Overview of Phase Change Materials in Modern Textiles: An Advance Smart Thermal Solutions

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Abstract: *Phase change materials (PCMs) have become important components in textile materials, offering enhanced comfort, performance, and temperature regulation. These materials operate based on the principle of absorbing and releasing thermal energy during their phase transition from solid to liquid and vice versa. When environmental or body temperatures increase, PCMs absorb heat, converting from a solid to a liquid state while storing this energy as latent heat. Conversely, as temperatures decrease, PCMs release this stored energy, returning to a solid state and providing warmth. This cyclical process contributes to maintaining a stable microclimate close to the skin, enhancing comfort, and reducing the effects of temperature fluctuations. The integration of PCMs in textiles has paved the way for innovations in various functional applications, particularly in activewear, outdoor clothing, medical textiles, and home furnishings. Activewear and sports textiles benefit from PCMs by ensuring wearer comfort during high-intensity activities, where body temperature regulation is critical. In medical textiles, PCMs provide therapeutic benefits, aiding temperature-sensitive individuals. Additionally, home furnishings such as bedding and upholstery now incorporate PCMs to improve sleep quality by providing temperature adaptability through the night. This article is focused on the advancements and developments in PCM technology and its incorporation into textiles to enhance durability, stability, and functionality across different conditions. Techniques like microencapsulation of PCMs within fibers or coatings on fabrics have improved the resilience of PCMs, making them more effective over prolonged use and washing cycles.*

Keywords: Comfort, Temperature regulation, activewear, Microencapsulation, Phase change materials.

1. Introduction

Textiles, whether woven, non-woven, or knitted, serve diverse purposes, including protection, aesthetic appeal, and specialized functionality. Over time, experimentation with various materials has led to substantial advancements in both the functional capabilities and comfort of textiles. These innovations have yielded a range of specialized properties, such as antimicrobial finishes, fire retardant coatings, and water-repellent treatments, significantly enhancing textiles' utility across various industries. Similarly, the use of phase-change materials (PCMs) in textiles marks another significant innovation. In recent years, thermoregulating textiles have emerged as a leading type of smart textile, specifically engineered to adapt to environmental stimuli and fluctuations. These advanced fabrics respond intelligently to changes in temperature and humidity, helping to maintain optimal comfort for the wearer. By dynamically adjusting to external conditions, thermoregulating textiles go beyond traditional materials to offer enhanced functionality, making them highly suitable for a wide range of applications, from everyday clothing to specialized outdoor and athletic wear [1]. Phase change materials are widely used in the textile industry. In the 1900s, PCM was discovered but, its application started in the 1970s. A large variety of PCMs with a wide range of melting temperatures are used in different storage systems for thermal applications [2,3].

PCMs when incorporated into textile material, can regulate the thermal behaviors between the textile and the human body and provide comfort to the wearer. Along with cooling, it can also be used for thermal insulation in the human body. Phase change materials (PCM) are known to store a large amount of thermal energy which can be used later [4,5]. In a certain temperature range, these materials change phase from solid to liquid absorb thermal energy in the process and release energy when changing back to solid phase. PCM has been used in textile materials for thermoregulation via coating or encapsulation methods [6,7]. For any material, there are two systems of thermal energy storage. Firstly, a sensible heat storage system where the material in the solid phase is heated with a rise in temperature of the material and stores thermal energy. Secondly, a latent heat storage system where the material is heated and when the melting temperature is reached it changes from solid phase to liquid while absorbing a large amount of thermal energy with the temperature being nearly constant. When the material's crystallization temperature is reached it changes back to a solid phase by releasing the absorbed thermal energy. Phase change materials (PCMs) are broadly categorized into three types: organic, inorganic, and eutectic. Inorganic PCMs, while useful, often encounter issues during melting, where they form anhydrous salts that precipitate, causing phase separation and supercooling. This phase instability can compromise their reliability and thermal consistency in applications requiring precise temperature control. To address these limitations, organic PCMs are widely favoured for their superior physical and chemical stability. Unlike inorganic options, organic PCMs maintain a stable phase change behaviour without separation or supercooling, making them highly effective for repeated thermal cycling and ensuring consistent, reliable thermal managementPhase change materials are extensively used in textiles for temperature regulation for both hot and cold environments by incorporation into fibres, fabrics, or foam [8,9].

2. Types of PCMs

2.1 Organic PCM

These are natural or carbon-based materials, there are several classes of phase change materials paraffin waxes are the most common PCM because they have a higher heat of fusion per unit weight good thermal stability, and a large melting point, they can continue functioning after multiple cycles of melting with suitable melting temperature and freezing and are non-corrosive which make them safe for use and chemically inert. *Paraffins* exhibit extremely high latent heat storage capacities, i.e., between 200 and 250 kJ kg^{-1}, and thermal stability up to 250 °C [10].

