Review

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Reviewing the Potential of Phase Change Materials (PCMs) in Concrete Pavements for Anti-Freezing Capabilities and Urban Heat Island (UHI) Mitigation

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Reviewing the Potential of Phase Change Materials (PCMs) in Concrete Pavements for Anti-Freezing Capabilities and Urban Heat Island (UHI) Mitigation

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Abstract: The study presents an overview of how phase change materials (PCMs) can enhance the freeze-thaw resistance of concrete pavement and mitigate urban heat island (UHI) effects. It discusses various types of PCMs and methods for incorporating them into concrete pavement, along with the mechanical properties of concrete pavement and its compressive strength when using different PCMs. Also, a Python script was used to simulate the effect of PCMs on the surface temperature of concrete pavement in different cold regions. Previous research suggests that porous aggregates, microencapsulation, and pipelines containing liquid PCM are the most common methods for incorporating PCMs into concrete pavement. The researchers reported that using PCMs in concrete pavement results in beneficial thermal properties, indicating that PCM concrete pavement has the potential for anti-freezing and UHI applications. Additionally, this study's simulation results suggest that local climate conditions should guide the selection of PCM materials.

Keywords: PCM; Concrete; Pavement; UHI

1. Introduction

Pavements are a vital part of our modern life, and their coverage is up to 45% in some cities [1–3]. The pavement can be applied to roads, driveways, parking lots, sidewalks, commercial plazas, playgrounds, and airstrips, which play an essential role in our everyday lives [4]. They are categorized into three groups: 1. flexible (full-depth asphalt pavement, conventional layered flexible pavement, and rock-contained asphalt), 2. rigid pavements (conventional concrete pavements, pre-stressed and precast concrete, roller compacted concrete, and pervious or porous concrete), and 3. composite pavements (semi-rigid pavement structures, premium composite pavements, long-life pavements, flexible composite pavements, and maintenance-free pavements) [5–9] (Figure 1).

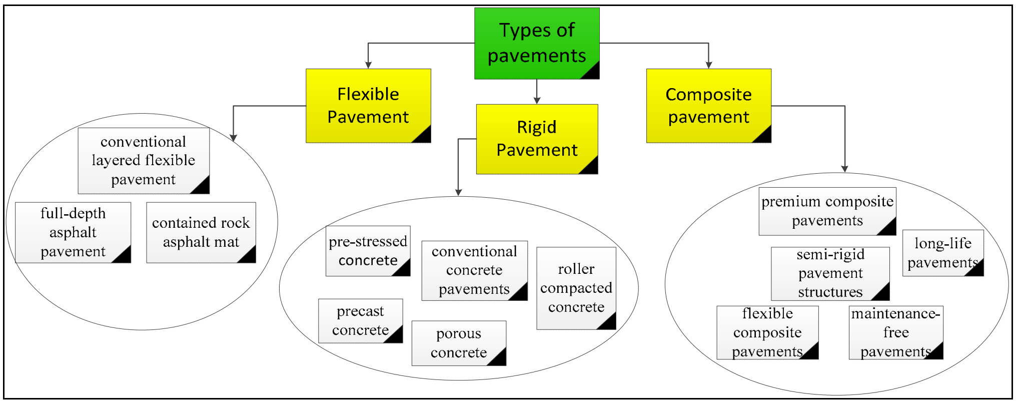

Figure 1. Different types of pavements [5–7].

Prior literature attempted to develop pavements technically in terms of physical, thermal, and mechanical properties. However, the freezing and urban heat island (UHI) phenomenon are the two main critical issues interacting between pavement and the surroundings during cold and hot seasons.

Due to freeze-thaw, internal frost damage and surface scaling are the most common types of frost damage on pavements [10]. Depending on the type of exposure (water, deicer), the rapid freezing of water inside the concrete causes hydraulic pressure or cryosuction and/or Glue-Spall stress due to the deicer solution on the surface, causing scaling damage [11–13] and decreases pavement life. Also, frost and snow are critical factors in traffic jams and accidents during cold seasons. Therefore, it is necessary to thaw ice and snow through different methods [11] of snow removal and/or melting, etc. The most used techniques for removing ice and snow from the concrete pavement surface are deicing salts and snowplowing in urban areas, including transport to dumping sites, which are costly, time-consuming, and labor-intensive. It should be noted that using deicing salts also negatively affects the environment [14–16]. Therefore, considering a more sustainable (less energy consumption, less emissions, less consumption of primary raw materials) technique for removing ice and snow on pavements appears to be necessary.

Regarding the UHI, some prior studies showed that the ambient temperature of 450 cities has increased [17,18] due to the UHI phenomenon [19–22], which can negatively affect energy consumption, the environment, and people's health. Forecasts of future cooling energy consumption of residential and commercial buildings reveal that by 2050, it may increase up to 750% and 275% due to local and global climate change, tremendous population growth, and the expected rise in cooling system employment worldwide [23]. The building and pavement materials have an essential role in UHI mitigation. Akbari and Rose [24] found that the average urban surface of four different metropolitan areas was 29-41% vegetation, 19-25% roofs, and 29-39% paved surfaces. This demonstrates that hard, man-made, heat-absorbent surfaces can cover over 60% of an urban surface. Therefore, the impact of pavements on UHI development is significant. Reflecting materials such as light-color materials can reflect most solar radiation to reduce the surface and ambient temperature. However, they may be dangerous for the thermal comfort of people on the street [25]. Based on the available literature, many researchers developed new materials and technologies to reduce the surface temperature of pavements as an essential method to mitigate UHI [26–29]. The high temperature on the pavement's surface is one of the reasons for the UHI phenomena [30,31]. Thus, reducing the surface temperature of pavements through the deduction of solar gains, enhancing heat transfer, and increasing the heat capacity of pavement are the most reported strategies to mitigate UHI [19].

