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Critical factors for the selection of phase change materials for asphalt mixtures: A systematic review

David Salvo-Ulloa [a], Irune Indacoechea-Vega [a], Felipe Ossio [b], Daniel Castro-Fresno [a,*]

[a] GITECO Research Group, Universidad de Cantabria, Av. Los Castros s/n, 39005, Santander, Spain

[b] School of Civil Construction, Faculty of Engineering, Pontificia Universidad Católica de Chile, Casilla 306, Correo 22, Santiago, 8331150, Chile

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ABSTRACT

Phase change materials (PCMs) have emerged as a solution to control the in-service temperature of asphalt pavement, minimizing pavement distress and mitigating the effects of the Urban Heat Island (U.H.I.). This review article provides a comprehensive analysis of the critical factors for selecting, incorporating and evaluating a PCM for asphalt mixtures. It explores the types of existing PCMs (organic, inorganic and eutectic) and the methodologies of incorporation into the asphalt mixture according to the PCM format (direct incorporation, carrier materials or encapsulation) and the moment in which it is combined in the asphalt mixture (wet or dry process). It also emphasizes the importance of performing thermal and mechanical tests to verify the properties of the PCM and the impact on the asphalt mixture, together with the conditions under which the PCM is exposed during manufacture, compaction and commissioning of asphalt mixture for a correct selection of the PCM. The results of this review reflect that the most investigated PCM for an asphalt mixture is polyethylene glycol (PEG) and the format of use of PEG has been two carrier materials, SiO2 and Polyacrylamide, while the most used combination in asphalt mixture is the addition of PCM to bitumen before mixing with aggregates. Finally, this review shows that the temperature reduction ranges from 1.5 °C to 10.5 °C and it is noteworthy there is no single solution on the use of a PCM in the asphalt mixture, since it depends on the purpose and the effect to be generated in the pavement.

1. Introduction

High temperatures affect the properties and service life of asphalt pavements, as they are prone to absorb and store solar radiation (Dai et al., 2021) and consequently the viscoelastic behavior changes with temperature variations (Betancourt-Jimenez et al., 2022), (Bueno et al., 2019a). Also, as asphalt pavements increase their surface temperature, they produce the Urban Heat Island (UHI) effect (Dai et al., 2021), which in turn increases the temperature in urban areas (Kumalasari et al., 2018).

An UHI is basically an urban area significantly warmer than rural areas (Mohajerani, 2018), estimated to be about 3 °C–4 °C warmer (Zhou et al., 2018). Anthropogenic heat release such as urban roads, concentration of urban areas, alterations in urban evapotranspiration and convective efficiency have been identified as the main drivers of UHI. At the same time, this phenomenon contributes to higher water and energy consumptions (Betancourt-Jimenez et al., 2022), (Wang and Guan, 2011). Therefore, new sustainable solutions are urgently needed to mitigate the effects of UHI, which has become a challenge for research and the asphalt industry.

The use of Phase Change Materials (PCM) in asphalt mixtures has emerged as a promising strategy, as shown in Fig. 1, where the last few years have seen a significant increase in PCM-related research and is positioned as a potential field for alleviating UHI (Betancourt-Jimenez et al., 2022) (Huang et al., 2023), and reducing pavement temperature distress (Bueno et al., 2019a), (Kumalasari et al., 2018), (Montoya et al., 2022), (Minh Phan et al., 2021), (Çaktı et al., 2022), (Anupam et al., 2020). It should be noted that the publications are current as of October 2024.

PCMs are capable of storing thermal energy in the form of latent heat. During the day, PCM pavements undergo a phase change by absorbing thermal energy and when the ambient temperature drops, the PCM undergoes a phase change releasing the stored heat energy (Dai et al., 2021), (Montoya et al., 2022), (Sharifi and Sakulich, 2015), (She

* Corresponding author.
E-mail addresses: david.salvo@unican.es (D. Salvo-Ulloa), irune.indacoechea@unican.es (I. Indacoechea-Vega), faossio@uc.cl (F. Ossio), castrod@unican.es (D. Castro-Fresno).

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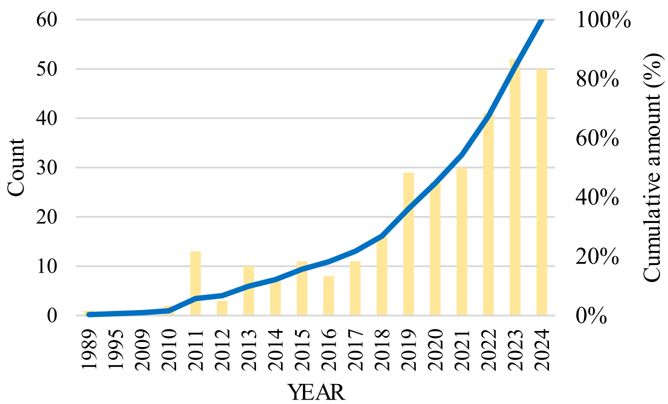

Fig. 1. Number of publications per year according to Scopus (search by title and keywords: phase change material, pavement, asphalt, bitumen and asphalt binder).

et al., 2019), (Chen et al., 2020), (Sha et al., 2022), (Cheng et al., 2023a), (Ren and Hao, 2022a). This ability has significant potential in regulating the temperature extremes faced by asphalt, as demonstrated by recent research.

However, the effective integration of PCM into asphalt mixtures poses challenges, especially in terms of maintaining the balance between the desired thermal regulation and preserving the mechanical properties of the pavement (Betancourt-Jimenez et al., 2022), ((Sha et al., 2022), (Pinheiro et al., 2023). Proper selection of the type of PCM, the method of incorporation into the mixture and the optimum amount to be used are crucial considerations for achieving satisfactory results.

There are three main types of PCM: organic, inorganic and eutectic (Kumalasari et al., 2018), (Vega-Zamanillo et al), (Wang et al., 2022a), each with its own specific characteristics and applications. Methods of incorporation into the asphalt mixture include direct incorporation, use of carrier materials and encapsulation, each with its own particular advantages and disadvantages. In addition, the incorporation processes, whether wet or dry, also affect the final properties of the pavement.

To ensure the successful integration of PCM into asphalt mixtures, it is essential to perform a series of tests, both thermal and mechanical, to evaluate the properties of the PCM and its impact on the pavement. These tests help determine the suitability of the selected PCM, as well as the optimum amount to incorporate in order to achieve the desired balance between thermoregulation and mechanical strength.

It should be noted that thermal modeling and simulations have emerged as tools to evaluate the performance of asphalt pavement with PCM in service conditions and thus take better advantage of the qualities of PCM. Several researches have developed predictive models to analyze heat transfer and the impact of PCM on pavement thermal regulation. For example, energy balance (Gavin Gui et al.) and heat transfer (Anupam et al., 2024) models have allowed estimating pavement surface temperatures and evaluating the effectiveness of PCM, while finite element models (Si et al., 2018) (Si et al., 2020) (Deng et al., 2022a) have demonstrated their usefulness in calculating pavement temperature and thermal regulation capacity. In addition, numerical studies have optimized parameters such as PCM melting temperature (Refaa et al., 2018), accuracy in predicting pavement temperatures (Rajapaksha M et al., 2024), and determination of the optimum PCM content in the asphalt mixture (Phan et al., 2020).

Based on this context, the objective of this review article is to provide a comprehensive overview and a useful tool in the selection, incorporation methods and evaluation of phase change materials for asphalt mixtures, addressing both their thermal and mechanical properties. In addition, current methodologies are synthesized, critical gaps in the literature are identified and practical criteria for PCM selection and evaluation are proposed based on their applicability under real-world conditions to perform optimally. This review not only provides practical guidance for researchers and practitioners, but also highlights priority areas for future research. Table 1 summarizes the scope of this article review.

Despite the growing interest and promising evidence of the benefits of PCMs in asphalt pavements, there are still aspects to be explored, such as the long-term evaluation of PCM performance under real-world conditions and their economic feasibility on a large scale. It should be noted that PCMs have been successfully employed in other fields, such as buildings and construction materials, thermal energy storage, electronics, food preservation, pharmaceuticals, textiles and the space industry (Dai et al., 2021), (Betancourt-Jimenez et al., 2022), (Bueno et al., 2019a), (Zhou et al., 2018), (Montoya et al., 2022), (Chen et al., 2020), (Ismail et al., 2022), (Agyenim et al., 2010) (Ma et al., 2013).

Table 1
Key factors for the selection of a PCM for asphalt mixtures.

