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Review

An Overview of Phase Change Materials and Their Applications in Pavement

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Abstract: The composite of a phase change material (PCM) and bitumen or asphalt as a matrix is expected as a new, advanced material for road construction. The main motivation for this article was to show the new possibilities and perspectives of developing the pavement with the usage of PCMs. Incorporating PCMs into paving materials can improve their properties, including allowing the regulation of the pavement temperature, enhancement of the pavement durability, and avoiding the phenomenon of a heat-island on the road. The main purpose of this article was to evaluate contemporary investigations in the area of the application of PCMs in pavement materials, especially asphalt and bitumen; to summarize the advantages and disadvantages of the implementation of PCM for road construction; and to discuss further trends in this area. This manuscript explored the state of the art in this area based on research in the literature. It shows the possible material solutions, presenting their composition and discussing their key properties and the manufacturing technologies used. The possibilities for further implementations are considered, especially economic issues.

Keywords: PCM; phase change material; asphalt; bitumen; road construction; pavement; concrete

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Citation: Korniejenko, K.; Nykiel, M.; Choinska, M.; Jexembayeva, A.; Konkanov, M.; Aruova, L. An Overview of Phase Change Materials and Their Applications in Pavement. *Energies* **2024**, *17*, 2292. https://doi.org/10.3390/en17102292

Academic Editors: Umberto Berardi, Antonio Caggiano and Facundo Bre

Received: 12 March 2024
Revised: 1 May 2024
Accepted: 8 May 2024
Published: 10 May 2024

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1. Introduction

A phase change material (PCM) can be defined as a substance that has the possibility to store thermal energy by absorbing or releasing a large amount of latent heat in the process of changing physical state, especially between a liquid and a solid [1,2]. These materials react to environmental changes and their properties are modified depending on the external conditions by absorbing, storing, or releasing heat without changing their temperature [3]. The first time this kind of material was discovered and successfully applied was in the 1970s [2,4]. The early applications were connected with different kinds of building materials to improve their thermal efficiency through thermal energy storage [4–6]. Since then, these materials have also found many other applications, including in cooling systems, heat transfer, and thermal protection devices [7,8]. They also find an application in foamed materials to enhance their thermal properties [9,10]. Nowadays, they also find applications in thermoplastic materials, such as asphalt [3,11,12].

The wide range of applications for these materials is possible thanks to the many advantages that PCMs have compared to traditional materials [7,13]. The most important seems to be the simplicity of application and high reliability of this technology [7]. This led to there being some commercial applications for PCMs today, including in the building, electronic, and logistics industries [13]. In other applications, such as pavements, this technology is still being developed. This group of materials is attractive because of its high energy storage density and low power use at the same time [7]. Nowadays, when the price of energy is rising, it is an additional reason to develop PCMs. It is also worth stressing that during the phase transition process, they have a nearly isothermal temperature, which gives them high energy efficiency [7]. Due to their numerous advantages, PCMs are applied in many areas, including developing energy efficiency in free cooling defrosting, thermal management, and air-conditioning [7,13,14].

One of the promising areas of application for PCMs is pavements. The basic reason for applying PCMs in this area is temperature regulation [15]. These materials can be used for the reduction of consequences of low temperature (anti-ice and snow melting) as well as high temperature (helps in avoiding heat islands). Beyond these most obvious uses, these materials are also used for the improvement of functional properties, including the reduction of oxidative aging, rutting reduction, and the minimalization of creep [16]. However, while the benefits of implementing this kind of solution are significant, implementing a PCM into asphalt and bitumen mixtures as well as concrete for pavement applications is a challenging task [15]. The main challenges in this area are connected with the material properties' deterioration as a consequence of the implementation of PCMs, including lowering the mechanical properties, increasing the cracking tendency, and others connected with chemical changes [17].