Table 1: Paraffinic hydrocarbons, showing the relation between carbon atom number and melting temperature [10]

Hydrocarbons	No of Carbon atoms	Latent heat(J/g)	Melting Temperature° (C)
n-hexadecane	16	235.2	18
n-heptadecane	17	176.4	21.1-22.2
n-octadecane	18	244.8	28-30
n-nonadecane	19	177.6	32
n-eicosane	20	242	36-38

As shown in Table 1, Eicosane and *n*-octadecane have close phase transition temperature with human skin temperature. When designing the paraffin PCM void management is important due to the volume change from solid to liquid paraffin PCMs also have low thermal conductivity so designing a sufficient conduction path is another key design consideration.

Fatty acids are the type of organic compound that falls under the category of carboxylic acids. They consist of a carboxyl group (- COOH) at one end and a long aliphatic (non-aromatic) carbon chain. The length of the carbon chain can vary, typically ranging between 4 and 28 carbon atoms. These chains can be either saturated or unsaturated. Because of the carboxyl group, fatty acid base PCM are chemical, heat, and colour stable and non-toxic. The raw materials are derived from renewable vegetable and animal sources. They can withstand thousands of freezing and melting cycles without thermal degradation. Commonly used as Phase Change Materials (PCMs) are typically those that have melting points within the range needed for thermal energy storage applications Ex- capric acid, lauric acid, palmitic acid. Some of the fatty acids used in PCMs include [11]

Table 2: Commonly used Phase Change Materials (PCMs) and relative melting points.

Phase Change Materials (PCMs)	Melting point:	Common Uses
Capric acid (C10):	~31.6°C	commonly used due to its low melting point and good thermal stability.
Lauric acid (C12):	~43.2°C	Known for its relatively high latent heat of fusion, making it effective for energy storage.
Myristic acid (C14):	~54.4°C	Its moderate melting point makes it suitable for certain thermal energy storage applications.
Palmitic acid (C16):	~63°C	Widely used in PCMs due to its high latent heat and thermal reliability.
Stearic acid (C18)	~69.6°C	Often used for higher temperature thermal storage applications, with good thermal conductivity and stability.

Fatty acids like these are preferred as PCMs because they undergo phase transitions (solid-to-liquid or vice versa) at temperatures suitable for building temperature regulation or other energy-saving applications. They also exhibit high latent heat capacity, which allows them to store and release large amounts of energy efficiently.

Polyethylene glycols (PEGs) are a type of polymer commonly used in various applications, including Phase Change Materials (PCMs). These are polymers made of repeating units of oxyethylene groups ($–O–CH_2–CH_2–$). The number of repeating units can vary, resulting in PEGs of different molecular weights, which in turn affects their physical properties such as melting point and solubility. The structure of PEG is a straight or linear chain of repeating oxyethylene units. Each unit consists of an oxygen atom (O) bonded to two carbon atoms ($CH_2–CH_2$). These chains can be long or short, depending on the molecular weight of the PEG. PEG molecules have hydroxyl groups (–OH) at both ends of the chain. These functional groups make PEGs hydrophilic (water-attracting) and allow PEGs to interact with water and other substances, which can be useful for different chemical reactions or applications. The molecular weight of the PEG will determine its melting and freezing points, making it tunable for specific applications. these PCMs have higher latent heat of fusion per unit weight and can absorb and release a large amount of heat and volume have a relatively high thermal conductivity for non-metals and show small volume changes between solid and liquid phases they are less commonly used since they are corrosive and long-term reliability is uncertain, unstable over a repeated thermal cycle. They are used in environments where more precise and powerful temperature control is needed, such as industrial processes or high-temperature areas. These have an economical price in the market concerning paraffin wax. PEG-1000, a type of polyethene glycol with a specific molecular weight of 1000, states that it undergoes a phase transition at 35°C. such as in building insulation or temperature regulation systems.

Other PCM materials such as metallics, and nonparaffin organics phase change materials are available but tend to be used less for these applications.

3.2. Inorganic PCMs

Composed of salts, salt hydrates, metals, and alloys, often in the form of hydrated salts having an “n” number of water molecules can be used in the development of thermo-regulating textiles that exhibit phase transition temperatures ranging from 20 to 40 °C [10].

This range is ideal for thermo-regulating textiles because it is close to typical human comfort temperatures. It means these textiles can absorb excess body heat when the temperature goes above 20°C and release that heat when it falls below 40°C. Such as sodium sulphate decahydrate ($Na_2SO4 \cdot 10H_2O$) or calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$), are commonly used because they have well-defined melting and freezing points, making them suitable for thermal regulation. The water molecules help in storing and releasing energy during phase changes.

High thermal conductivity and high volumetric storage capacity, are important for efficient energy storage and transfer in PCMs. High thermal conductivity ensures that the heat absorbed or released during the phase transition is distributed rapidly and evenly throughout the material. This makes the PCM more effective in temperature regulation and has an economical price in the market with respect to paraffin wax. (Volumetric storage capacity refers to the amount of energy a material can store per unit of volume. A high volumetric storage capacity means the material can store a large amount of thermal energy in a relatively small space).

Table 3: Inorganic phase change materials.