As an innovative method, the phase change materials (PCMs) have been incorporated into the concrete pavement to increase the anti-freezing effect and mitigate the UHI by enhancing latent heat capacity. PCMs have the potential to be deployed to save energy during the phase change in terms of solidification (exothermic process) and melting (endothermic process) [32,33]. Thus, the current study aims to evaluate the current knowledge of PCMs in concrete pavements. Authors searched the

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keywords on online databases and found that considerably more recent studies incorporated PCMs into asphalt pavement [34–70] compared to concrete pavement (Figure 2). However, the scope of this study is limited to the effect of PCMs on freezing and UHI mitigation of concrete pavements. For this reason, the following sections are related to the prior literature on using PCMs in concrete pavement for anti-freezing and UHI mitigation applications.

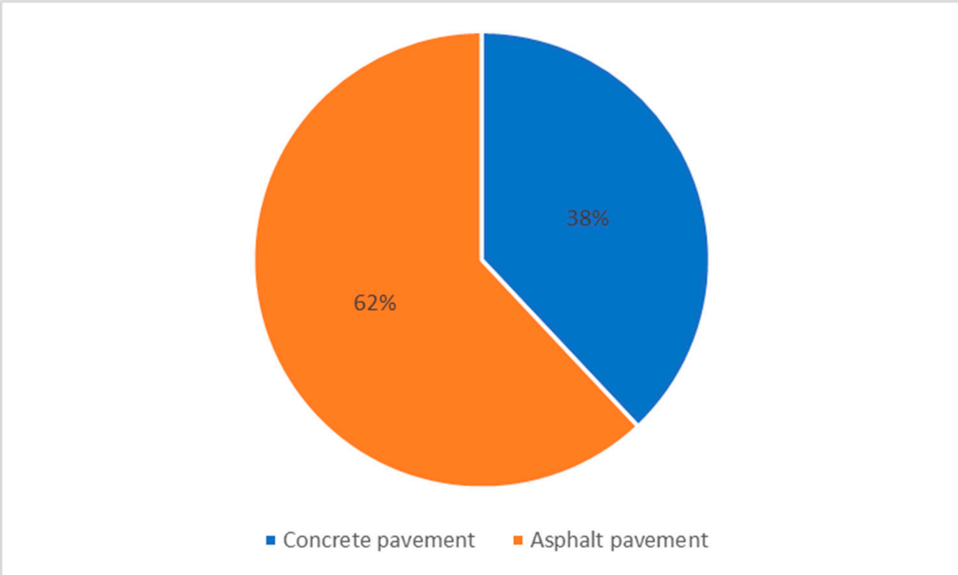

Figure 2. The number of publications on the PCM asphalt pavement vs. PCM concrete pavement during 2016-2022.

2. Phase change materials (PCMs) in concrete pavements

One of the most promising methods for increasing the thermal energy storage of pavement is incorporating Phase change materials (PCMs). Incorporating PCMs into the concrete can increase heat storage capacity by minimizing temperature fluctuation despite heat transfer to/from materials[71,72]. By heating a PCM, the temperature rises before solidus temperature (T_s) and after liquidus temperature (T_l). It should be noted that the temperature of PCM does not change by heating/cooling of the PCM between T_s and T_l, and only the phase of material changes (Figure 3). The solid and liquid phases are available during this process and their amount changes over time. The fraction of liquid phase (f_l) and solid phase (f_s) as a function of temperature can be calculated by the following equations [66]:

$$f_l(T) = \begin{cases} 0 & T < T_s \\ \frac{T-T_s}{T_l-T_s} & T_s \leq T \leq T_l \\ 1 & T_l < T \end{cases} \quad (1)$$

$$f_l = 1 - f_s \quad (2)$$

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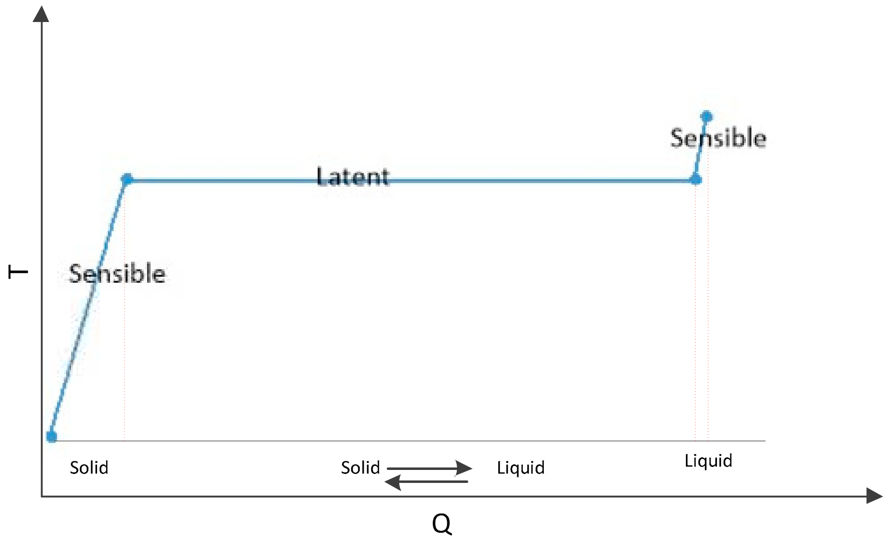

Figure 3. Temperature vs. heating or cooling during sensible and latent heat storage capacity.

Thus, the energy equation for the PCM based on the enthalpy can be written as follows:

$$(f_s\rho_s C_{ps} + f_l\rho_l C_{pl})\frac{\partial T}{\partial t} = \nabla.(k_{eff}\nabla T) - \left[(\rho_l C_{pl} - \rho_s C_{ps})(T - T_m) + \rho_l l_f\right]\frac{\partial f_l}{\partial t} \quad (3)$$

Where k_{eff} is $f_s k_{s+} f_l k_l$, T_m is the melting temperature ($T_m = T_s + \varepsilon$, $T_m = T_l - \varepsilon$, $\varepsilon > 0$), and l_f is the latent heat of fusion.