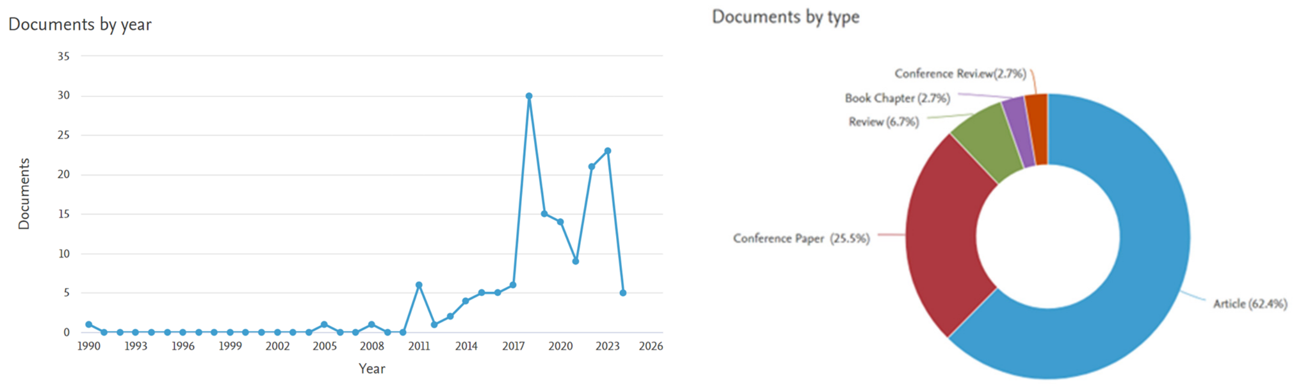
The challenges and limitations in applying PCMs in practice are connected to the temperature of the working and manufacturing technology. PCMs usually work within a temperature range between −50 °C and 150 °C and only part of them is suitable for high-temperature applications [18,19]. This is applicable in high temperatures, usually based on metals and salts, and their applications are connected with a relatively high-cost comparison with this one based on polymer materials. Therefore, it is a challenge to develop a new, low-cost PCM dedicated to higher temperatures [20]. Another challenge is connected with the application of PCMs in the manufacturing process. The usage of bulk PCMs usually negatively influences matrix material properties. Because of that, PCM applications very often require the usage of the technology of encapsulation and closed PCMs in the form of macro- or microcapsules or the infiltration of different types of aggregates by PCMs [21]. It is usually connected with additional technological operations and increasing the cost of the composition. This problem also appears in the pavement applications.

The main goal of this article was to evaluate the current research in the area of the application of PCMs into pavement materials, especially asphalt and bitumen, to summarize the advantages and disadvantages of the implementation of PCM for road construction, and to discuss further trends in this area. This manuscript is based on the latest research in the literature, especially over the last 5 years. This article shows the overall knowledge in the area of PCM. It discusses the possibility of using compounds as a PCM and their applications. Next, it presents possible material solutions, presenting compositions for pavement applications in detail, including their key properties and the manufacturing technologies used. The possibilities for further implementations are considered, especially economic issues. Eventually, the challenges for further research are analyzed.

2. Methods

The Scopus (ScienceDirect) database was used as a main tool for the preparation of a systematic review. Also, some supportive tools have been used, especially Google Scholar, Wiley Online Library, ACS Publications, and IEEE Xplore Digital Library. In the first stage, overall search in the databases was conducted using the combination of two keywords: "pavement" and "PCM". The 149 results were found in Scopus in this topic (Figure 1).

Single publications on the analyzed topic were published in 1990, 2005, and 2008. However, only since 2011 have articles been regularly published that explore topics related to the use of PCM in road applications (Figure 1a). The number of publications is changeable year by year, but it is worth noting that the topic started to be popular after 2017. Thus, this conception is very new.



(**a**) (**b**)

Figure 1. The results of searching in the Scopus database: (**a**) numbers of publications per year; (**b**) the information about the publications by type [22].

Most of the scientific works were focused on research articles (approximately 62%) or conference papers (approximately 25%). In this area there was only a few review articles; this type of structure of the publication types is also typical for a new topic, where there is a lack of articles that can summarize the new achievement in the area. Taking this fact into consideration, this review article will be a precious supplementation to the state of the art in the application area of PCMs for pavement materials.

3. Phase Change Materials

PCMs can be divided into three main groups: organic, inorganic, and eutectic (Figure 2).

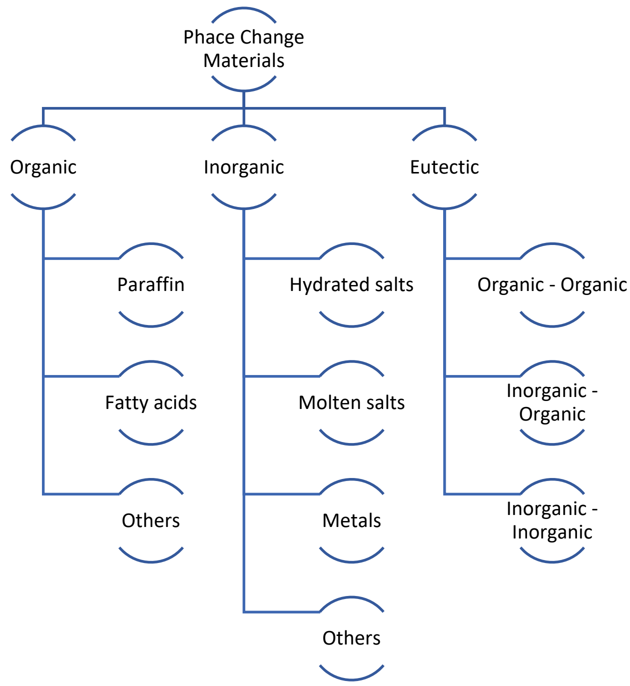


Figure 2. PCM classification according to the type of material.