PC Materials	Chemical Formula	Melting Point	Latent Heat	Applications
Sodium Sulphate Decahydrate (Glauber's Salt)	$Na_2SO_4 \cdot 10H_2O$	32.4°C (90.3°F)	254 kJ/kg	Building materials, and climate-controlled packaging.
Calcium Chloride Hexahydrate	$CaCl_2 \cdot 6H_2O$	Around 29°C (84.2°F)	190-230 kJ/kg	Solar heating systems, underfloor heating, and as a coolant in refrigeration systems.
Sodium Carbonate Decahydrate	$Na_2CO_3 \cdot 10H_2O$	Around 32°C (89.6°F)	254 kJ/kg	Building materials for passive temperature control.
Magnesium Nitrate Hexahydrate	$Mg(NO_3)_2 \cdot 6H_2O$	89°C (192°F)	142 kJ/kg	Solar power plants.
Sodium Acetate Trihydrate	$CH_3COONa \cdot 3H_2O$	58°C (136.4°F)	264 kJ/kg	Heat packs, thermal energy storage, and applications requiring rapid heat release.

Potassium Fluoride Tetrahydrate	$KF \cdot 4H_2O$	18°C (64.4°F)	231 kJ/kg	Mainly used in low-temperature thermal energy storage applications.
Lithium Nitrate Trihydrate	$LiNO_3 \cdot 3H_2O$	Around 30°C (86°F)	296 kJ/kg	Used in low-temperature energy storage systems and in solar thermal applications.

4. Eutectic PCM

Eutectic Phase Change Materials (EPCMs) are mixtures of two or more substances that melt and solidify at a temperature lower than their individual components, making them highly efficient for thermal energy storage and temperature regulation. Unlike single-component PCMs, which face challenges such as unsuitable phase change temperatures, phase segregation, and thermal decomposition, EPCMs offer precise phase transition temperatures. For example, a eutectic mixture of lauric acid and stearic acid (4:1) has a phase change temperature of 39°C, ideal for applications like near-infrared triggered drug release. Additionally, EPCMs like $Na_2CO_3 \cdot 10H_2O$-$Na_2HPO_4 \cdot 12H_2O$ (40:60) create stable solutions, avoiding common issues with single-component materials. While some solutions for single-component PCM issues exist (e.g., thickening agents or microencapsulation), they often reduce thermal storage capacity, making EPCMs a more efficient alternative for precise temperature control and energy storage [11].

Eutectic PCMs are known for their sharp, well-defined melting points, making them ideal for applications requiring precise temperature control. They can absorb and release significant amounts of latent heat during phase changes, making them particularly effective for maintaining stable temperatures over extended periods [11]. Eutectic PCMs are used in temperature control systems, such as cooling for electronics, medical equipment, and pharmaceutical storage. They play a key role in maintaining required temperatures during the transportation of temperature-sensitive products like vaccines and food also incorporated into construction materials to regulate indoor temperatures and improve energy efficiency. By incorporating eutectic PCMs, industries can achieve more efficient thermal management, reduce energy consumption, and maintain precise temperature control in critical processes.

Methods of Incorporating Phase Change Materials (PCMs) into fibres is a technique to enhance textiles' thermal regulation properties [10].

4.1 Composite Spinning (Direct Mixing of PCM with Polymers)

In this method, PCMs are directly mixed with polymers, such as wet-spun or melt-spun fibres. The PCM is dispersed within the polymer matrix during the spinning process. This leads to fibres that have PCM integrated uniformly throughout, allowing for efficient thermal regulation. The fibres can absorb and release heat as the PCM transitions between solid and liquid states.

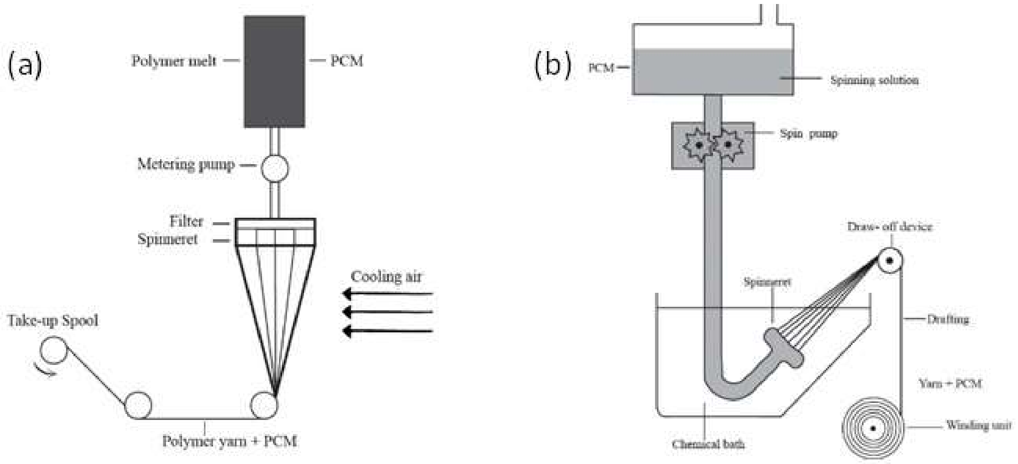

Figure 1: (a) Melt spinning, (b) wet spinning [12,13].

4.2 Hollow Fiber (Core-PCM Structure)

Hollow fibres are designed with a core-shell structure, where the core contains the PCM and the outer layer is made of fibre material. This encapsulation technique protects the PCM while allowing it to perform its phase change function. The outer fibre layer maintains the structural integrity, while the PCM inside absorbs and releases heat, providing thermal regulation without affecting the fabric's mechanical properties.