It should be noted that the PCM is incorporated into the concrete pavement in different percentages and methods, which are discussed in section 2.2. Thus, the pavement temperature is not constant during the phase changing of PCMs in actual conditions; however, it can fluctuate less than the pavement without PCMs. Athukorallage et al. [66] suggested the following model for the heat transfer in a pavement layer containing different amounts of PCMs:

$$((\emptyset(f_l\rho_l C_{pl} + f_s\rho_s C_{ps})) + (1-\emptyset)(\rho C_{ppa}))\frac{\partial T}{\partial t} = \nabla.(k_{eff}\nabla T) - \left[\emptyset(\rho_l C_{pl} - \rho_s C_{ps})(T - T_m) + \rho_l l_f\right]\frac{\partial f_l}{\partial t} \quad (4)$$

Where $\emptyset$ is the volume fraction of PCM in the matrix, C_{pa} is the heat capacity of pavement and k_{eff} is the thermal conductivity as a function of k_{pa}, k_{pcm}, $\emptyset$.

$$k_{eff} = \frac{k_{pa}(1-\emptyset)(2k_{pa} + k_{pcm}) + 3\,k_{pa}k_{pcm}\emptyset}{(1-\emptyset)(2k_{pa} + k_{pcm}) + 3\,k_{pa}\emptyset} \quad (5)$$

2.1. Type of PCMs in concrete pavements

As demonstrated in equations 2 and 3, selecting the proper PCM for different applications is related to the thermodynamic properties such as entropy (S), latent heat of fusion (l_f) (i.e., enthalpy (H)), and melting point (T_m) of PCMs. Entropy measurement during the changing phase is a challenging issue. However, the enthalpy of phase change and melting temperature can be measured using a differential scanning calorimeter (DSC). Figure 4 shows different PCMs categorized based on the enthalpy of fusion and phase-changing temperature [73]. Generally, organic, inorganic (MnH2O), and eutectic are the three main types of PCMs used in cement-based materials. Organic PCMs are paraffin-based (C_nH_{2n+2}) and non-paraffin-based $CH_3(CH_2)_{2n}COOH$ [74]. Salt hydrates and metal are the two main inorganic PCMs. Eutectics can be organic-organic, inorganic-organic, and inorganic-inorganic [75]. Recently, another classification was illustrated based on the state of PCMs as solid-liquid, liquid-gas, and solid-solid [76].

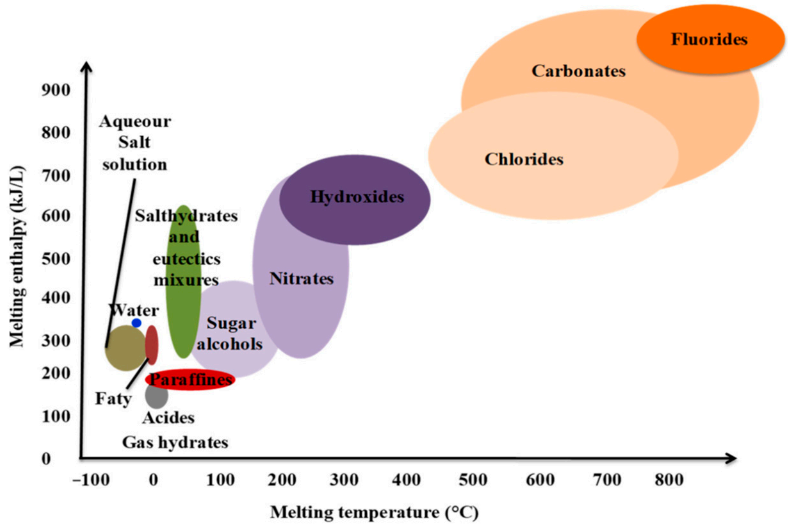

Figure 4. Melting point vs. heat storage capacity of various PCMs [73,75].

As mentioned previously, the phase change temperature of PCMs should be appropriate based on their application [29]. Prior literature showed that the latent heat of PCMs used in the concrete pavement for anti-freezing and UHI mitigation applications is 122 to 240.5 J/g. Besides, the phase change temperature of PCMs used in the concrete pavement for melting ice and anti-freezing purposes is slightly above zero (in the range of -0.5 to 5.7 °C). However, PCMs with higher phase change temperatures (temperature range of 28 to 51 °C) were applied for other applications, such as reducing the surface temperature of concrete pavement.

2.2. Methods of incorporation

Generally, the PCMs are incorporated into the materials by immersion, impregnation, and encapsulation (macro and microencapsulation) (Figure 5) [77–81]. Regarding the cement-based materials, the previous literature revealed that the incorporation of PCMs directly into the binder (cementitious system) might have significantly reduced the strength of concrete due to the displacement of some of the cementitious materials by the PCMs. This displacement minimizes the amount of cement paste to bind the aggregate together. Moreover, PCMs may interfere with the chemical reactions that occur during the hydration process of cement, which is critical for developing concrete strength. [82–84].

The following Ref. [74,85–89] have explained the methods of incorporating PCMs into the concrete. Impregnating PCMs in different carrier agents such as lightweight aggregates (LWA) or encapsulation is common to integrate PCMs into cement-based materials [90–93]. Moreover, the available literature revealed other methods to incorporate PCMs into the concrete pavement, such as immersion or pipes filled with PCMs. However, a few studies also used direct incorporation and immersion in concrete pavement. Table 1 summarizes the type, physical properties, and incorporation method of PCMs.

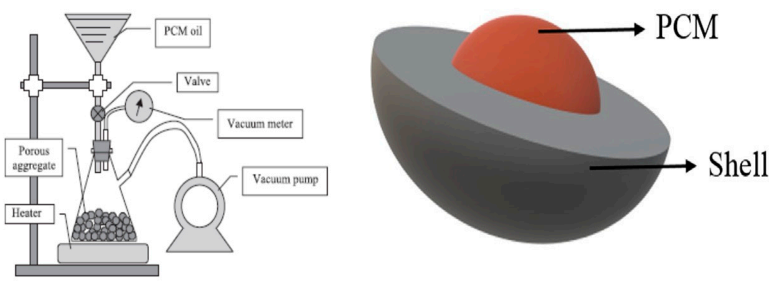

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Figure 5. Methods of PCM incorporation: a) impregnation [77], b) microencapsulated PCM [29], and C) using PCM in the concrete pavement through pipe adopted from [94].

Table 1. Physical properties and method of incorporation of PCMs into the concrete pavement.