Factor	Parameter	Description
Type of PCM	Organic	E.g.: paraffins, polyethylene glycols, fatty acids, among others.
	Inorganic	E.g.: salt hydrates and eutectic mixes of molten salt.
	Eutectic	E.g.: mix of two or more PCM substances.
Incorporation of the PCM	PCM Usage Format	Direct incorporation (PCM directly into the asphalt mixture). Carrier materials (porous material or support material). Encapsulation (surface coating of the PCM).
	Combination of PCM in the asphalt mixture	Wet process (combination of a proportion of PCM with the asphalt binder). Dry process (replacement of a portion of fine/coarse aggregate or incorporation as an additive).
	Tested doses in research	The proportion of PCM varies between 1.5 % and 20.0 % by mass of asphalt mixture and 3.0 %–50.0 % in addition of bitumen mass.
Thermal Properties	Characterization of the PCM	E.g.: FTIR, TGA, DSC, SEM, XRD, others.
	Thermal test of the new asphalt mixture	Exposure of the asphalt mixture with PCM to temperatures to determine its impact on the asphalt mixture.
	Temperature adjustment according to investigations	Temperatures vary between 1.5 °C and 10.5 °C with respect to the conventional sample.
Mechanical Properties	Mechanical testing of the new asphalt mixture	Asphalt mixture: Marshall, Water Sensitivity, Wheel Tracking, Resistance to Fatigue, Stiffness, others. Asphalt binder: Penetration, Ring and Ball, Rheology, others.
General Considerations	Manufacturing temperature of an asphalt mixture	Between 140 °C and 180 °C
	Pressure and friction with the aggregates during asphalt mixture	Coarse and fine aggregates
	Compaction of the asphalt mixture	Pressure exerted by mechanical tests and when put into service
	Asphalt mixture temperature in service	Between 30 °C and 60 °C in extreme heat and freezing weather
	External efforts	Traffic and water erosion loads

2. Types of PCM

If PCM is considered to be incorporated into an asphalt mixture, it could regulate the extreme temperatures that the asphalt can reach (Bueno et al., 2019a), as represented by the example in Fig. 2, where two curves reflecting the comparison between an asphalt mixture with and without PCM subjected to thermal radiation are shown in a representative manner. These curves show that the sample with PCM, when absorbing thermal energy, takes time to reach the same temperature as the sample without PCM and when the cooling period begins, the sample with PCM starts to release the thermal energy. However, a direct incorporation of PCM into the asphalt mixture, without knowing the chemical composition and its interaction with other agents, could negatively affect the mechanical properties of the pavement (Bueno et al., 2019a) (Kakar et al., 2020a), (Anupam et al., 2021).

There are mainly 2 types of PCM, according to their chemical composition (Vega-Zamanillo et al). Fig. 3 shows the different types of PCMs according to their enthalpy and melting temperature. PCMs are grouped according to the properties of the chemical compounds and melting points. Firstly, *Organic PCMs* are chemically stable and non-reactive, maintain efficiency in thermal cycling and present high latent heat storage capacity, but usually have low thermal conductivity (Chen et al., 2020). Some examples of organic PCMs are: paraffins, polyethylene glycols (PEG) and bio-based PCMs such as fatty acids and esters. Secondly, *Inorganic PCMs* have high latent heat storage capacity and a wide melting point range. On the other hand, this PCM can experience loss of efficiency with thermal cycling, is corrosive and cannot be encapsulated. Examples include salt hydrates and eutectic molten salt mixes. Finally, more recent research has explored the potential of combining two or more organic and/or inorganic PCM substances (Ismail et al., 2022), called *Eutectics* (Zhang, 2023), which consist of modifying the composition of each substance to achieve the desired phase change temperatures and enthalpies, thus achieving a tailor-made product (Deng et al., 2022b). This type of PCM can be classified as organic-organic eutectic, organic-inorganic eutectic or inorganic-inorganic eutectic (Zhang, 2023), (Dai et al., 2022).

3. Methods of incorporation of PCM in an asphalt mixture

To incorporate PCM in the asphalt mixture, according to several researches, 3 factors are considered: the PCM phase change state, the PCM format to be used and the PCM combination process in the asphalt mixture (Kumalasari et al., 2018), (Chen et al., 2020).

3.1. PCM phase change state

One factor to consider in the selection of the incorporation method is the resulting phase change state of each type of PCM, as this would allow the best performance of the PCM to be obtained. According to the phase change state, they can be categorized mainly by solid-liquid or solid-solid (Vega-Zamanillo et al). From this, the most widely used is solid-liquid, while solid-solid PCM has the potential of no leakage, adjustable temperature, thermally stable and high enthalpy (Wei et al., 2019a), (Wei et al., 2019b). In particular, solid-solid PCM offers a promising leak-free solution and better volume control during phase change (Sharifi and Sakulich, 2015).

Most studies have used the type of organic PCM such as kerosene which has a liquid to solid state change (Kumalasari et al., 2018). One of the most emerging organic PCMs, however, is Polyethylene Glycol (PEG) (Bueno et al., 2019a), (Chen et al., 2020), (Pinheiro et al., 2023), (Zhang et al., 2019), (Du et al., 2019), which has a solid-to-liquid state change and is characterized by significant latent heat, an adjustable phase change temperature, excellent thermal/chemical stability and is non-corrosive (Sha et al., 2022), (Pielichowska et al., 2016). This behavior makes PEG useful for use in asphalt mixtures because of the potential change it would generate in pavement temperature. Fig. 4 shows the analysis of 51 investigations which show that the most explored PCM is PEG (34 %), followed by n-Tetradecane (17 %), commercial PCMs (14 %) and Paraffin (10 %).

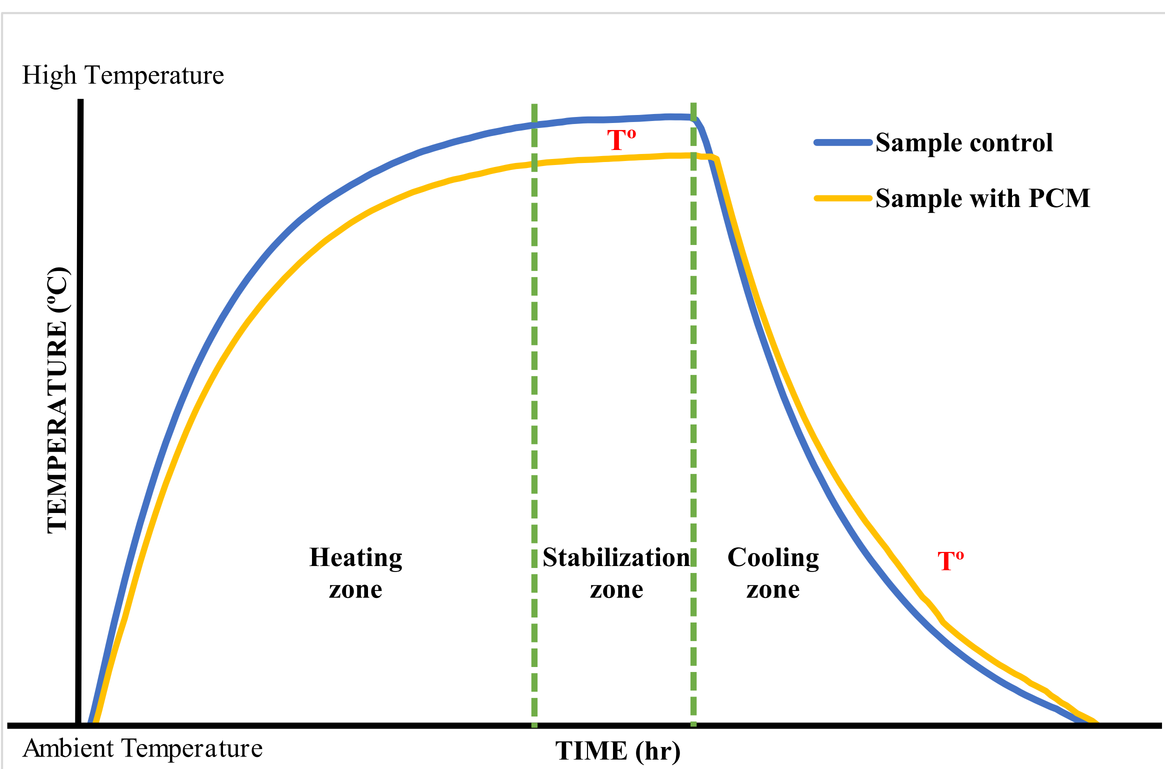

Fig. 2. Theoretical graph of asphalt behavior with and without PCM.