3.1. Organic

Organic PCMs can be divided into paraffin, fatty acids, and others [15]. The main advantage of this group is that they do not cause corrosion problems [18]. They are usually chemically and physically stable and available for a wide range of temperatures [15]. The potential problem that touches this group is flammability [15].

Paraffin is the most widely used PCM from this group. It finds a lot of applications, especially as a component of building materials with improved thermal properties [23,24]. In the case of application in building materials, including pavements, paraffin is very often encapsulated in other organic polymers, such as a polymer shell made of polymethyl methacrylate [25]. In the case of paraffin materials, the melting point is usually between 1 and 6 °C; however, in the case of some materials it can be much higher, for example, for n-Eicosane it is 36.5 °C [15]. This range of temperature is favorable for application in construction where the temperature phase transition is near 0 °C as it is, for example, in Kazakhstan or Poland. The latent heat for this group is usually approximately 200 kJ/kg and the heat conductivity is between 0.15 and 0.45 W/mK [15]. An alternative method for the effective application of paraffin in pavements is the incorporation of it in lightweight porous aggregate [26,27].

Another wide group of organic PCMs is fatty acids. These compounds are characterized by a long aliphatic chain capped by a carboxyl group. They can have a straight or branched structure and be saturated or unsaturated [15]. The exemplary substances that are used as PCM are lauric acid, myristic acid, palmitic acid, and stearic acid [28].

Other popular organic PCMs are different kinds of polymers, especially polyethylene glycol (PEG). This substance has a lot of advantages: among others, it can be easily tunable to phase change temperatures, is characterized by a lack of toxicity, and has high melting/freezing enthalpies [29]. It is worth stressing that PEG as PCM is mostly used in asphalt mixtures [30]. Nevertheless, it has also some disadvantages, including low thermal conductivity [29].

Also, another organic PCM has been tested for pavement solutions, including eicosane, tetradecane and organic mixes [28,31]. Organic PCMs, such as PEG and tetradecane, are often applied to regulate the high and low temperatures of asphalt pavement [15].

3.2. Inorganic

The next group is inorganic PCMs. They can be divided into hydrated salts, molten salts, metals, and others. This group is characterized by high heat fusion, high thermal conductivity, and low volume changes [15]. For example, fatty salts have a more diverse melting point from 0.5 °C for RTM up to 64 °C for palmitic acid [15]. The latent heat is also in the wider range of 46–196.9 kJ/kg [15]. Another advantage is the lack of flammability. They are also relatively easily available [15]. The main problem is their sensitivity to corrosion problems [18]. Among this group, the most popular are salt hydrates and metals [32].

This group of materials was investigated for thermal energy storage applications [33]. In the area of building applications, some of them, such as hydrated salt, were also tested as a part of the composition for roof applications [1,34]. In the case of pavement applications, this group of PCMs is rarely used, although an investigation was conducted by adding NiTi alloy to asphalt mixtures [35].

3.3. Eutectic

The popular classification of this group is based on the organic and inorganic character of the compounds. It can be divided into organic–organic, inorganic–organic, and inorganic–inorganic [15]. This group is a combination of two or more components with different chemical and physical characteristics [36].

The group of eutectic PCMs is characterized by sharp melting points, and high volumetric thermal storage. The main advantage of eutectic PCM is the possibility of the customization of the desired melting temperature [36]. Compared to the two previous groups the properties of these materials are not fully investigated and still require research [15].

The eutectic PCM is also a subject for applications in the building industry. Haily et al. [37] tried to apply a eutectic mixture of lauric acid and capric acid into geopolymer materials to improve the energy efficiency of buildings [37]. They obtained satisfactory results and assessed the material possible to apply for sustainable and energy-efficient buildings. Another study was conducted by Baskar et al. [38] with the addition of lauric and palmitic as PCMs to the paints. The results showed the efficiency of the created paints for thermal regulation, especially in reducing the surface temperature of the concrete that was covered by it [38]. In the last few years, eutectic PCMs also started to be investigated as a potential additive to pavement applications [16,36].