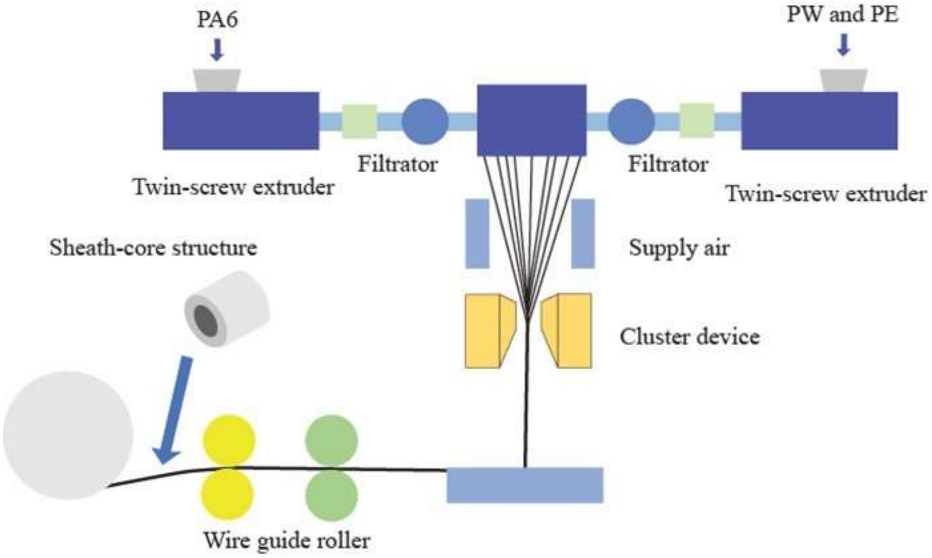

Figure 2: Hollow fibre core method of PCM incorporation in fibre [14].

4.3 Encapsulated PCM (Incorporation into Fibers):

In this method, microencapsulated PCMs (small particles of PCM coated with a protective shell) are blended into fibres during the wet or melt-spinning process. These microcapsules are embedded within the fibre or filament, providing thermal management properties. The encapsulation prevents PCM leakage during phase transitions and ensures durability.

4.4 Pad-Dry-Cure/Coating (MPCM on Fabric Surface):

Microencapsulated PCMs (MPCMs) are applied to fabrics using coating methods like dip coating, transfer coating, knife over the roller, or knife over air. A binder, typically polyurethane, is used to fix the MPCM to the fabric. After coating, the fabric is dried and cured to secure the PCM onto its surface. This method is efficient for applying PCM to already woven or knitted fabrics, enhancing their thermal performance.

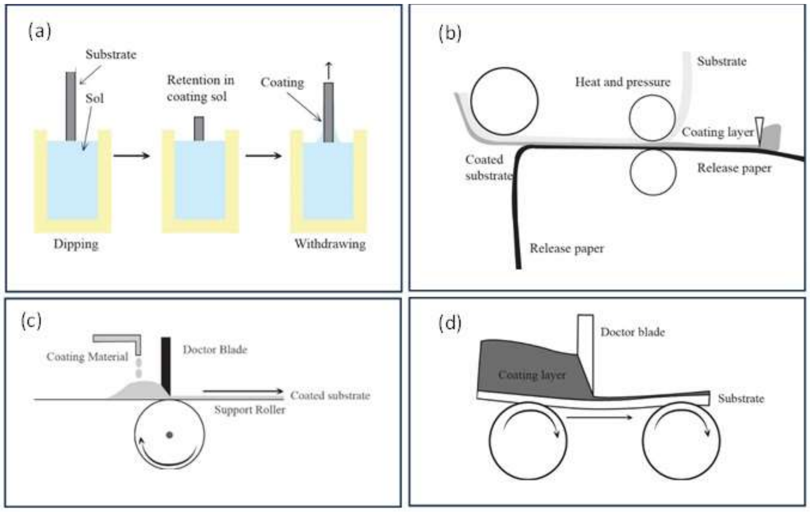

Figure 3: Coating of MPCM on fabric surface (a) dip coating, (b) transfer coating, (c) knife over roller method, (d) knife over air method [15,16].

4.5 Lamination of MPCM (Film Between Two Fabrics)

In this method, a polymer film containing PCM is sandwiched between two fabric layers. This laminated structure provides a barrier, preventing PCM leakage while allowing the fabric to benefit from the thermal energy storage and release properties of the PCM. It is often used in high-performance fabrics where thermal regulation is crucial, such as in outdoor gear or protective clothing. Each method offers unique benefits and applications depending on the desired outcome, such as thermal regulation, durability, or specific fabric characteristics.