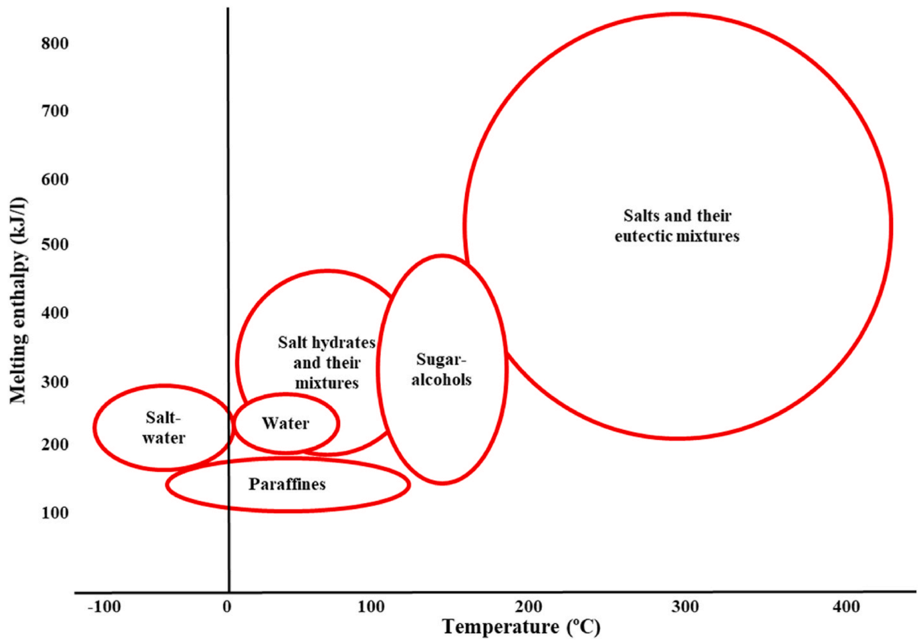

Fig. 3. Enthalpy and melting temperature for the different types of PCMs.

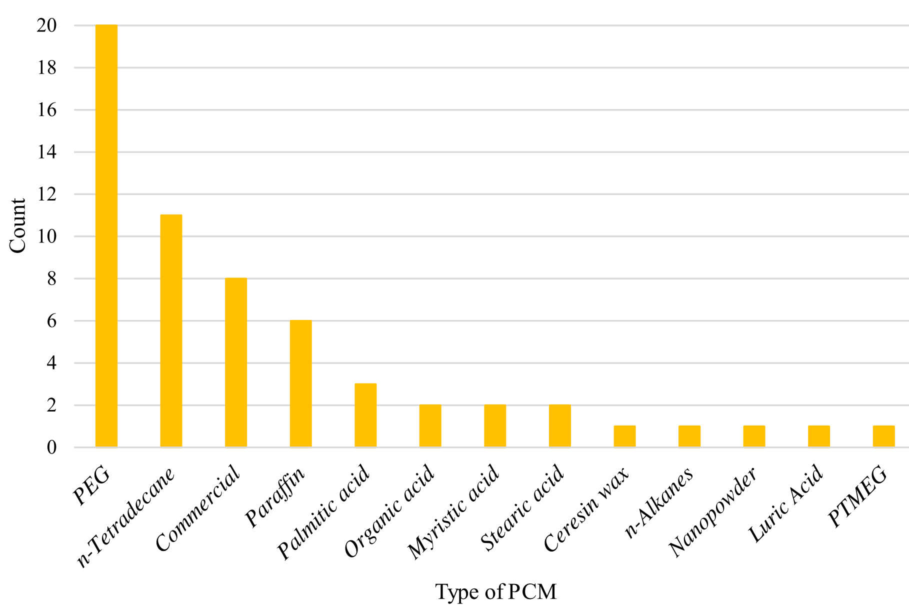

Fig. 4. Types of PCMs used for research.

3.2. PCM usage format

The format of the PCM is fundamental to determine how it will be used in the asphalt mixture; i.e., depending on the phase change states it undergoes and the thermal properties it possesses, the appropriate means to incorporate the PCM and obtain maximum performance are selected. However, the processes described below can be combined with each other; i.e., there is no single solution and it will depend on the objective to be achieved with the incorporation of PCM in the asphalt mixture (Pinheiro et al., 2023) The most frequent types of incorporation according to the type of PCM, based on the analysis of 51 investigations, are support and encapsulated materials, followed by porous materials (see Fig. 5).

3.2.1. Direct incorporation

Direct incorporation implies that the PCM is incorporated directly into the asphalt mixture manufacturing process, without the need to modify its thermal and chemical properties, an example of which is research using commercial PCMs. Also, this method makes the PCM more vulnerable to breakage due to contact with the components of the asphalt mixture, either with the aggregates or bitumen that are hot, and this could melt the PCM affecting its thermal properties (Kakar et al., 2019), (Bueno et al., 2019b). On the other hand, the disadvantage of direct incorporation is that the PCM can leak into its surroundings and reduce its content, break, melt due to high temperatures or react with its surroundings, thus affecting the mechanical properties of the asphalt (Betancourt-Jimenez et al., 2022), (Bueno et al., 2019a), (Kumalasari et al., 2018), (Chen et al., 2020), (Cheng et al., 2023a), (Anupam et al., 2021), (Zhang, 2023), (Yinfei et al., 2020).

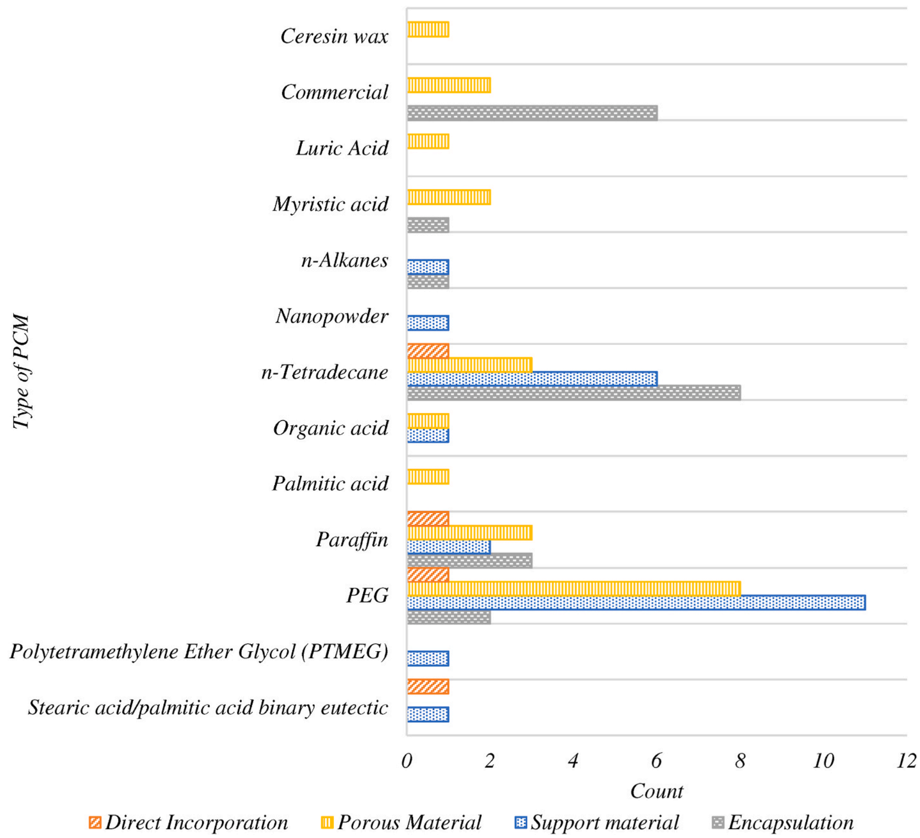

Fig. 5. Types of incorporation according to PCM.

3.2.2. *Carrier materials*

This method is also known as *shape stabilized* and its main characteristic is that the PCM uses a porous material to be stored (see Fig. 6) or a chemical compound as a support material. That is, the porous material allows the PCM to be absorbed and retained by capillary forces and surface tension (Chen et al., 2012). In other words, the porous material protects the PCM by reducing direct contact with the other elements of the asphalt mixture. On the other hand, the support material helps to modify the thermal and/or chemical properties of the PCM to change its phase change state or to change its leakage behavior (Sha et al.).