3.4. Current Application of PCM

Nowadays, PCM materials find a wide area of applications (Figure 3). They are used in different kinds of industries for many applications; among the most popular are as follows [15,39]:

- Thermal energy storage, primarily in solar thermal applications [15,39];
- Cooling and heating applications, especially in the building industry and logistics [15,39];
- Heat dissipation of electric circuits in electronic applications and transportation areas [15,39];
- Energy-absorbing clothes (textile industry) [15,39];
- Temperature regulation in pharmaceutical and food preservation [15,39];
- Others, including energy management [15,39].

Figure 3. PCMs—main applications.

Among others, an important application is in the area of energy management, in which a PCM was also investigated as an element of Li-ion battery thermal management system to improve energy efficiency [40]. Another application in this area is a reduction of heating loads for rooms with air-conditioners [18]. It is also worth mentioning modern applications for these materials such as thermo-responsive dielectric switching/pulsing materials and temperature-sensitive electrical switching materials [41,42]. This kind of solution has potential in applications of next-generation smart electronic/electrical technology, including temperature sensors, smart switches, phase shifters, and varactors [41,42].

Among the mentioned applications, it is worth paying attention to the building industry. Li et al. [7] also explored some applications in the building industry, including the usage of PCMs for roofs, ceilings, and walls in residential houses. They showed that thanks to the application of PCM it is possible to reduce heating demand, enhance thermal comfort, and better utilize solar energy through effective storage [7]. The investigation in this area supports the development of PCMs in pavement applications [43].

4. Pavement Application of Phase Change Materials

4.1. Main Area of Investigations

There are many criteria for selection for PCMs for pavement applications. Different authors have different preferences and criteria that decide about the selection of particular substances [44–46]. The two main criteria seem to be latent heat and thermal conductivity [15]. However, in the literature there are a lot of other factors that should be taken into consideration [15]. The key properties of PCMs are connected with the following [39]:

- Thermal properties: latent heat of fusion, thermal conductivity, specific heat capacity, and phase change temperature.
- Chemical properties: corrosive, toxicity, flammability, chemical stability.
- Physical properties: volume changes, density, durability against multiple freeze and thaw cycles.
- Kinetic: nucleation rate, speed of crystal growth, and supercooling.
- Economic factors: availability and price.

Moreover, the selection of a PCM will also be dependent on the matrix material and the purpose of the pavement modification and technology of the implementation of the PCM into the material [47,48]. In Table 1, the most important research in the area of the application of PCMs in pavements is summarized based on selected literature.

Table 1. Application of PCMs in pavements.

No	Type of Application	Matrix	PCM	Main Findings	Reference
1	Snow removal system with solar thermal energy collector	Lack of typical matrix. Liquid was delivered to concrete material by the system of pipes.	Organic: n-octadecanol (agglomerated in cylindrical can made of aluminum)	PCM was used for storing thermal energy from solar collectors; it was possible to store 58 MJ. Thanks to the discharge of solar energy, the temperature of pavement rose by 30 °C. The test confirmed the possibility of effective snow removal: the pavement temperature was above 2 °C during a snowfall.	[47]
2	Reduction of the pavement surface temperature to avoid the thermal stress in high temperatures	Concrete	Organic (OM35 and OM42) encapsulated.	The most important for effective cooling are the latent heat and phase change temperature of PCM. In the night, the pavement surface temperature rose by approximately half of the reduction in temperature during the daytime. It was caused by the slower solidification rate of the PCMs.	[49]
3	Road temperature regulation	SBS-modified asphalt	HDPE, expanded graphite, and paraffin (directly mixed)	PCM addition influenced reduction consistency and temperature sensitivity. It also enhanced low-temperature performance. The deformation resistance of modified material decreased but the fatigue performance increased. The asphalt had good rutting resistance and elastic recovery ability at 64 °C.	[50]