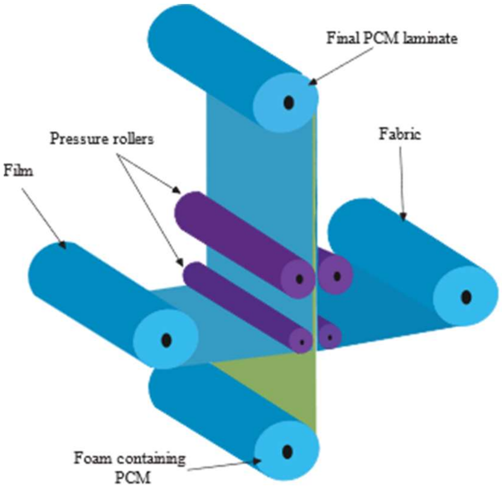

Figure 4: Lamination of MPCM on fabric [17]

4.6 Microencapsulation

Microcapsules are microparticles with a core-shell structure containing the active agent (PCM), which absorbs or releases heat during phase transition. The outer polymer shell acts as a protective barrier, controlling the release of the PCM, enhancing its stability, and preventing leakage during the phase change process. The thickness of the polymer layer can vary, which affects the thermal performance, durability, and mechanical properties of the microcapsules. The shell materials for microencapsulating PCMs serve to protect and encapsulate the core material, ensuring stable phase change behaviour and enhancing durability.

Table 4: Organic Shell Materials and its properties

PC Materials	Properties
Polyurea	Offer excellent mechanical and thermal stability.
Poly (Methyl Methacrylate) (PMMA)	Provides high transparency and weather resistance.
Melamine Formaldehyde (MF) Resins	Widely used for their good thermal and chemical resistance.
Polystyrene	Lightweight and provides a good barrier to gases and liquids
Urea-Formaldehyde Resins	Low-cost and commonly used for encapsulation, but with formaldehyde concerns.
Bio-Based Polymers	More eco-friendly options, including.
Arabic Gum	A natural resin with biocompatibility and biodegradability.
Agar	Derived from seaweed, used for its gel-forming ability.
Gelatin	A biodegradable and renewable material that is used in biopolymer capsules.

Table 5: Inorganic Shell Materials and its properties

PC Materials	Properties
Titanium Dioxide (TiO_2)	Provides UV protection and is chemically inert.
Silica (SiO_2)	Offers excellent thermal stability and is often used for high-temperature applications.
Calcium Carbonate	Inexpensive and improves the structural properties of the capsules.
Aluminium Oxide	Known for its high thermal conductivity and mechanical strength.

Each of these shell materials provides specific properties based on the application, from enhancing thermal conductivity to improving mechanical strength and biodegradability. The choice of the shell depends on the end-use, environmental considerations, and performance requirements.

4.7 Nanoencapsulation

Nanoencapsulation is a method of reducing particle size to the nanometre scale (around 100 nm in diameter), nanoencapsulation enhances surface properties such as thermal stability, durability, and better distribution of PCMs in the host materials, like cotton fabrics. Example of NPCM (Nano-encapsulated PCM) applied to cotton fabric: 20% NPCM loading provides a latent heat storage capacity of 15.2 J/g. 40% NPCM loading increases this capacity to 19.1 J/g.

This demonstrates how increasing the concentration of NPCM improves the fabric's ability to store and release heat. Higher PCM content enhances the thermal regulation properties of the fabric, making it more effective in applications like thermal comfort textiles and energy-saving building materials. The use of nanoencapsulation allows for uniform integration of PCMs into fabrics without compromising the fabric's mechanical properties or breathability, while still maintaining efficient thermal performance.

5. Development of Fibres with PCM

Extensive research has been conducted by various scientists to incorporate microencapsulated phase change materials (MPCMs) into synthetic fibres using different methods. In 1988, Bryant and colleagues successfully embedded eicosane-based PCM capsules into acrylic and viscose rayon fibres through a dry/wet spinning process and subsequently patented their work. These filament yarns exhibited thermo-regulating properties when exposed to heat and cold. Outlast® Technologies later successfully commercialized viscose rayon and acrylic fibres infused with leak-resistant PCM capsules [10], as shown in Figures 6 and 7, respectively.

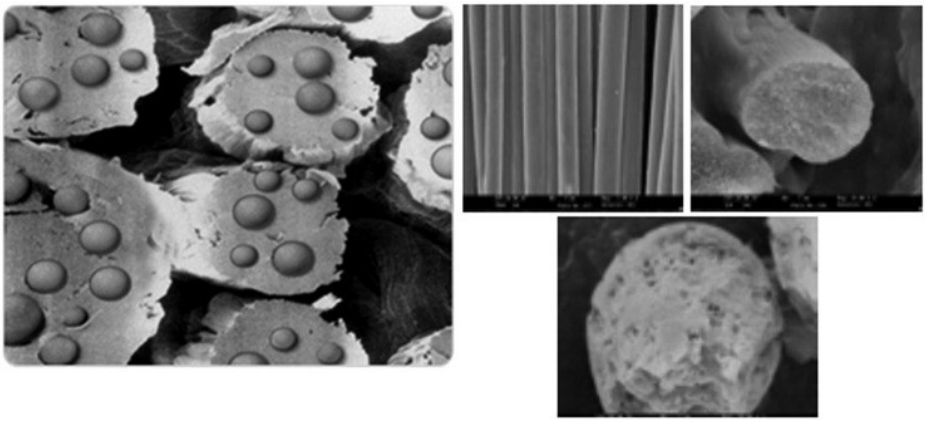

Figure 5: Outlast® Technologies developed viscose fibres with integrated (MPCM).