It is important to confirm that the carrier materials are able to maintain the PCM content without leaking during the manufacturing process of the asphalt mixture or that during the chemical melting process it can change its state without weakening the carrier material and thus guarantee a better thermal performance.

The most successful investigations have used porous materials to stabilize PCMs. For example, lightweight aggregates (LWA) such as expanded clay can be used as a carrier aggregate (Kakar et al., 2020b). However, this technique involves problems of PCM leakage, reducing the content available for temperature regulation and affecting the mechanical properties of the asphalt mixture. Therefore, a capsule is necessary to contain the PCM in the carrier aggregate and allow its feasibility of implementation (Betancourt-Jimenez et al., 2022) and preserve the useful life of the pavement (Wang et al., 2022a).

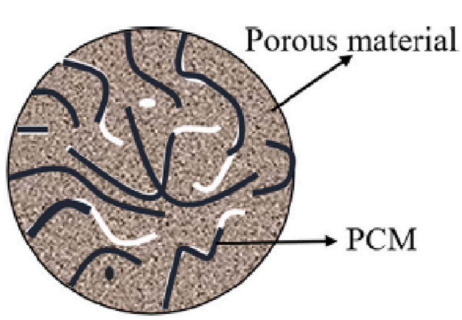

Fig. 6. Carrier materials PCM (Anupam et al.) of porous material type.

Some carrier materials used in research are shown in Table 2, where it can be seen that the porous material that has been mostly used is Expanded graphite and the support material that has been most used is SiO_2 and Polyacrylamide.

3.2.3. *Encapsulation*

The encapsulation method consists of coating the PCM with a shell (see Fig. 7), since this coating is applied as a surface seal keeping the PCM contained and at the same time isolating it from harmful environmental factors (Kumalasari et al., 2018), (Zhou et al., 2018). This feature increases the hardness of the PCM and reduces the risk of breakage during the manufacture of the asphalt mixture (Chen et al., 2020), either by high temperatures or by rubbing against the aggregates. It also prevents PCM from leaking during phase change (Akeiber et al., 2016) and protects the mechanical properties of the asphalt (Kumalasari et al., 2018), (Guo et al., 2020). However, the surface seal can generate an isolation with the medium and this may cause the encapsulated PCM not to absorb energy and not to fulfill its purpose. Therefore, it is important to know the material to be used in the encapsulation so that it favors thermal transmittance. Some of the types of encapsulation used in research are presented in Table 3.

3.3. *Combination of PCM in the manufacture of asphalt mixture*

In this process, the PCM is incorporated into the bitumen or asphalt mixture (Pinheiro et al., 2023), also known as wet or dry process, respectively. Besides, a variable to consider in this process is the possible amount of the asphalt mixture to be replaced since approximately 4.0

Table 2
Carrier materials by type of PCM.

Type of carrier materials	Organic Acid	n-Tetradecane n-Octadecane	Paraffin	Polyethylene Glycol	n-Tetradecane
Carbon and silica	–	–	–	–	Ma et al. (2013)
Diatomite	–	–	–	(Liu et al., 2020), (Jin et al., 2017)	–
Expanded graphite	Chen et al. (2012)	–	–	(Zhang et al., 2019), (Zhang et al., 2021), (Cheng et al., 2021), (Zhang et al., 2018a)	–
Fly ash ceramsite	–	–	–	(Yinfei et al., 2020)	–
Hydrophobic fumed silica	–	–	–	(Hu et al., 2021)	–
LWA	–	–	Zhou et al. (2018)	–	–
Polyacrylamide	–	–	–	(Cheng et al., 2023a), (Cheng et al., 2021a), (Cheng et al., 2021b)	–
SiO_2	–	–	–	(Hu et al., 2021), (Gao, 2022), (Wang et al., 2023), (Gong et al., 2022), (Kuai et al., 2021)	–
Slag Steel	–	(Xu et al., 2022)	–	–	–

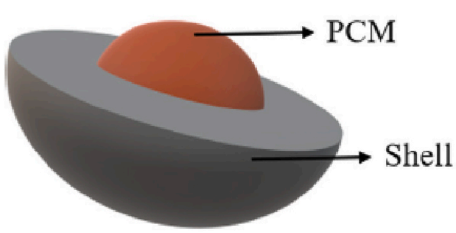

Fig. 7. Encapsulated PCM (Anupam et al.).

%–6.0 % of the total mass corresponds to the asphalt binder while 94 %–96 % corresponds to the aggregates. Therefore, modifications to the asphalt binder limit the effect of PCM due to its low presence in quantity while in the aggregate as the main component, it is an effective option to consider the means to incorporate PCM (Kakar et al., 2020b).

In addition, the combination processes influence the mechanical properties of the asphalt mixture. By adding PCM to the bitumen by the wet process, the bitumen content is modified and its properties may vary; likewise, in the dry process by replacing part of the aggregates with PCM or adding PCM as an additive, it may result in transformations in the overall performance of the mixture (Zhang, 2023).

On the other hand, the analysis of 51 studies shows that the process for combining PCM in the asphalt mixture is almost similar between the wet and dry methods (45.45 % and 47.27 % respectively); however, in the dry method, two types of combinations can be distinguished: replacement of aggregate or use of PCM as an additive (27 % and 20 % respectively). Fig. 8 shows the most frequent combination processes by type of PCM.

3.3.1. Wet process

This process combines PCM with bitumen or asphalt binder to produce a modified bitumen that is then mixed with the rest of the asphalt mixture components (Bueno et al., 2019a), (Sha et al., 2022) (Zhang, 2023), This method can result in the PCM being exposed to heating for a shorter time, allowing for less risk of breakage during mixing and a more uniform distribution of the PCM in the asphalt mixture (Anupam et al., 2020). However, it is necessary to analyze the mechanical and thermal properties of the modified bitumen, as they may vary compared to conventional bitumen.

On the thermal side, there are two factors to consider: (1) the amount of bitumen in the asphalt mixture; and (2) the proportion of PCM added to the bitumen (percentage by mass). These factors imply that the presence of PCM in the asphalt mixture is small and consequently has a limited temperature regulating effect. However, the research discussed in Fig. 8 shows that the use of PCM-modified bitumen is frequently explored.

3.3.2. Dry process

In this process, PCM is incorporated as part of the aggregates during the manufacture of the asphalt mixture (Zhang, 2023), (Cheng et al., 2021), (Wei et al., 2022), (Phan et al., 2022) or as an additive; i.e., it is added when the asphalt components are mixed (Betancourt-Jimenez et al., 2022), (Cheng et al., 2023a), (Cheng et al., 2023b), (Ma et al., 2020), (Phan et al., 2022), (Cheng et al., 2023b), (Ma et al., 2019), (Ma et al., 2014), (Si et al., 2015). However, attention must be paid to the exposure to heating, risks of PCM leakage or breakage, as well as

Table 3
Encapsulations types.

Type encapsulate	Lauric Acid	n-Alkanes	n-Tetradecane	Paraffin	Polyethylene Glycol
Cement mortar	–	(Xu et al., 2022)	–	–	–
Cement paste	–	–	–	–	(Yinfei et al., 2020)
Emulsion polymerization	–	–	Çaktı et al. (2022)	–	–
Gelatinous solution	–	–	Ma et al. (2020)	–	–
Liquid Epoxy Resin + Cement	–	–	Kakar et al. (2020b)	–	–
Melamine formaldehyde resin	–	–	(Bueno et al., 2019a), (Ren and Hao, 2022b)	–	–
Polyester resin	–	–	–	Zhou et al. (2018)	–
Polymer shell	–	–	–	(Betancourt-Jimenez et al., 2022)	–
Polytetrafluoroethylene dish	(Yinfei et al., 2020)	–	–	–	–
SiO_2	–	–	Minh Phan et al. (2021)	(Wang et al., 2023)	(Deng et al., 2022b), (Gao, 2022), (Kuai et al., 2021), (Chen et al., 2020)