Aim of using PCM in concrete pavement	PCM	Density (g/cm³)	Latent heat (J/g)	Phase change temperature (°C)	Method of Incorporation	Ref
Anti-freezing	Polyol	0.82	240.5	4.53	Pipe	[11]
	Paraffin	0.77	129.4	2.9	Using LWA and embedded tube	[95]
	Methyl laurate	0.87	160.4	1.9		
	Paraffin oil (C_{14}-C_{16})	0.77	157.8	5.7	Impregnation Pipe	[94]
	Paraffin (C_{14}-H_{13})	0.75	224.5	4.5	Microencapsulate	[96]
	paraffin	0.88 (solid) 0.77 (liquid)	200	1-3	Impregnation	[59]
	paraffin	---	200-225	4.5	Microencapsulate	[97]
	Methyl laurate	0.87	---	5.2	Impregnation	[98]
	Paraffin (OP2E)	0.77	205	1-3		
	Paraffin (OP3E)	0.77	250	3-5		
	paraffin	0.75	193	4.5	Impregnation	[99]
	paraffin	0.77	122	2-2.5		
	paraffin	0.78	171	-0.5		
Reduce surface temperature	paraffin	---	150	28	Impregnation	[100]
	paraffin	0.86	180	45	Microencapsulate	[101]
	paraffin	0.96	172	48-51	Direct mixing	[102]
	paraffin	0.96 (solid) 0.87 (liquid)	171	34-35	Impregnation	[103]
	paraffin	0.90 (solid) 0.86 (liquid)	199	43-44		

In the impregnation method, the porous carrier agent (LWA is the most familiar carrier agent because of its high porosity and absorption capacity) is impregnated by liquid PCMs [59,94,95,98–100,104]. The porosity of LWA can be filled with liquid PCMs through the vacuum saturation technique (Figure 5a). Evaluation of the previous studies indicated that the water absorption capacity and size of LWAs (expanded shale, expanded clay, and expanded perlite) used as a PCM carrier are 9-250% and 0-8 mm, respectively. However, the water absorption capacity and size of normal coarse and fine aggregate depend strongly on the type of material. Still, examples are in the 0.4-0.57%, 5-20 mm, and 1-1.52%, 0-5 mm, respectively (Table 2).

The main disadvantage of impregnation in concrete pavement is the leakage of PCMs while changing phases. Therefore, encapsulating PCMs into a polymer shell before incorporating them into the mixture can reduce leakage and incompatibility problems [89]. The microencapsulation method encapsulates the micro-sized PCMs within the polymeric shells in different sizes from 1mm to 300 mm [105–107]. However, the typical core size (Paraffin) and the shell were reported to be around 40 mm and 2 mm, respectively [108]. The shell can protect the PCMs from environmental conditions and leakage (Figure 5b). prior literature revealed several advantages and disadvantages of microencapsulated PCMS [109,110]. One of the main advantages of this method is optimizing heat transfer because of the high surface area-to-volume ratio [88]. However, the low durability, low stiffness, and chemical and thermal stability of the polymer shell can be mentioned as the main drawbacks of this method [109].

It is expected to use water pipes to cool massive concrete [111]. Recently, the closed pipe system was applied to increase the heat capacity of concrete using liquid PCMS instead of water inside the pipeline [11,94,95]. The main advantages of this method are reducing the leakage and limiting the chemical and physical damage of PCMs if the pipes do not corrode, which may occur in the other methods. This method provided frost-resistant concrete pavement simply by avoiding concrete freezing. However, the practicality of this method is in doubt due to its cost and applicability in extremely cold countries like Norway, where temperatures remain below freezing for several months.

Table 2. Examples of physical properties of aggregate used in PCM concrete pavement.

Ref	Aggregate	Fineness modulus	Specific density	Water absorption capacity (%)	PCM absorption capacity (%)	Sieve size (mm)
[104]	Standard Sand	-	2.61	-	-	-
	Expanded shale LWA	-	1.5	17.5	-	-
[11]	River sand	2.5	-	-	-	-
	Macadam	-	-	-	-	5 -20
[95]	Expanded shale LWA	2.94	1.5	32±0.50 (vacuum)	18.8±0.50 (ambient)	0-5
[100]	LWA	-	1.5	17.5	13.3	-
[94]	Expanded shale LWA	2.94	1.5	32±0.50 (vacuum)	23.7±0.50 (ambient)	-
[96]	Standard sand	2.87	2.65	1.02	-	-
[59]	LWA	-	-	-	10	0-8
[97]	Crushed rock	6.5	2.69	0.57	-	ASTMC33
	crushed sand	2.74	2.58	1.53	-	
[46]	quartz sand	-	2.65	-	-	ASTM C778
[98]	Expanded clay A	-	-	25	6	2-5
	Expanded clay B	-	-	10	9	0-5
	Expanded perlite	-	-	250	200	3-5
	Broken expanded shale	-	-	9	-	0-5
	River sand	3.45	-	-	-	-
[99]	Standard sand	2.87	2.65	1.02		
	LWA artificially manufactured by mixing fly ash with dirt spoil	4.49	1.40	12	-	0-5
[102]	River sand	2.67	2.62	1	-	0-5
	crushed natural stone (10mm)	5.79	2.70	0.4	-	5-10
	crushed natural stone (20 mm)	7.02	2.70	0.41	-	10-20

3. The effect of PCMs on the mechanical properties of concrete pavement

Incorporating PCMs into concrete pavements may affect the mechanical properties differently. Incorporating PCMs in concrete pavements can impede the chemical reactions that happen during the hydration process of cement, which is essential for the formation of CSH and concrete's strength development. This hindrance can slow down or lessen the rate of hydration, leading to a reduction in the amount of CSH produced and weaker concrete. Also, using LWA as a PCM carrier agent decreases the strength of cementitious materials due to its pore structure compared to natural aggregate [82,92,112]. In a study, 10% LWA as sand replacement on a volumetric basis decreased the compressive strength by 2%. However, incorporating LWA and Rice Husk Ash (RHA) presoaked in PCM decreased the compressive strength of cementitious materials by 10% and more than 35%, respectively [104]. Due to its high absorption capacity, RHA is investigated as a PCM carrier agent in cementitious materials. It is reported that using RHA decreased compressive strength by about 28%.