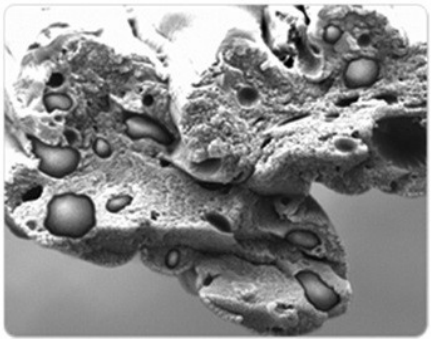

Figure 6: Outlast® Technologies developed acrylic fibres with integrated (MPCM).

In 2006, Zhang, Wang, Tao, and Yick developed a polyacrylonitrile-vinylidene chloride fibre with flame-retardant properties using a wet spinning method. They incorporated organic n-octadecane as the phase change material (PCM) and used a urea melamine formaldehyde (MF) copolymer for encapsulation. Their study examined the amount of MPCM integrated into the fibre, ranging from 0% to 40% by weight. For practical spinning, up to 30% MPCM was used. The experiment, conducted in a nitrogen atmosphere, showed that fibres with 30% MPCM had a crystallization enthalpy of 30 J/g, while those with 40% MPCM had 44 J/g. Scanning Electron Microscopy (SEM) analysis revealed that MPCM-incorporated fibres had increased density, more cross-sectional holes, and rougher surfaces compared to fibres without MPCM.

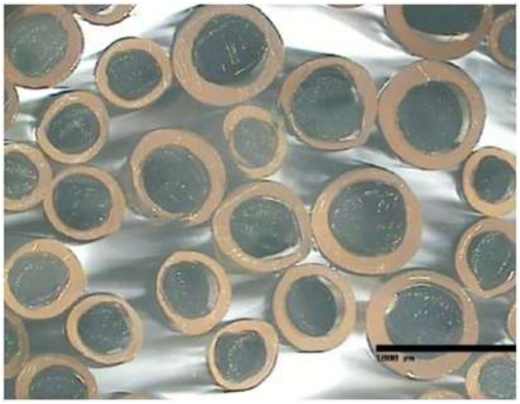

Figure 7: SEM images of polyacrylonitrile-vinylidene chloride fibres

In 2010, Swedish scientist Hagstrom developed polyamide 6 (PA6) and polyester (PET) fibres using a melt spinning technique, incorporating n-octadecane as the active core material. He found that to optimize the development of bi-component fibres, the viscosity of the phase change material (PCM) needed to be adjusted by blending it with high-density polyethene (HDPE). This blending process modified the PCM's viscosity to closely match that of the sheath material. To achieve high latent heat and appropriate viscosity, 70% of the PCM was mixed with HDPE by weight. Hagstrom's research highlighted two main challenges in the manufacturing of melt-spun yarns with microencapsulated PCM (MPCM). The first challenge was the poor stability of the capsules during the melt-spinning process, and the second was the need for capsules with a small molecular size [10].

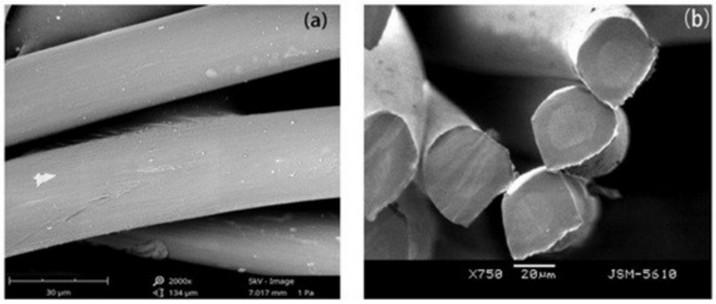

Figure 8: Surface and cross-sectional morphology of the phase change thermoregulated fiber preparation (PCTF) (a) surface view (b) cross-sectional view.

6. Applications of PCM in textile

6.1 Protective clothing of Mine rescuers

Underground mining faces numerous hazards, including rock bursts and fires, and in the near future, coal mining processes may be conducted in temperatures exceeding 50°C. Therefore, it is crucial to protect miners and rescue personnel from these extreme conditions. To provide thermal protection and support thermoregulation, specialized undergarments and protective clothing have been developed to prevent overheating. Phase Change Materials (PCMs) with a melting temperature between 32–37°C were chosen for use in both the undergarments and outer protective clothing. PCM pouches, designed with 4-6 channels [Fig. 10(a)], have been integrated into the undergarments, which are made from a knitted fabric comprising 90% Lenzing FR, 8% p-aramid, and 2% antistatic fibre. These pouches are placed in areas of the body prone to high heat exposure [Fig. 10(b)]. To offer even greater protection, an additional outer layer of clothing has been developed [Fig. 10(c)] [18].

Figure 9: Mine Rescuer's Protective clothing incorporated with PCM (a) PCM pouches, (b) Placement of PCM in the undergarment, (c) Protective clothing.