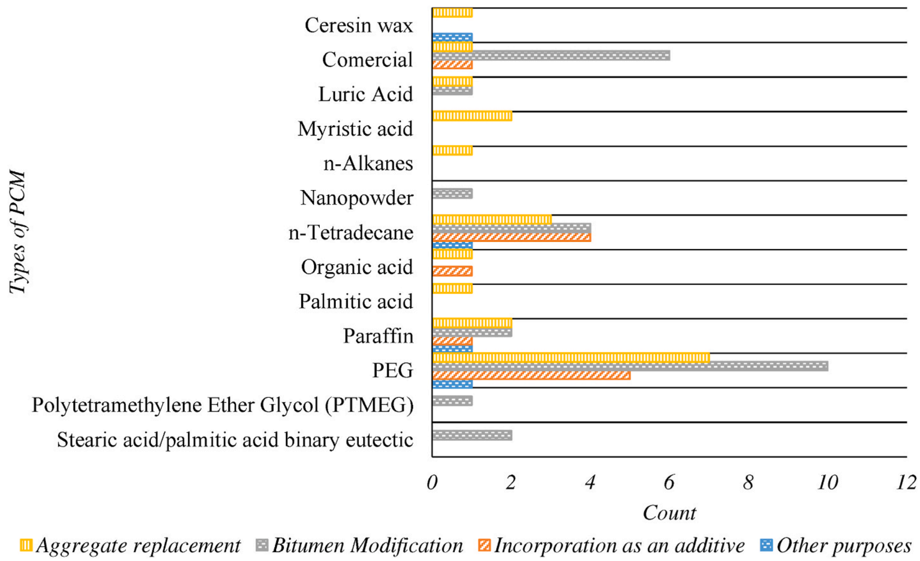

Fig. 8. Combinations per PCM type in the asphalt mixture.

possible segregation during mixing (Gao, 2022) or not being completely distributed in the asphalt mixture. Depending on the characteristics of the PCM, this process is distinguished in 2 ways.

- Incorporation as fine or coarse aggregate: due to the difficulty of transformation of PCMs into fine mineral particles, PCMs have been mainly applied in the asphalt mixture in the form of aggregates (Dai et al., 2021). The use of this method depends on the size of the particles loaded with PCMs (Chen et al., 2020), since it is necessary to know their particle size distribution to determine the aggregates to be replaced in the mixture or to add them as a new aggregate. In addition, it is important to know the density of the particles loaded with PCM to know the volume of contribution in the asphalt mixture. Finally, PCM aggregates are added by replacing them in volume or equivalent mass (Zhang, 2023). In general, the PCMs used in the investigations show a diversification of particle sizes, from 0.0002 mm to larger than 9.5 mm (Pinheiro et al., 2023).
- Incorporation as an additive: PCM is added during the mixing process of the asphalt components, thus guaranteeing the presence and functionality of the aggregates and conventional bitumen (Zhang, 2023), (Wang et al., 2023), (Kong et al., 2017). In this type of incorporation, an addition is also made according to the volume or mass of the asphalt mixture, the total amount to be added being lower than in the previous case.

The physical and chemical-mechanical compatibility of PCM in asphalt mixtures is crucial for its effective incorporation. On the physical side, if the PCM has a structure that breaks down easily, dissolves in water or reacts with aggregates, it is preferable to use it by the wet process, while encapsulated or solid-solid PCMs allow its use by the dry process. On the chemical-mechanical side, the interaction of PCM with bitumen should not generate chemical reactions that modify the rheological properties and affect the performance of the mixture, for example, the study of Zhao et al. (2022a) determined that PCM mixed with asphalt had no chemical reactions, although the compatibility between both materials was poor, also that the addition of PCM can improve the physical properties of asphalt (resistance to rutting) but the viscosity of asphalt does not meet the requirements specified in standard. On the other hand, the research carried out by Wang et al. (2024) studied the compatibility of asphalt modified with PCM by adding naphthenic oil to improve the compatibility between both materials, thus achieving greater cohesion and concluded that more tests should be carried out to check whether the method used can improve the compatibility with other types of PCM and to evaluate mechanically whether the increase between the compatibility of PCM and bitumen achieves better performance in the asphalt mixture.

3.4. PCM dosage in an asphalt mixture

The dosage of PCM to be used is a fundamental variable to achieve the thermoregulation effects in the pavement and to meet the mechanical standards of the asphalt mixture (Guo et al., 2020). The dosages employed by research show that there is variability between each study and this is mainly attributed to the different PCM chemical compounds that researchers have experimented with. For example, a study by Cheng et al. (Cheng et al.) which employed Polyethylene Glycol/Polyacrylamide determined that the optimum dosage of PCM in the asphalt mixture is between 7.5 % and 10 % to ensure the mechanical performance of the pavement. Another research, according to Liu et al. (2020), who used Polyethylene Glycol impregnated in Diatomite, found that the appropriate proportion to obtain high performance of PCM at high temperatures and good thermoregulation should be 10 %.

Also, it is important to test different dosages to determine the optimum amount to be incorporated into the asphalt mixture. This optimal dosage is based on the balance between temperature regulation and preservation of the mechanical properties of the asphalt mixture, for example, a research carried out by Kumalasari et al. (2018), used a PCM called Linolenic acid and analyzed the impact of different dosages in the asphalt mixture (0 %, 5 %, 10 % and 20 % on the asphalt content). The results showed that when the amount of PCM is higher than 10 %, there is a reduction in the stability at high temperatures, which is explained by the fact that when PCM becomes liquid, it causes a reduction in rutting resistance and consequently pavement deformation. Therefore, to effectively use PCM in asphalt pavement, it is essential to regulate the incorporation rate (Zhang, 2023).

It is relevant to reiterate that there is no direct relationship between the percentage of PCM addition in the asphalt mixture and temperature regulation. This is due to the fact that there are different variables that make each study unique. Some of the influencing variables are: (1) objective of the PCM in the asphalt mixture, since the purpose can be to avoid freezing of the pavement or to make the mix cooler to avoid extreme temperatures; (2) effective amount in the asphalt mixture (dosage), since there are different formats of use (see point 3.2) and methods of combination in the asphalt mixture (see point 3.3); and (3) thermal properties of the PCM such as enthalpy and phase change temperature. Table 4 shows the analysis of 23 investigations where it can be observed that there is an inverse relationship between the PCM dosage in the asphalt mixture and the temperature regulation.

4. Characterization of the PCM

In order to know the composition of PCM, it is necessary to perform thermal and chemical studies to verify its properties, such as phase change temperature and enthalpy (Pinheiro et al., 2023). The tests that help characterize the PCM are: (1) *Fourier-transform Infrared Spectroscopy (FTIR)*: is an analytical technique that helps to identify and quantify chemical compounds by absorption analysis of a sample to obtain the chemical structure (Dai et al., 2021), (Huang et al., 2023), (Zhang et al.), (Wang et al., 2023), (Wang et al.); (2) *Thermogravimetric analysis (TGA)*: is used to determine the thermal stability of a material subjected to increasing temperatures over time (Dai et al., 2021), (Huang et al., 2023), (Sha et al., 2022), (Zhang et al.), (Wang et al., 2023), (Wang et al.), (Wadee et al., 2022); (3) *Differential Scanning Calorimetry (DSC)*: helps to evaluate the behavior and temperature of phase change and thermal energy storage (enthalpy) (Dai et al., 2021), (Huang et al., 2023), (Çaktı et al., 2022), (Chen et al., 2020), (Sha et al., 2022), (Zhang et al.), (Wang et al., 2023), (Wang et al.); (4) *Scanning Electron Microscope (SEM)*: is used to magnify the PCM sample and observe its microscopic structure. The objective is to analyze the porous structures in porous materials; for example, it can be observed whether the voids of the particles are filled with PCM and determine the particle size (Huang et al., 2023), (Çaktı et al., 2022), (Chen et al., 2020), (Ma et al., 2013), (Zhang et al.), (Wang et al., 2023), (Wang et al.); and, (5) *X-ray diffraction (XRD)*: this analysis helps to know the crystalline structure of PCM by diffraction (Dai et al., 2021), (Huang et al., 2023), (Çaktı et al., 2022), (Sha et al.), (Dai et al., 2022), (Wei et al., 2019b), (Kakar et al., 2020b), (Gao, 2022), (Wang et al.), (Zhang et al., 2018b).

The analysis of 45 studies shows the trend of the most recurrent tests

Table 4
Relationship between PCM dosage and temperature regulation.