Table 1. *Cont.*

No	Type of Application	Matrix	PCM	Main Findings	Reference
4	Capacity to store thermal energy; slow down the cooling rate; improve of the thermomechanical characteristics	Bitumen	D-Mannitol (high-speed shearing with bitumen)	The melting point of the modified material was without significant changes. PCM improved the physical characteristics of the basic material. The specific heat capacity rose gradually with the PCM content.	[51]
5	Improving rheological and thermal properties	Gilsonite-modified asphalt binder	PEG (directly mixed)	PCM balances the impacts of gilsonite. The binder PCM and gilsonite have good rutting resistance and are possible for application in low temperatures (cracking resistance).	[52]
6	Temperature control (high-temperature reduction)	Cement	(1) paraffin wax (2) myristic acid (encapsulated)	Composites had low crushing ratios during rut-forming tests. PCMs were thermally and chemically stable (minimal mass loss at 180 °C, lack of PCM leakage).	[53]
7	Cooling asphalt pavement	Asphalt	Eutectic mixture of fatty acid (palmitic acid and stearic acid), incorporated in coarse steel slags aggregate	The composition had sufficient cooling performance and durability. Additions of PCM increased the high-temperature rutting resistance of pavement by 30.7%.	[28]
8	Temperature regulation and ice-melting effects	Asphalt	PEG 800, a phase change energy storage material and polyacrylamide backbone structure (directly mixed)	Investigated composites were in line with the specification requirements. The addition of PCM enhanced mechanical properties and moisture resistance. PCM positively influenced thermal insulation performance and heat storage efficiency. PCM reduced the long-term high-temperature performance and low-temperature strength.	[54]
9	Temperature regulation; reducing the urban heat island effect	High-viscosity modified asphalt (HVMA)	(1) Paraffin/expanded graphite/high-density polyethylene composite (2) polyethylene glycol (PEG) (mixed, not explained in detail)	PCMs were uniformly distributed in HVMA. PCMs did not affect the softening points of asphalt. Composites had excellent high-temperature rutting resistance regardless of PCM addition. The effect of the regulation of temperature was visible for both PCMs.	[55]
10	Temperature regulation	Asphalt	PCM based on polyurethane (included in fine aggregate)	The viscoelastic properties of composites were related to the curing temperature, loading frequency, PCMs content, and particle sizes.	[56]

Table 1. *Cont.*

No	Type of Application	Matrix	PCM	Main Findings	Reference
11	Cooling pavement	Concrete	Organic (OM42), incorporated in expanded clay aggregate	PCM effectively decreased pavement surface temperature (2.24 °C was the annual average).	[57]
12	Cooling pavement	Concrete	Organic (OM35 and OM42), encapsulation	The cooling potential of pavements PCM improved by more than 80%. The thermal conductivity of the material increased.	[58]
13	Preventing the low-temperature impact on pavements	Asphalt	PCM based on polyurethane (directly mixed)	PCM slightly affected the high- and low-temperature performance. PCM improved the anti-aging properties. The energy storage properties of composition were found to be satisfactory.	[59]
14	Road temperature regulation	Hot-mix asphalt	Paraffin (microencapsulation)	PCM could withstand asphalt mixing and placement conditions. PCM reduced the dynamic modulus.	[60]
15	Increasing the functionality of pavements made from waste materials	OPC + waste materials (bricks)	PEG 400 Tetradecane (incorporated in recycled aggregate)	The study proved the possibility of using the waste materials as a matrix for PCMs for pavement applications.	[61]
16	Cooling pavement	Asphalt	Paraffin (mixed, not explained in detail)	PCM decreased the frequency of pavement high-temperature rutting damage. With the amount of PCM the cooling effect increased.	[62]
17	Preventing the temperature impact	Asphalt	Eutectic (solid-solid), directly mixed	PCM increased the physical properties of asphalt. PCM increased the high-temperature rutting resistance. PCM improved the low-temperature creep behavior.	[16]
18	Cooling pavement	Asphalt	Eutectic (stearic acid/palmitic acid), directly mixed	PCM application improved the rutting resistance. The structure of PCM inside the composite was stable and had a layered form. The distinguished temperature regulating property was clearly visible (more than 11 °C difference). The temperature peak was delayed 40 min.	[63]
19	Thermal stress reduction	Asphalt	Melamine–formaldehyde resin with graphene (microencapsulation)	PCM increased thermal conductivity and volume-specific heat capacity. The investigation confirmed reducing the temperature variation-induced cracking.	[64]