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However, incorporating PCMs into cementitious materials with the RHA decreased the compressive strength by 36%.

Decreasing the compressive strength with the use of PCMs filled in the LWA in concrete is reported by other studies, which is due to the chemical interaction of leaked PCMs with hydration products, which cause expansion and cracking and decrease the connection at the interfacial transition zone (ITZ) [112,113]. ITZ is a **region between the** aggregate particles and the bulk cement paste [114]. However, it is reported that coating the LWA as a PCM carrier agent with a capillary crystalline waterproofing material and Portland cement can prevent PCM leakage. The investigation showed that cement as a coating material might be beneficial for providing a proper ITZ and preventing leakage of PCM [98].

When PCMs are directly added to cementitious materials, the compressive strength decreases significantly, which could be attributed to its destructive effect on the hydration reaction and reduction in ITZ connection [82,92,104]. It is reported that the compressive and flexural strengths of cementitious materials containing raw PCM are lower than specimens containing PCM filled in LWA [99]. The results indicated that incorporating 10% and 15% PCMs (by mass of cement) filled in LWA and raw PCM decreased the compressive strength by 13%, 18%, 27%, and 36%, respectively. Also, the flexural strength for specimens with 10% and 15% PCMs (by mass of cement) filled in LWA decreased by 5.5% and 7%, and for samples with raw PCMs by 8% and 14%, respectively[99]. However, the investigation showed that the PCMs could be directly mixed in the concrete pavement in both solid and liquid states. The results showed that the specimens in the dry state had higher compressive strength values than those in the liquid state. According to the IRC 58:2015 standard for concrete pavement, which limits the 28-day compressive strength to more than 40MP, the PCMs by 6% and 8% at liquid and dry states can be used in concrete pavement, respectively [102].

According to another study, cementitious materials' compressive and flexural strengths were negatively impacted by the microencapsulation of PCMs with a melamine-formaldehyde resin. Incorporating 10% and 20% microencapsulated PCMs (by cement mass) decreased the compressive strength by 27.7% and 46.9%, and the flexural strength reduced by 17.5% and 22.3%, respectively [96]. Microencapsulated PCMs make voids in the matrix and cracks in cementitious materials, leading to decreased compressive and flexural strengths. Also, the structure of microencapsulated PCMs inside the cementitious materials is weaker than cement hydration products, which could be considered a weak point for failure [112,115–117].

Thus, incorporating PCMs into the concrete pavement (i.e., LWAs, directly and by microencapsulation) could decrease its mechanical properties by about 46%. However, considering the required costs and advanced technology for manufacturing microcapsules and high strength decrease for microencapsulation and direct methods, using LWA as a PCM carrier agent could be recommended. Notably, using cement or any other coating material might be beneficial for providing a proper ITZ and preventing leakage of PCM. According to previous studies, Figure 6 shows the percentages of compressive strength reduction with the incorporation of PCMs filled in LWA, raw PCMs, and microencapsulated PCMs compared to the control mixture (without any PCM) [86,97,102]. All the percentages of PCMs in this figure are by mass of cement.

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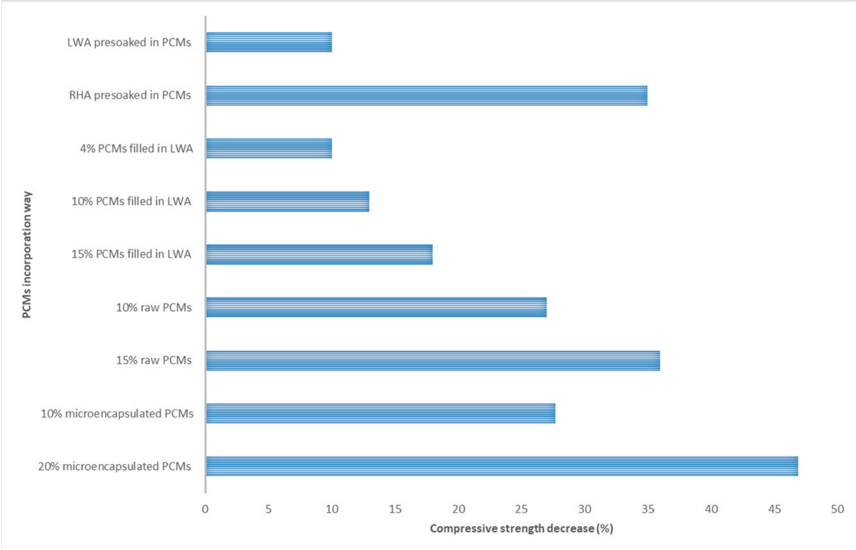

Figure 6. Percentages of compressive strength reduction with the incorporation of PCMs in cementitious materials.

4. The effect of PCMs on the heat of hydration of concrete

The heat released during hydration can be divided into typically four stages: initial, dormant, acceleration, and retardation. The maximum heat of hydration is usually released during the acceleration and the post-acceleration phase, which typically takes place between two and ten hours [118]. Some countries, such as China, Japan, and Korea, have been developing a new technology that can reduce the heat of hydration by encapsulating PCMs [119]. Generally, there is an inverse relationship between the amount of heat released during the hydration process and the mechanical properties of concrete. Also, a higher amount of heat of hydration contributes to the micro-cracking of massive concrete elements, leading to lower mechanical performance during service life [120]. Therefore, incorporating materials with latent heat storage capacity, i.e., PCMs, into cementitious materials is receiving increasing interest among researchers worldwide.

Fernandes et al. [121] used paraffin-based microencapsulated PCMs in cement mortars and reported a reduction in peak temperature during cement hydration. In another study [120], a small amount of two paraffin-based microencapsulated PCMs (up to 1% in weight of cement) with different melting temperatures of 18 and 25°C were used in cement-based cubes. The results showed a decrease in the internal temperature of the cement paste by 5°C. Mihashi et al. [122] applied a retarder containing PCMs in a paraffin microcapsule to control the heat of hydration. They reported that the maximum temperatures in semi-adiabatic curing could be reduced in large concrete specimens. Choi et al. [123] investigated different types of inorganic PCMs in conditions similar to concrete materials. They found a strontium-based PCM the most appropriate to decrease the heat of hydration in mass concrete. Yun et al. [87] evaluated the feasibility of adding strontium-based powder ($Sr(OH)_2$-$8H_2O$) PCMs into concrete to mitigate the hydration heat of mass concrete. The mixed PCMs in concrete were 3% of the weight of the binder. The results showed a delay in initial and final setting time and about a 15–21% decrease in the temperature rise of concrete.