T° regulation	Optimal dosage	Enthalpy (J/g)	Melting Point (°C)	PCM	Carrier materials	Objective	Reference
1,5 °C	7,5 % by wt mix	97,73	5,31	n-Tetradecane	SiO_2	Prevent freezing	Minh Phan et al. (2021)
2,0 °C	1,5 % by wt mix	60,8	8,28	n-Tetradecane	SiO_2	Prevent freezing	Phan et al. (2022)
2,5 °C	50,0 % by wt binder	62,7	4,4	n-Tetradecane	Melamine formaldehyde resin	Prevent freezing	Bueno et al. (2019a)
2,9 °C	10,0 % volume mix	200	43,0	Commercial	Non-specified	Cool down	(Betancourt-Jimenez et al., 2022)
3,3 °C	20,0 % by wt binder	14,1	38,4	Polyethylene Glycol	Non-specified	Cool down	Du et al. (2019)
3,4 °C	7,2 % by wt mix	179,6	2,87	n-Tetradecane and n-Octadecane	Slag Steel	Prevent freezing	(Xu et al., 2022)
3,4 °C	7,0 % by wt mix	43	22,5	Polyethylene Glycol	Diphenylmethane diisocyanate, Dimethylformamide	Cool down	Wei et al. (2022)
3,8 °C	7,5 % by asphalt binder volume in asphalt concrete	72,2	25,1	Polyethylene Glycol	Polyacrylamide	Cool down	Cheng et al. (2021)
3,8 °C	4,0 % by wt binder	53,3	10,5–29,0	Commercial	Non-specified	Cool down	(Dong et al., 2024)
4,5 °C	3,0 % by wt binder	73,8	26,6–55,5	Polyethylene Glycol	Methylenediphenyl diisocyanate/Methylenebis	Cool down	Wei et al. (2019a)
4,8 °C	50,0 % replacement mineral filler	93,5	48,3–36,0	Polyethylene glycol	Methylenediphenyl diisocyanate/Methylenebis	Cool down	(Sha et al., 2022)
4,8 °C	11,9 % replace the aggregate in equal volume	138,5	55,4	Myristic acid	Ceramsite	Cool down	Huang et al. (2023)
5,0 °C	Replacing equal volume of aggregate with the same particle size range	11,2	52,7	Polyethylene glycol	Fly ash ceramsite	Cool down	(Yinfei et al., 2020)
5,1 °C	Replacing equal volume of aggregate with the same particle size range	17,2	53,0	Polyethylene glycol	Fly ash ceramsite	Cool down	(Yinfei et al., 2020)
5,18	Replacing equal volume of aggregate with the same particle size range	56,3/ 39,42	54,2/55,1	Polyethylene glicol/ ethylene glycol distearate	Encapsulate with cement	Cool down	Jin et al. (2025)
6,3 °C	Filler replacement 100,0 %	23,3	39,9	Polyethylene Glycol	Diatomite	Cool down	Saberi Kerahroudi et al. (2024)
6,6 °C	12,1 % replace the aggregate in equal volume	133,3	54,5	Paraffin wax	Expanded clay aggregate	Cool down	Huang et al. (2023)
8,0 °C	5,0 % by wt binder	73,8	26,6–55,5	Polyethylene Glycol	Methylenediphenyl diisocyanate/Methylenebis	Cool down	Wei et al. (2019a)
8,9 °C	7,5 % by wt binder	70,4	−3,1 y 40,4	Polyethylene Glycol	Polyacrylamide	Cool down	Cheng et al. (2023b)
9,0 °C	Replacing the original mineral aggregate	125,2	59,6	Ethylene glycol distearate	SiO_2	Cool down	(Gao, 2022)
9,0 °C	Replacing the original mineral aggregate	137,6	52,8	Polyethylene Glycol	SiO_2	Cool down	(Gao, 2022)
9,0 °C	7,0 % by wt binder	73,8	26,6–55,5	Polyethylene Glycol	Methylenediphenyl diisocyanate/Methylenebis	Cool down	Wei et al. (2019a)
Approx. 9,0 °C	14,0 % by wt binder	9,0	24,4–50,3	Polyethylene Glycol	Diatomite	Cool down	Liu et al. (2020)
9,3 °C	15 % by wt binder	226,27	53.12	Stearic acid/palmitic acid binary eutectic	Non-specified	Cool down	Dai et al. (2024)
10 °C	20,0 % volume mix	200	43	Commercial	Non-specified	Cool down	(Betancourt-Jimenez et al., 2022)
10,5 °C	15,0 % by wt binder	27,7	48,9	Stearic acid/palmitic acid binary eutectic	Non-specified	Cool down	Dai et al. (2022)

used by the authors to characterize the PCMs they have applied, such as FTIR, TGA, DSC, SEM and XRD. Fig. 9 shows that 100 % of the analyzed studies used DSC, 47 % TGA, 42 % SEM, 36 % FTIR and 22 % XRD.

On the other hand, in order to know the effective behavior of the temperature regulation of the new asphalt mixture with PCM, different investigations have used a thermal test that shows the temperature variation reached by mixtures with and without PCM (see example in Fig. 10). In general, to carry out this test, one or more asphalt specimens with and without PCM are prepared (Ma et al., 2019) and temperature sensors are placed in them to monitor and record the effect of PCM when exposed to solar radiation (Montoya et al., 2022), (Sha et al., 2022), (Yinfei et al., 2020), (Cheng et al., 2021), (Xu et al., 2022), (Ma et al., 2020), (Cheng et al., 2023b), (Qureshi et al., 2021), (Yang et al., 2021). The results of the pavements with and without PCM are then compared to determine the actual effect of PCM on the asphalt mixture. This experiment can be used in two ways; first, by subjecting the samples to lamps that simulate sunlight in a controlled environment within a laboratory, thus simulating sunlight and the second way is to perform a field experiment by subjecting the samples to real conditions.

From the thermal analysis of the PCM, valuable information can be obtained when determining the amount to incorporate in the asphalt mixture, since certain PCMs have a higher latent heat than others and thus more heat can be stored per unit volume. This would help to use less PCM to achieve the desired thermal performance and thus modify the minimum of the conventional dosage of an asphalt mixture (Pinheiro et al., 2023).

5. Benefits of PCM in asphalt mixtures

5.1. Temperature control

Extreme temperatures cause disturbances in the structure of the asphalt mixture, in summer the pavement absorbs large amounts of solar energy and the asphalt becomes visco-plastic, causing rutting and aging. In winter, the asphalt stiffens and becomes brittle and elastic, which increases the risk of shrinkage cracks and water damage during freeze-thaw cycles, and also reduces the friction between the surface and the tires (Bueno et al., 2019a), (Montoya et al., 2022), (Dai et al., 2022), (Phan et al., 2022), (Cheng et al., 2023b).

Research has shown that the use of PCM in the asphalt mixture serves as a temperature regulator (see Table 4), reducing the occurrence of high temperatures in the asphalt layer to prevent rutting and delay the occurrence of icing or prevent cracking of the asphalt pavement at low temperatures. For example, the research Xu et al. (Xu et al., 2022) using n-Tetradecane and n-Octadecane as PCMs showed that resistance to cracking at low temperatures and reduction of ice or snow on the pavement surface is achieved. Also, the study by Zhou et al. (2018) that used a paraffin-based PCM concluded that it is able to decrease the temperature of the mixture when the pavement is heated and that it also manages to increase the temperature when it is cooled.

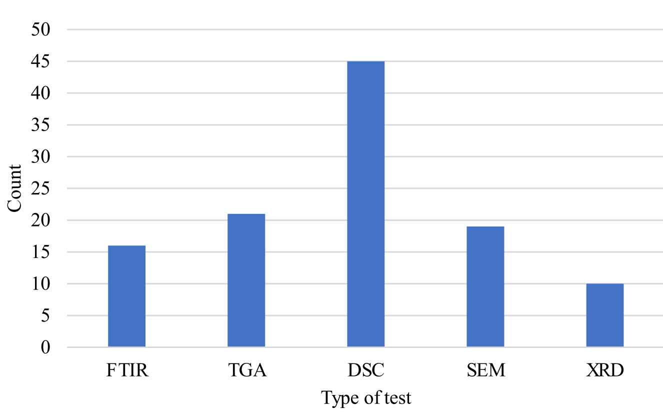

Fig. 9. Most frequent characterization tests.

Also, the results of an investigation by Bueno et al. (2019a) confirmed that a PCM composed of n-Tetradecane is capable of slowing down cooling, demonstrating a maximum displacement of 2.5 °C compared to the conventional sample. A study by Ma et al. (2014) performed a field simulation employing an organic acid-based PCM and concluded that the PCM aids temperature adjustment by slowing down the heating rate as the outside temperature increases and delays the occurrence of temperature extremes. Another research by Kumalasari et al. (2018) showed that the asphalt mixture can reduce the temperature by 8 °C–10 °C experimentally and by 3 °C–4 °C in a field simulation.