6.2 Sportswear

Sportswear is essential for individuals engaged in strenuous physical activities. These garments play a crucial role in enhancing performance, making comfort a priority during sports like running, mountain climbing, and cycling. To maintain confidence during such activities, sportswear must offer breathability and effectively manage heavy sweat production. To address these challenges, the brand ASRV collaborated with Outlast Technology, incorporating phase change material (Outlast®) into its collection [Fig. 11(a), (b), (c)]. Outlast PCM absorbs excess heat when generated and releases it as temperatures drop, maintaining a balanced microclimate during intense, dynamic activities. This technology has been shown to reduce sweat production by 48%. Additionally, ASRV textiles use Matrix Infusion Coating (MIC) [Fig. 11(d)], which applies multiple wafer-thin layers of micro-encapsulated phase change materials, further enhancing performance and comfort[19].

Figure 10: Phase change materials in sportswear maintaining microclimate (a) Outlast® incorporated headband by ASRV, (b) Outlast® incorporated full-sleeve by ASRV, [(c), (d)] textile coated with Outlast® utilizing MIC method.

6.3 Subgrade construction

The subgrade is the foundational layer in road construction, railways, pavements, and similar infrastructure projects. It lies at the deepest level and is constructed using soil and rock materials, providing essential support to the structures above. Despite its critical role, the subgrade is vulnerable to deformation caused by factors such as heavy loads and thaw settlement. Thaw settlement is a major concern, especially in permafrost regions, where the permanently frozen soil beneath the subgrade can shift as it thaws. Approximately 50% of the world's landmass lies in the Arctic region, with 25% of this area consisting of permafrost. In these permafrost regions, thaw settlement occurs due to high temperatures, global warming, melting the ice in the soil and releasing excess water. This causes a change in the volume and formation of the surface above, therefore destabilizing the structures [20,21,22]. The degradation of these structures can be mitigated by controlling temperature, specifically by reducing heat transfer through the subgrade to lower permafrost temperatures. To address this issue, phase change geotextiles (PCG) have been developed, combining the thermoregulation of phase change materials (PCMs) with the anti-water seepage properties of traditional geotextiles. By incorporating PCG into the subgrade, a phase change energy storage subgrade is created. The PCMs help regulate temperature peaks, reducing temperature increases in the subgrade and preventing thaw consolidation [23, 24].

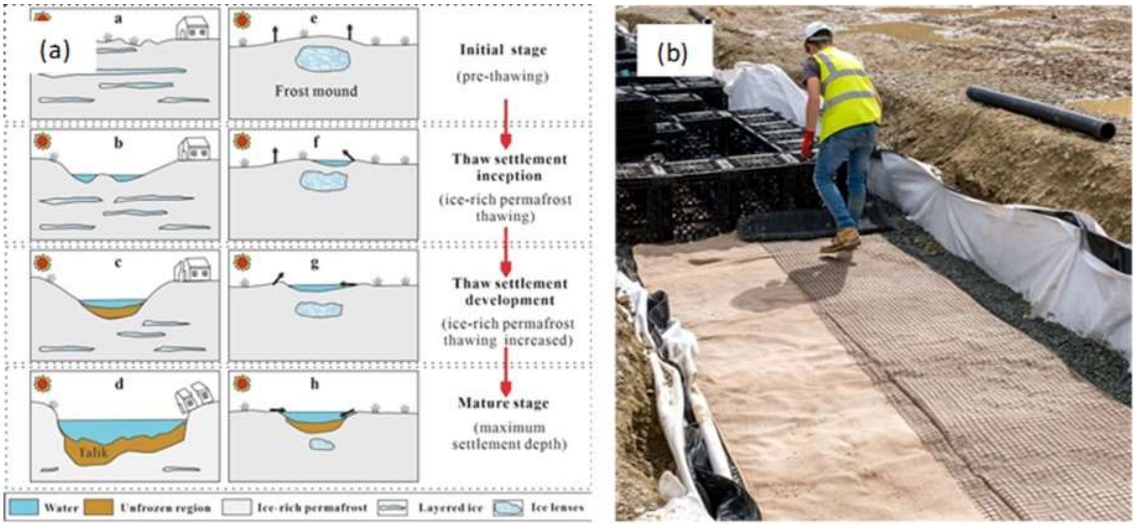

Figure 11: (a) Process of thaw consolidation of permafrost region, (b) application of phase change geotextiles in the subgrade.

6.4 Automobiles

Experimental testing in Fremont, California, revealed that the temperature inside a closed vehicle rises by 22-27°C within an hour. During the study, a commercial phase change material (PCM), RT-27 from Rubitherm, was used. The PCM was applied to the vehicle's cabin, with placements under the roof and within the steering wheel. By placing the PCM beneath the roof, the goal was to maximize the heat exchange area between the cabin air and the PCM, enhancing thermal regulation [25]. To support the PCM plates under the roof, an aluminium structure was built, which allowed for easy replacement of the PCM plates. The total amount of PCM used in the cabin was 4 kg (4.55 litres), accounting for 0.22% of the cabin's internal volume. Since the PCM was in bulk form, aluminium plates were used for encapsulation in the cabin, while for the steering wheel, a plastic bag was used to shape and contain the PCM. The impact of the PCM was evident, as lower temperatures were recorded when it was implemented. The roof, head, and back areas, which are closest to the PCM, experienced the greatest reduction in temperature. In the reference system without PCM, these areas reached 56°C, 46°C, and

46°C, respectively. With PCM in place, the temperatures dropped to 52°C, 44°C, and 42°C, indicating a decrease of 2-4°C. Even in areas further from the PCM, such as the floor and footwell, a temperature reduction of 2°C was observed [26].