Table 1. *Cont.*

No	Type of Application	Matrix	PCM	Main Findings	Reference
20	Temperature regulation; avoiding urban heat island	Concrete	Organic (OM35 and OM42) incorporation in expanded clay aggregates	PCM stored latent heat at different temperatures. The material is stable up to 196.6 °C. PCM reduced the maximum pavement surface temperature by approximately 2 °C.	[65]
21	Temperature regulation	Asphalt	PEG 800, a phase change energy storage material and polyacrylamide backbone structure (directly mixed)	PCM enhanced the moisture and low-temperature cracking resistance PCM increased the thermal conductivity. PCM improved the heat preservation capacity.	[66]
22	Temperature regulation	Asphalt	PEG 800, a phase change energy storage material and polyacrylamide backbone structure (directly mixed)	PCM improved the Marshall stability and flexural–tensile strain as well as other parameters such as moisture resistance, low-temperature crack resistance, and thermal insulation properties. PCM reduced the mechanical strength and long-term high-temperature stability performance.	[67]
23	Cooling pavement	Asphalt	Eutectic (stearic acid/palmitic acid)-directly mixed	Between PCM and asphalt, no chemical reaction was detected. PCM has to be applied at higher temperatures than traditional PCM, especially organic.	[68]
24	Improvement of thermomechanical characteristics; mitigation of thermal curling.	Concrete	Paraffin incorporated in porous lightweight aggregate	The element made from composite containing PCM had lower linear strain because of the lower coefficient of thermal expansion.	[69]
25	Regulating temperature and resisting UV aging	Bitumen	PEG–PCM ZnMgAl-mixed metal oxides support (directly mixed)	ZnMgAl mixed-metal oxides as a carrier can include up to 65% of PEG. This mix has good thermal and chemical stability, sufficient phase change enthalpy, and excellent UV absorption properties.	[70]
26	Low-temperature behavior, avoiding cracking	Bitumen	Tetradecane (directly mixed)	PCM raised penetration and lowered the conventional characteristics of bitumen such as softening temperature. Direct addition of PCM also significantly influenced the rheological properties of bitumen; because of that, encapsulation is recommended.	[3]

Table 1. *Cont.*

No	Type of Application	Matrix	PCM	Main Findings	Reference
27	Temperature regulation	Asphalt	NiTi alloy (directly mixed; replacement for fine aggregate)	PCM was used as a replacement for aggregate (partially). PCM slightly reduced the water stability. PCM significantly reduced the heating rate.	[35]
28	Temperature regulation	Asphalt	Tetradecane (microencapsulation)	Different PCMs can have different thermoregulation ranges. PCM significantly improved its thermal behavior.	[71]
29	Improvement of thermophysical parameters	Asphalt	Pentadecane (microencapsulation)	The composition had good thermal stability, thermal storage performance, and mechanical properties	[72]
30	Aging	Asphalt	Tetradecane (microencapsulation)	PCM reduced temperature influence during seasonal and diurnal cycles. PCM gives only benefits in encapsulated form. The melting enthalpy decreases upon aging. PCM increased rheological properties.	[73]
31	Temperature regulation	Bitumen	Tetradecane (microencapsulation)	PCM did not affect rheological properties; it effectively regulated temperature variations.	[74]
32	Cooling pavement	Asphalt	PEG (directly mixed)	PCM complicated effect on the rheological properties. PCM harms the shear strength.	[75]
33	Temperature regulation, avoiding thermal distresses	Asphalt	PEG (microencapsulation)	Confirmation of thermal storage capacity. PCM positively influences rheological properties.	[76]
34	Freeze–thaw performance	Asphalt	Paraffin (pure and microencapsulated)	PCM helps in controlling freeze–thaw impact on subgrade soil	[77]
35	Freeze–thaw performance	Concrete	Paraffin (pure and microencapsulated)	PCM decreased the magnitude of the temperature drop. PCM deteriorated the mechanical properties.	[78]
36	Mechanical and thermal performance	Pavement (not specified)	Paraffin (macro encapsulation)	Anti-ice properties. PCM increased thermal stability and heat storage capacity.	[79]
37	Anti-freezing, temperature regulation bridge decks	Concrete	Composite organic polyol (seamless steel pipe layer with PCM)	Good effect on melting ice and snow.	[80]

The experiments in the last few years were connected with various matrices of asphalt as well as concrete. They also involve other kinds of PCMs—organic, inorganic, and eutectic. Also, different techniques of implementation were used such as encapsulation, infiltration of aggregates by PCMs, joining with backbone structure, and direct implementation. All the provided research shows a high potential of PCMs for delaying peak temperatures and accumulating heat (regulating the temperature). Depending on the application, the applied PCMs' distinguished temperature regulating was between a few and a dozen degrees Celsius. The experimental works outside the laboratory also confirmed the effectiveness of regulation between day and night. The regulation of temperature influence also affects the durability and long-term properties of the investigated materials, especially by increasing the rutting resistance. The influence of the additives on other mechanical and physical properties was not always the same and was dependent on the used material and technology. Selected research also shows that the application of PCMs has the potential for defrosting pavements, thereby increasing the safety for traffic. It is worth noticing that the effectiveness of the material, especially the latent heat effect, can influence external factors such as the solar radiation and airflow conditions [81–83].