Also, a study by Betancourt-Jiménez et al. (Betancourt-Jimenez et al., 2022) showed that encapsulated PCMs can be successfully used to regulate the temperature of the asphalt mixture. During the heating stage, once the mixes with 10 % and 20 % addition by volume of the mix reached the melting point of the PCM, their temperatures were 5 °C and 10 °C lower, respectively, compared to conventional mixtures. On the other hand, during the cooling stage, the blends with 10 % and 20 % PCM showed higher temperatures than the conventional ones of 2.9 °C and 5.4 °C, respectively.

Research by Cheng et al. (2023b) showed that when PCM consisting of polyethylene glycol and polyacrylamide was added at 7.5 % of the asphalt binder mass, the maximum pavement temperature in summer was reduced by 8.9 °C compared to the reference asphalt pavement. In winter, the experimental asphalt mixture showed the potential to melt snow more efficiently. This same study determined that as the amount of PCM in the asphalt mixture increases, it can improve mechanical performance and then gradually deteriorate; i.e., an optimum amount was found that allows for a balance between temperature regulation and mechanical properties.

On the other hand, a study by Mallick et al. (2009) using the concept of heat extraction from the pavement by piping the interior, which also simulated different traffic and climate conditions, concluded that pavement service life can be extended up to 5 years with the 5 °C temperature reduction.

5.2. Impact of PCM incorporation on the mechanical behavior of the asphalt mixture

A conclusive factor in determining the feasibility of using PCM in the asphalt mixture is the effects it would have on the mechanical properties of the pavement. Therefore, it is essential to carry out routine tests for the new asphalt mixture to check whether it meets the regulatory standards. This is key to validate this technology. Results of the impact of PCM on the mechanical performance of the asphalt mixture are summarized in Table 5.

There is research that has obtained results confirming that the use of PCM at an optimal dosage can achieve a balance between temperature regulation and mechanical performance of the mixture (Cheng et al., 2023a), (Cheng et al.); however, there is also research that points out the need to further explore the optimal balance between the thermal and mechanical aspects (Montoya et al., 2022), (Chen et al., 2020), (Cheng et al., 2023a), (Pinheiro et al., 2023), (Anupam et al.), (Zhao et al., 2022b). Similarly, a literature review conducted by Zhang et al. (Zhang et al.) analyzed the impacts on mechanical properties in the asphalt mixture, concluding that properties vary when PCM is incorporated, and that despite this there were investigations that still meet the regulatory parameters and others that did not meet the design criteria.

6. General considerations when selecting a PCM

It is important to consider the context in which the PCM will interact, since an asphalt mixture has different stages: manufacture, construction and service. This implies that a PCM faces the action of high temperatures and stresses or loads due to compaction and traffic (Cheng et al., 2023a). Therefore, the incorporation of the PCM into the asphalt

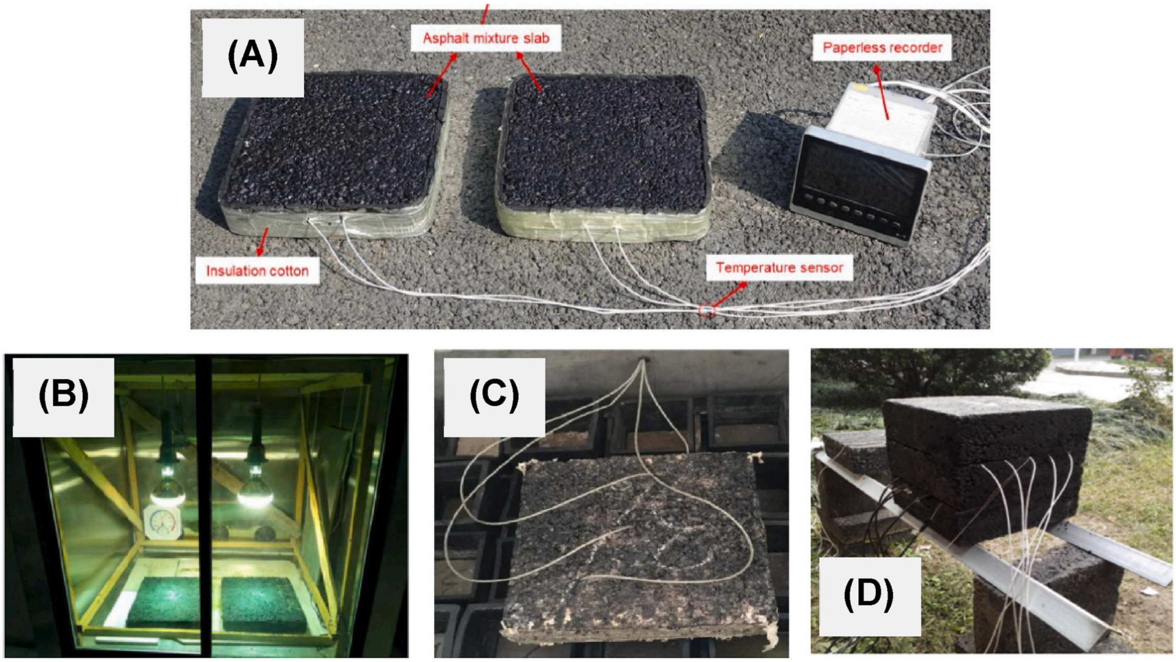

Fig. 10. (A) Temperature sensors in asphalt slabs (Sha et al.); (B) and (C) Laboratory thermal test (Cheng et al., 2021); (D) Outdoor or field thermal test (Ma et al., 2019).

mixture, regardless of its type or incorporation process, must have similar properties or conditions to which it will be subjected. Specifically, the PCM must be stable or maintain its condition under the following conditions.

- Asphalt mixture manufacturing temperature: between 140 °C and 180 °C (Betancourt-Jimenez et al., 2022), (Chen et al., 2020), (Sha et al., 2022), (Ma et al., 2013), (Zhang et al.).
- Crushing and friction due to collision with the aggregates during mixing (Betancourt-Jimenez et al., 2022), (Zhou et al., 2018), (Chen et al., 2020), (Sha et al., 2022), (Cheng et al., 2023a), (Wang et al., 2022a), (Zhang et al.).
- Compaction of the asphalt mixture (Montoya et al., 2022), (Cheng et al., 2023a), (Ma et al., 2013), (Anupam et al.), (Zhang et al.), (Ryms et al., 2015).
- Temperature and cyclic changes in temperature that the pavement withstands during the service stage: summer 30 °C – 60 °C and freezing during extreme cold weather (Betancourt-Jimenez et al., 2022), (Bueno et al., 2019a), (Zhou et al., 2018), (Montoya et al., 2022), (Cheng et al., 2023a), (Ma et al., 2013), (Xu et al., 2022).
- Traffic-related loads during the in-service phase (Betancourt-Jimenez et al., 2022), (Sha et al., 2022), (Cheng et al., 2023a), (Ma et al., 2013), (Anupam et al.), (Zhang et al.), (Ryms et al., 2015).
- Erosion due to the action of water (Betancourt-Jimenez et al.), (Cheng et al., 2023a), (Ma et al., 2013), (Zhang et al.).

Therefore, to select a PCM, in addition to knowing its chemical and thermal aspects, it is essential to consider the mechanical conditions to which it will be subjected. First, the interaction between the PCM and the asphalt must not generate chemical reactions between them nor be toxic for the workers who work with the mixture (Chen et al., 2020), (Wang et al., 2022b). Secondly, the PCM must maintain its stability during the phase change process; that is, it must not generate significant volume changes or leakage. Also, the phase change temperature of the PCM must be similar to the target climatic condition in order to generate the expected benefit (Anupam et al., 2020), (Deng et al., 2022b). Finally, the maximum temperatures that the PCM can withstand must be considered, since it may experience disintegration or decomposition and not be able to store heat energy (Qiu et al., 2020).

For example, a study by Sha et al. (Sha et al., 2022) that employed a Polyurethane-based PCM determined that the PCM is thermally stable below 240 °C, what confirmed it withstands a high-temperature environment, as the one found in manufacturing. Similarly, the research result of Wang et al. (Wang et al.) concluded that a PCM composed of micro-encapsulated Paraffin has an initial decomposition temperature at approximately 240 °C, which shows that it possesses superior thermal stability and is able to survive in hot asphalt bitumen. On the other hand, the research by Si et al. (2015) recommends that the phase change temperature should be higher than 5 °C and lower than 40 °C to mitigate low temperature cracking and rutting. Also, the PCM should have a high enthalpy or latent heat to ensure the accumulation or release of heat energy during temperature extremes reached by the asphalt pavement (Dai et al., 2021), (Chen et al., 2020), (Kakar et al., 2020a), (Zhang et al.).