Therefore, incorporating PCMs into the concrete pavement could considerably decrease the heat of hydration. In addition, the thermal cracking could be reduced by adding PCMs into the concrete mix. However, very few investigations exist in the literature on the relationship between the uses of PCMs and thermal cracking in concrete. Thus, future studies on these issues can explore more critical findings.

5. Frost-resistant concrete pavement with PCMs

PCMs can meet various working temperatures (see Figure 4). Researchers invested in using phase change materials (PCMs) in concrete pavements as an anti-freezing and snow-melting method.

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They evaluated the impact of PCMs on the thermal response of concrete pavements in cold winter regions through experimental and numerical simulation frameworks utilizing finite element analysis [11,93–96,98,124,125].

The results of studies indicated that utilizing PCMs can prevent ice formation and decrease the number of freezing-thaw cycles in concrete due to the release of heat during phase changing. Moreover, some of these studies reported that PCMs could increase the service life of pavements due to the prevention of sudden temperature drops. Also, the results showed macro encapsulation of PCMs via LWA had desirable performance to maintain a temperature of concrete pavement above 0° C.

In summary, limited studies consider the effect of PCMs on concrete pavement freezing compared to other applications like UHI. As mentioned, most reported that incorporating PCMs can effectively increase freeze-thaw resistance and ice melting. However, the effectiveness of PCM can be related to the amount of utilization, latent heat of fusion, and, of course, the phase-changing temperature. Table 1 demonstrated that the literature's phase-changing temperature of applied PCMs varies from -0.5 ° C to 5.7 ° C. The results seem acceptable for regions with mild snow and moderate winter. However, the efficiency of utilizing PCMs in areas with severe cold winters is a controversial issue. For example, the air temperature in many Nordic countries like Norway regions remains below 0 for several months.

In this study, therefore, we applied a Python script to simulate the effect of volume and phase changing point of PCM on the surface temperature of concrete pavement. We simplified the heat transfer in one direction while the air temperature was sinusoidal (See Appendix A). Selected phase change materials that undergo a phase change within the temperature range of minimum and maximum air temperatures were utilized to replicate the surface temperature of concrete pavements, both with and without PCM, in various locations, including Trondheim (Norway), Beijing (China), Zanjan (Iran), Berlin (Germany), and New York (US). Historical air temperature data for January 15 from 2010 to 2023 were gathered from World Weather Online (https://www.worldweatheronline.com). Table 3 shows the maximum surface temperature increment ($T_{s\ with\ PCM}$-$T_{s\ without\ PCM}$) by applying 5% to 20% PCM. It should be noted that the phase change temperature is assumed to be equal to the temperature that makes the maximum differences.

Table 3. Surface temperature with and without PCM.

Location	Average air temperature at the 15th January (° C)		Surface Temperature difference (° C) Maximum ($T_{s\ with\ PCM}$-$T_{s\ without\ PCM}$)		
	Min	Max			
Trondheim	-8.2	-4.2	f= 0.05	Tm= -3	1.9
			f= 0.1		2.5
			f=0.15		2.6
			f= 0.2		2.8
Beijing	-7.0	0.2	f= 0.05	Tm= -2	2.8
			f= 0.1		3.3
			f=0.15		3.5
			f= 0.2		3.6
Zanjan	-5.5	2.5	f= 0.05	Tm= -0.5	2.9
			f= 0.1		3.3
			f=0.15		3.5
			f= 0.2		3.6
Berlin	-0.1	4.0	f= 0.05	Tm= 2	0.9
			f= 0.1		1.0
			f=0.15		1.0
			f= 0.2		1.0
New York	-2.5	3.5	f= 0.05	Tm= 0	1.7
			f= 0.1		1.9
			f=0.15		2.0
			f= 0.2		2.0

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According to the findings, the choice of PCM for preventing freezing depends on the specific weather conditions of the location. For Zanjan and New York, for example, it seems likely that PCM can bring the surface temperature above freezing. For Trondheim, it seems less likely. (More detailed simulation examples are given in Figure 8 and discussed further). Moreover, it's important to mention that the surface temperature difference in Table 3 represents the maximum variation between the surface temperature of concrete with and without PCM. However, in some instances throughout the day, the surface temperature of concrete with PCM is lower than that of concrete without PCM, as shown in Appendix B. Table 3 shows that PCM is ineffective on peak surface temperature in some specific melting points. Appendix B shows the effect of different phase-changing temperatures on the peak surface temperature of the pavement.

6. The effect of PCMs on the surface temperature and UHI phenomena

Generally, the UHI effect of pavement should be controlled by reducing its surface temperature. Pavement can significantly reflect a considerable amount of solar radiation to decrease the surface temperature. Using titanium dioxide (TiO_2), lime (calcium hydroxide), and/or colored coating are the usual methods to increase the reflection of concrete pavements [126,127]. Thermal properties of concrete pavements, such as thermal conductivity (k) and specific heat capacity (Cp), are also influential factors in their surface temperature [74,128–130].

Pavements are heated by the sun and increase the surrounding air due to poor thermal conductivity and heat capacity [131,132]. Thermal conductivity is a material property that demonstrates its capability in heat transfer through conduction [133,134]. It has been reported that the PCMs with higher thermal conductivity must change their phase faster. Also, a concrete pavement with higher thermal conductivity is desirable to reduce surface temperature and melt ice and snow [101]. The heat capacity of a material is its ability in heat storage capability. Concrete pavements with higher heat capacity are valuable for improving temperature stability against changing temperatures. Incorporating the PCMs increases cement-based materials' thermal performance [82,135]. Therefore, most researchers correctly hypothesized that incorporating the PCMs with concrete pavement can increase the heat capacity of pavement. However, incorporating the PCMs with the reflective coating is a proper method to enhance the cooling surface efficiency [136].