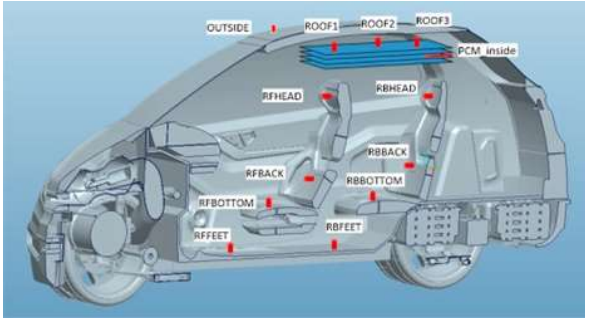

Figure 12: Location of the air temperature sensors located on the right side of the vehicle [25].

6.5 MiraCradle® Neonate Cooler

The MiraCradle® - Neonate Cooler is a cost-effective, passive cooling solution designed for newborns suffering from Hypoxic Ischemic Encephalopathy (HIE) due to birth asphyxia. It employs advanced savE® phase change material (PCM) technology to induce therapeutic hypothermia. Developed by Pluss® in partnership with Christian Medical College (CMC) Vellore in Tamil Nadu, the device ensures precise temperature regulation between 33-34°C for up to 72 hours. It requires minimal manual intervention and operates without the need for continuous electricity, making it highly practical in various healthcare settings. Three savE® FS29 modules are positioned at the base of the cradle, effectively absorbing heat from the newborn's body. This process helps achieve and maintain the desired therapeutic temperature for up to 72 hours. Quickly brings the temperature of the newborn down to 33.5°C. Once the target temperature is achieved savE® FS-21 is removed [25].

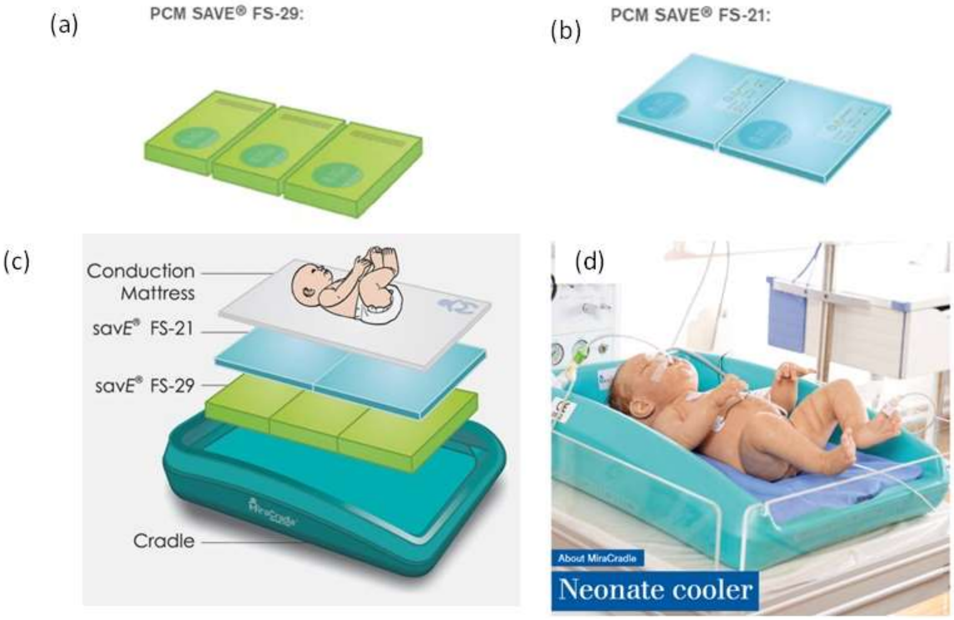

Figure 13: Mira Cradle for newborn babies suffering from (HIE) (a) PCM savE® 29, (b) savE® FS-21, (c) position of PCM in the cradle, (d) MiraCradle® Neonate Cooler [25].

Conclusion

The application of phase change materials (PCMs) in textiles has expanded across various sectors, enhancing performance through innovative temperature-regulating capabilities. Originally developed for astronaut suits to protect against extreme temperature fluctuations in space, PCMs have since been commercialized for widespread use. Today, they are utilized in protective clothing, activewear, and bedding products like mattresses, where they significantly improve comfort and functionality by maintaining an ideal microclimate. Their use in medical field has shown to improve efficiency and comfort, aligning with the needs of an aging population and modern healthcare demands. As the demand for smart, responsive textiles continues to grow, PCMs represent a vital avenue for meeting both consumer and industry expectations. With ongoing advancements, PCM-incorporated textiles are set to play an increasingly significant role in providing thermal regulation, user comfort, and environmental benefits, positioning them as a key innovation in the smart textiles industry.

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