Although much of the current research on PCM is focused on design, manufacturing and chemical-thermal analysis, it is important to mention that there are companies that manufacture and market PCMs for different fields of application. This could be key to focus efforts on studying the products and determine whether they are suitable for asphalt mixtures. One investigation studied the properties of a commercial PCM with robust walls and high thermal stability, showing that approximately 90 % of the capsules remained intact after being subjected to 140 °C for 20 min, which implies that they are capable of resisting the mixing and compaction stages of the asphalt mixture (Betancourt-Jimenez et al., 2022).

7. Future works

Despite advances in research on the use of PCM in asphalt mixtures, the existing literature reveals that there are several critical areas that require further exploration to ensure the feasibility and effectiveness of PCM use. The following future work is expected to contribute significantly to the development of more effective and sustainable solutions for the paving field, as well as to complement existing research.

Table 5
Impact of PCM on the mechanical performance of the asphalt mixture.

PCM/Support	Test in	Results	Reference
Commercial (paraffin)	Asphalt mixture	- The addition of PCM microcapsules lowers the modulus of the mixtures, which is attributed to the low angularity, smooth texture and the low density of the capsules.	(Betancourt-Jimenez et al.)
n-Tetradecane/ Graphene	Asphalt mixture	- Comply with technical requirements regarding water stability. - High-temperature stability.	Ren and Hao (2022a)
n-Tetradecane/SiO_2	Asphalt binder	- Increase of penetration grade and decrease of softening point. - However, the direct addition of PCM into bitumen does not considerably affect the physical properties of bitumen and also it is understood that bitumen retains its known properties.	Çaktı et al. (2022)
Netradecane-Noctadecane/Slag Steel	Asphalt mixture	- The asphalt mixture presents high temperature stability. - Low temperature cracking resistance. - High moisture stability. - High bond strength.	(Xu et al.)
Polyethylene Glycol/ Diphenylmethane diisocyanate, Dimethylformamide	Asphalt mixture	- Better low-temperature crack resistance of asphalt mixture and high-temperature stability. - No significant adverse effect on the water stability of the asphalt mixture. - The road properties of the mixture meet the specification use requirements. - High temperature stability and low temperature crack resistance improve with increasing PCM's particle size.	Wei et al. (2022)
Polyethylene Glycol/ Expanded graphite	Asphalt binder	- Higher dynamic stability and lower rutting depth of the asphalt mixtures. However, resistance gradually diminishes with the increase in PCM content. - Better low-temperature cracking resistance of asphalt mixtures at low PCM's content. Adverse effects gradually emerge when increasing the dosage. - Worse moisture stability of asphalt pavements; however, the impairment is negligible with low PCM's content. - Shorter fatigue life of the asphalt mixture. Result that worsens with PCM content.	Zhang et al. (2021)
Polyethylene Glycol/ Polyacrylamide	Asphalt mixture	- As the amount of PCM addition increases, the comprehensive performance of asphalt mixture can be improved. - Gradually deteriorates.	Cheng et al. (2023b)
Polyethylene Glycol/ Polyacrylamide	Asphalt mixture	- The performances of asphalt mixture with different PCM contents meet the requirements of specification. Compared to the control mixture, adding PCM increases Marshall stability and flexural-tensile strain by 8.86 %–14.3 %. - PCM improves the mechanical performance, moisture resistance and insulation of the asphalt mixture. - However, care must be taken with the long-term high-temperature and low-temperature performance.	(Cheng et al.)
Polyethylene Glycol/ Polyacrylamide	Asphalt mixture	- The road performance of asphalt mixtures with PCM meets specification requirements. Adding PCM improves mechanical properties, moisture resistance, and low-temperature cracking resistance. - But it negatively affects high-temperature performance.	Cheng et al. (2021)
Polyethylene Glycol/ SiO_2	Asphalt binder	- The addition of PCM to the asphalt binder reduces penetration and ductility, while increasing the softening point. This is because the PCM weakens the cohesive strength of the asphalt molecules, limiting their ductility.	Wang et al. (2023)
Stearic acid and palmitic acid/No Support	Asphalt binder	- The PCM-modified asphalt binder has better rheological properties below 30 °C.	Dai et al. (2021)

(continued on next page)

Table 5 (*continued*)

PCM/Support	Test in	Results	Reference
		- However, it begins to liquefy above 30 °C, which negatively impacts the binder.	

(1) Long-term evaluation of the PCM asphalt pavement to analyze performance in terms of repeatability of thermal properties, degradation, and phase change capability under different environmental and loading conditions.
(2) Analyze whether the new asphalt mixture with PCM meets existing design standards for different pavement thicknesses, traffic categories and climates. This aspect is relevant to ensure design and road safety standards for its feasibility of implementation.
(3) Scale the PCM pavement to real traffic and climate test sections to check thermal and mechanical behavior. In this way, optimal parameters could be obtained to implement the PCM to an asphalt pavement.
(4) Evaluate the cost-benefit ratio of implementing asphalt pavement with PCM on a large scale, determining the associated costs and the social impact of this innovative material in the paving field.
(5) Explore the combination of PCM with other additives or sustainable technologies to improve asphalt pavement properties.
(6) Promote the advancement of intelligent infrastructure systems through the combination of disciplines complementary to civil engineering, such as chemistry, mechanics, thermodynamics, environmental science, among others. The purpose is to investigate new PCMs that can improve the performance of the asphalt mix and ensure its sustainability by considering factors such as carbon footprint reduction, recyclability and reduction of UIH. In addition, including sensors in the pavement would allow real-time recording of the behavior of these mixtures, and through data analysis, optimize the design in future applications.

8. Conclusions

A PCM can play an excellent role in controlling the temperature of asphalt pavement, avoiding extreme temperatures and consequently minimizing the deterioration of its condition, which means that it has great value for research and use in the field of asphalt pavements. At present, a large number of studies have confirmed that PCMs could contribute to reducing the effects of U.H.I. by reducing temperature extremes and improving the service life of asphalt pavement.

This review of research provides a practical summary of the meaning of a PCM and provides practical guidance for future studies on the use of PCMs in an asphalt mixture. The following critical factors for the selection of a PCM can be derived from this review.

(1) Types of existing PCMs (organic, inorganic and eutectic).
(2) Methodologies of incorporation of a PCM in the asphalt mixture according to the format of use (direct incorporation, carrier materials or encapsulation) and, once one or more of the above methods have been selected, the part of the asphalt mixture manufacturing process in which the PCM will be added (wet or dry process) must be selected.
(3) Thermally test the PCM manufactured in the laboratory to know its enthalpy, melting point or chemical characterization of the compound. Also, to check the effectiveness in the asphalt mixture, it is necessary to subject the new mixture with PCM to different temperatures to verify its performance.
(4) Mechanically test the new asphalt mixture to verify the impact of PCM on the rheological and mechanical properties of the pavement, by means of standardized tests.
(5) General considerations of the asphalt mixture process, such as manufacturing, compaction and commissioning.

Specifically, existing literature has shown that the most emerging PCM is the organic type called PEG, which has a solid to liquid state change and is characterized by a significant latent heat, an adjustable phase change temperature, excellent thermal/chemical stability and is non-corrosive. The format of using PEG in asphalt mixtures has been mostly employed with two carrier materials, SiO_2 and Polyacrylamide.

The incorporation dosages of PCM in the asphalt mixture vary between 1.5 % and 20.0 % depending on the mass of the mix, and in the mass of the asphalt binder it varies between 3.0 % and 50 %. The literature has evidenced different optimum quantities to guarantee the mechanical performance of the pavement, although variations are generated within the limits of the design criteria, it is possible to comply with the normative parameters. Also, the temperature regulation demonstrated by research ranges between 1.5 °C and 10.5 °C.

Finally, it is of considerable relevance to mention that there is no single solution for the use of a PCM in the asphalt mixture, since it depends on the purpose and the effect to be generated in the pavement. Therefore, it is suggested that future research should optimize the successful results to obtain a standardized pattern.

CRediT authorship contribution statement

David Salvo-Ulloa: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Irune Indacoechea-Vega:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis. **Felipe Ossio:** Writing – review & editing, Validation, Investigation, Formal analysis. **Daniel Castro-Fresno:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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