On the other hand, the surface temperature of pavement increases due to the absorption of solar radiation. The absorbed heat transfers to the lower layers through conduction. Also, the pavement's surface transfers heat to the surroundings through convection and radiation. The amount of heat transferred to the environment and the human body is related to the heat transfer coefficient and surface temperature. Thus, it is an excellent strategy to reduce pavement surface temperature for UHI mitigation by using PCMs.

Prior literature indicated that incorporating PCMs into the concrete pavement reduces the peak temperature and increases the time lag to reach the peak temperature. For example, the peak temperature of a mortar containing 1, 3, and 5% PCM was reduced by 9, 12, and 15%, and the time of reaching the peak temperature was 15, 18, and 22% Longer, respectively [83]. Another study predicted a 6-10 °C reduction in the peak temperature of concrete pavement when 5% of cement or aggregate is replaced by PCM [16].

In summary, this section presents the calculated or simulated PCMs concrete pavement surface temperature in the available literature. Sharifi and Mahboub [137] evaluated the surface temperature of samples in two different scenarios. In one design, the PCMs were incorporated into the entire samples; in another, the PCMs were incorporated into the top layer of concrete samples. The results revealed that the differences between the surface temperature of PCMs and non-PCM samples are not meaningful in the first scenario. However, they reported that increasing the thermal inertia just in the top layer of concrete (applying PCM in this layer) can significantly reduce the surface temperature of concrete pavement.

7. The chemical reaction of PCMs inside concrete

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Most organic PCMs are chemically stable, safe, recyclable, non-reactive, and compatible with conventional construction materials [124]. Also, organic PCMs do not suffer phase segregation and crystallize with little or no supercooling. However, most inorganic PCMs are corrosive to metals and undergo supercooling and phase decomposition [138]. There is limited data on the properties of many combinations of eutectic PCMs.

In most cases, chemical reactions between the PCMs and cementitious matrix, regardless of the incorporation, could result in fundamental problems inside the concrete. It has been observed that some PCMs leaking out of LWAs may chemically interact with hydration products, causing expansion and cracking [139]. An example of such a problem is given in the study by Wei et al. [117], who reported a 25% reduction in enthalpy of the phase change of PCM microcapsules due to a chemical reaction of the melamine formaldehyde shell with sulfate ions, causing the release of the core material and its reaction with the pore solution. The proposed mechanism is schematically described in Figure 7.

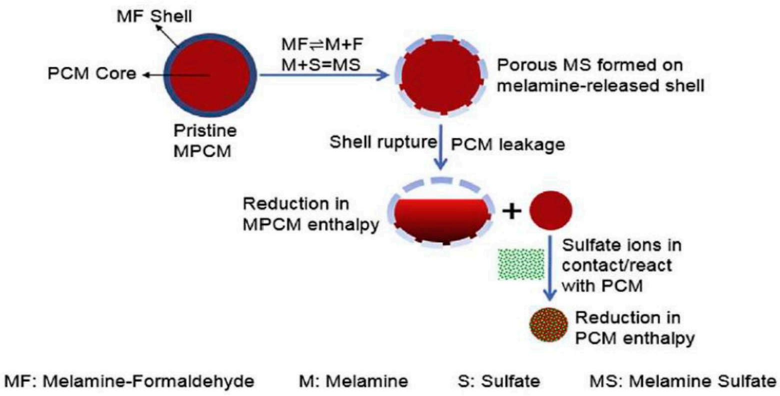

Figure 7. The proposed chemical interaction pathway results in enthalpy reduction of the PCMs following exposure to caustic solutions containing sulfate ions [117].

8. Discussion

Pavements cover up to 45% of urban areas [28,100]. One of the main distresses of pavements in the cold region is freezing, which causes them to face different types of cracking [96]. Reversely, many cities face the UHI. Thus, the surface temperature of concrete pavement is one of the main reasons for the freezing and UHI phenomena. Usually, the surface temperature is higher during daytime (solar radiation) and is lower than the ambient during nighttime (radiation from the surface to the sky) [140].

Regarding the freezing problem, several solutions have been proposed, such as entraining air voids [141], using high-strength concrete to avoid the need for air entrainment, making use of anti-freezing additives [142], utilizing fly ash or slag as supplementary cementitious materials [143], applying super absorbent polymer [144], and incorporating PCMs [96]. Regarding the UHI mitigation, Santamouris [145] suggested the following ways to reduce the surface temperature of pavements: i) enhancing the albedo of pavements by using lightweight aggregates, involving resin-based pavements, applying colorless reflective binders, adding fly ash, replacing gray cement by white cement, applying infrared-reflective, etc., ii) enhancing the evaporation process by increasing the porosity, permeability, etc., iii) decreasing the solar absorption by using shading, IV) dissipating the excess heat using water tubes as the cooling systems, and V) increasing the heat capacity of pavement using PCMs. Therefore, incorporating PCMs into the concrete pavement can be a good solution to decrease the surface temperature during daytime to mitigate UHI effect and increase temperature during night to protect freezing in cold regions due to its high latent heat of fusion [146–148].

The surface temperature of pavement is a function of several factors that affect the surface heat transfer coefficient a_c (W/m^{2}K) [149], such as air temperature, humidity, airspeed, solar radiation, etc. Generally, the maximum and minimum peak temperature differences ($T_{max, PCM}$ - $T_{max, control}$) or ($T_{min,}$