4.2. Technologies of Manufacturing Pavement Composite

There are three main technologies used for incorporating PCM materials into pavement: immersion, impregnation, and encapsulation (macro- and microencapsulation) [32]. The other methods, such as the distribution of a PCM through a pipe system, are used quite rarely [47,80,84]. The direct addition of a PCM has a negative impact on the mechanical strength of concrete because this additive hinders the cement hydration and has a negative impact on aggregate bonding. It also affects the physical and rheological characteristics of bitumen [32,49]. Because of that, in most technologies the material is applied in the form of an encapsulated material or through impregnation into a lightweight material which is next encapsulated in the cementitious material [49]. In this case, it is also important to properly select the encapsulation medium. It has to be resistant to the stresses generated due to traffic loads. Destruction of the incorporated capsules under the influence of mechanical loads will cause PCM leakage and a loss of the material's properties [49,85].

Nowadays, the most common technology for manufacturing this kind of composite is filling the pores in the material with PCM liquid. In the first step, the matrix material is produced and the water is incorporated into the material pores. A porous matrix for filling is commonly used, such as expanded shale, clay, perlite, diatomite, and others [32,85,86]. Previous research shows that the selection of the carrier material is important for the effectiveness of the whole system [87]. In the next step, the material is drying and the usual parameters are a temperature above 100 °C and a time of approximately 24 h [49]. After this time the material is immersed in PCM liquid. To be effective, the PCM is usually heated above the melting point and the time of exposition is approximately 24 h [49]. This step caused the PCM to infiltrate the material pores. The capsules prepared this way are covered by cementitious material and the composite is eventually encapsulated [49,88].

The technologies of incorporation and encapsulation for PCMs in pavement applications are still being developed to increase the efficiency of the system and avoid potential negative influences on the matrix material [89]. The authors stressed the benefits connected with these technologies, such as preventing leakage, improving heat transfer by raising specific surface area, and protecting the PCM from the external environment [21]. Among the technologies of encapsulation, the microencapsulation of PCMs plays a special role. In the case of pavement applications, it allows for the avoidance of a huge agglomeration of the phase of the PCM in one place, which reduces the negative impact on mechanical properties.

It is also worth mentioning a new perspective for the application of PCM materials, such as fiber-based PCMs by solution spinning [90]. This method was developed over several years and involves a joint fiber reinforcement with PCMs. This kind of combination in pavement materials, besides the enhancing properties typical of a PCM application, can simultaneously improve the flexural strength and reduce brittle behavior. However, this kind of solution has not been tested in pavement applications yet.

4.3. Key Advantages

There are several reasons for incorporating PCMs in pavement materials. The most important is preventing rapid changes in the temperature by properly regulating them. Proper temperature regulation helps to improve the pavement durability, and mitigate the cracks in the material and minimize the heat island effect [32]. The unwanted phenomena in the pavement material, such as cracking and rutting, are very often connected with temperature-related distress [15]. These are caused by high solar radiation and thermal convection between the pavement surface and the air [91]. The application of a PCM helps to avoid this process by lowering the thermal conductivity of the composition and increasing heat capacity [92].

The advantages of applying this technology have also been reflected in socio-economical indicators. Avoiding the urban heat island (UHI) effect has also influenced the minimization of air pollution and greenhouse gas emissions [93,94]. The usage of PCMs helps in lowering peak energy demand and decreasing air conditioning costs [93,94].

Additionally, Sharifi et al. [95] proved the positive influence of PCMs on the reduction of fatigue-fracture damage. The implementation of a PCM reduces the stresses that have a periodic nature. This mixture reduces the cyclic flexural curling stresses that lead to the cracking of the concrete slab and are connected with a changeable temperature [95]. They modified Paris' Law and adopted it to calculate the cumulative fatigue-fracture damage of the PCM-rich concrete slab under the cyclic thermally induced curling stresses. The results showed higher resistance to the surface modified by PCM in terms of fatigue-fracture performance [95].

