	Crystallization enthalpy
T_c	Crystallization temperature