4.4. Main Challenges

The main challenges with the wider application of PCMs in pavements are connected with the technology of implementing it into the pavement matrix [36]. Most of the problems are connected with potential PCM leakage and the influence of the physical and rheological properties of the concrete or asphalt binder [96,97]. The effects of PCM leakage have been categorized into two categories [17,39]: the reaction with the matrix and the influence on the process of material preparation, for example, cement hydration or lubricant effect in the matrix material. Also, the PCM content could cause other problems with the material's strength, especially the soft inclusion effect, which increases the material porosity and shell material reactions [17,39]. To avoid these problems, new research needs to be conducted.

Other important points connected with PCM applications are related to the proper PCM selection, not only to ensure proper efficiency but also to avoid potential problems. A lot of PCMs are sensitive to temperature, and because of that to avoid overheating the material the proper heat transfer should be designed [94,98]. It is only one among a number of design questions such as the proper selection of the copolymerization method, problems with in situ polymerization, and the appropriate preparation of mineral-supported effective absorption into the carrier [30,99]. Last, but not least, is the problem with the high cost of investment. This kind of technology requires a high initial cost and complex construction procedures, and the effects are visible only after a longer period of time [94].

5. Further Perspectives

Today, the usage of PCM in the road industry can seem to be not economically justified, because the road industry is focused on cost minimization. However, taking into consideration wider perspectives, including the cost of maintenance and the reduction in the number of potential accidents in the long term, this investment can be beneficial [43].

The further perspective of the development of PCMs in pavements is connected with thermal conductivity investigations, increasing the efficiency of the heat transfer speed as well as the energy consumption [32]. Technological developments will also play an important role, and these may include better methods of avoiding PCM leakage in encapsulation, the improvement of pavement fatigue, and the effective limitation of the

UHI effect [32]. New methods for PCM application can also play an important role in further applications, for example, polymer fiber-based PCM by solution spinning [90].

The further perspectives seem to be especially promising for nano-PCM additives [100]. Using nanoparticles and nanofibers as shells is still a very new topic in the area of application PCMs in pavement [39]. Some early-stage research suggests that binders containing nanoparticles of PCM show lower mass during mixing and compaction [49]. This topic is additionally supported by the previous research connected with the application of microencapsulated PCM that reported a wide range of applications, not only in the building industry, but also in other branches [21].

Also, incorporating other materials, for example, mixing in carbon fibers for the further improvement of material properties, seems to be a promising topic [101]. In this area, the possibility of using waste materials or by-products to support this process has to be mentioned. They can be used especially as carriers for PCM. Some previous trials have been performed in this area, including mixing PCMs with used bricks [61] or steel slag [102], as well as their usage as a carrier for industrial by-products such as fly ash [103].

Other environmental aspects worth mentioning are recyclability issues and life-cycle assessments for this kind of composition [104]. There is a lack of work in this area in the literature. The information in the area of the social and environmental effects is focused mainly on the UHI effect [30].

Another interesting area of research work is using PCM materials as an element of the system of harvesting energy from pavements. Tahami et al. [105] tested a heat storage system using renewable energy from solar radiation generated by thermal gradients and heat flow in the pavement layers [105]. This research confirmed the possibility of harvesting heat energy from roadway pavements with the usage of PCMs [94,105]. The development of this technology is one of the interesting points for the usage of this material for an efficient supplementation of green energy [106,107].

It is also worth noticing the development of modeling methods connected with PCM applications [108,109]. In many cases the traditional methods are not sufficient for providing a full insight into the topic and the development of more advanced models is required, including 3D simulation for the particular compositions and more detailed physical modeling [110,111]. Another challenge for simulations is taking into account real conditions, including data from existing roads [112–114].

6. Conclusions

The application of PCMs in pavement materials is a new trend and a promising area for research. The provided research shows the application of PCMs in pavement as a dynamically developed area with a lot of possibilities for innovative investigations. The development of this technology to application on a full scale requires interdisciplinary knowledge from the areas of numerical modeling, technology material science, civil engineering, and environmental engineering.

The analysis of further perspectives allows us to formulate the most important areas for the nearest period:

- Improvement numerical modeling for complex problems;
- Development of modern PCM materials with wider possibilities;
- Development carriers, also with usage waste materials;
- Improvement of the technology of encapsulation and impregnation;
- Implementation of complex methods for environmental assessment.

Author Contributions: Conceptualization, K.K. and M.C.; methodology, M.N.; validation, A.J., M.K. and L.A.; formal analysis, M.C.; investigation, K.K. and M.N.; resources, L.A.; data curation, K.K.; writing—original draft preparation, K.K. and M.N.; writing—review and editing, M.C., A.J. and M.K.; supervision, L.A.; project administration, A.J. and M.K; funding acquisition, L.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant number BR18574214).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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