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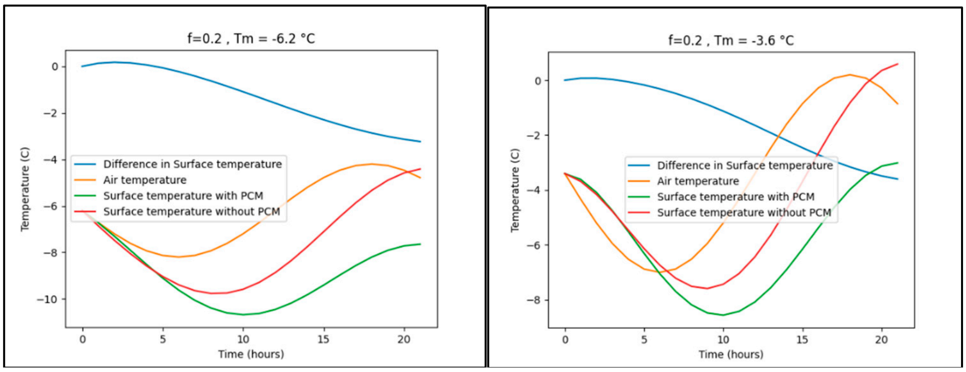
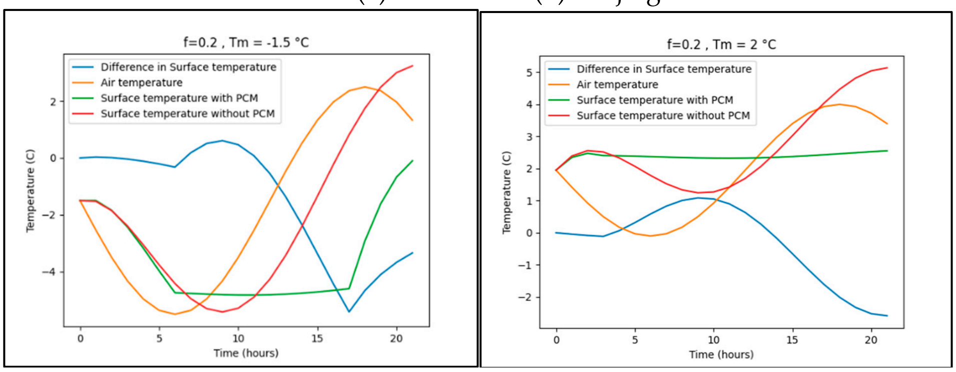
$_{PCM} - T_{min, control}$) can be varied based on the phase change temperature of PCMs and climate conditions. A study revealed that the maximum surface temperature of the control sample is higher than that of the PCM sample. Its minimum surface temperature is lower than the PCM sample [150]. It was attributed to the heat released by PCM while changing the phase. Thus, it can help the pavement reduce the UHI effect and melt ice and snow. These results agree with Ref. [102], which demonstrated that the temperature differences were reduced by adding PCMs to the concrete pavement.

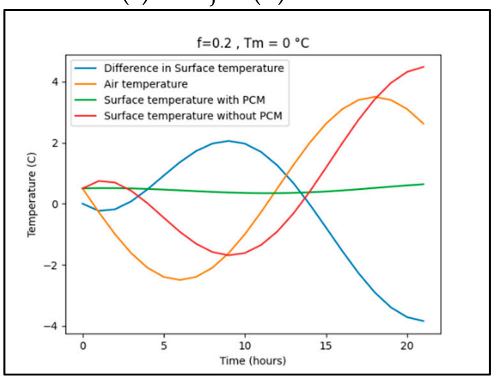
As reported in Section 5, there is a lack of knowledge about the effect of PCM on unfreezing concrete in icy regions. We simulated the effect of PCM on the surface temperature of concrete with and without PCM in these areas. Figure 8 shows the maximum difference in surface temperature of concrete pavement in different regions when 20% PCM with the phase-changing temperature of the average air temperature is applied in concrete (Table 3). Figure 8 shows simulation details that for 20 % of the actual PCM (melting temperature assumed equal to the average air temperature), only in Berlin and New York is 20 % PCM capable of keeping the surface above freezing. It should be noted that this is a simplified simulation of heat transfer in one direction to find out the peak difference. In real conditions, such a wide variety of conditions are effective on pavement surface temperature with PCM. For more realistic fluctuation in the surface temperature of pavement with/without PCM, see the finding by Nayak et al. [151], Yeon [99], and Somani and Gaur [102].



(a):Trondheim (b): Beijing



(c): Zanjan (d): Berlin



(e): NY

Figure 8. The effect of PCMs on the surface temperature of the pavement.

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However, there are some drawbacks to PCM concrete pavement, such as PCM leakage, the low thermal conductivity of PCMs, and strength reduction of the pavement due to insufficient strength of PCMs, delaying hydration and increasing the porosity [152–156]. Although there has been an increasing publication trend in recent years, there is still a lot of unknown knowledge related to using PCMs in concrete pavement. Thus, concerning the prior literature, some recommendations can be made for future work:

A. Thermal conductivity:

A.1) the surface temperature and temperature differences between different layers of concrete pavement are a function of several factors such as emissivity, absorptivity, thermal conductivity, heat capacity, wind speed, climate, etc. The heat capacity of concrete pavement is enhanced by incorporating PCMs. However, the thermal conductivity of concrete pavement has an essential role in the speed of heat transfer. The higher thermal conductivity accelerates the heat transfer from the surface to the other layers. Thus, considering the thermal conductivity of PCM concrete pavement is suggested for future studies.

A.2) concrete pavement with higher thermal conductivity will transfer the heat faster to the bottom layers. This is an excellent strategy to cool the surface more quickly. However, the stored heat in the bottom layers will return the heat to the top at night. It should be noted that the backing heat to the first layer is less than the initial value due to the soil's higher heat capacity and moisture availability. However, the top layer releases heat to the surface faster, which still affects energy consumption by the occupants of buildings. Thus, pavement design with higher thermal conductivity cannot be suitable in hot regions with warm nights. Therefore, it is suggested to conduct new studies considering high and low thermal conductivity for PCM concrete pavement in different climate conditions.

A.3) As mentioned, the high thermal conductivity of PCM concrete pavement is controversial and can have a diverse effect on UHI mitigation. Therefore, it is suggested to design, measure, and calculate the surface temperature of PCM concrete pavement when the PCM is applied in different layers to manage the backing heat to the top layer—for instance, using PCM concrete as a surface layer or as the sub surfaces layers.

B. PCMs:

B.1) The leakage of PCMs in the encapsulation method is a serious problem. Also, the efficiency of other types of incorporations needs improvement. Therefore, new technologies and innovative incorporation seem to be necessary.

B.2) The stability of PCMs in concrete pavement needs more consideration. The pavement is under different loads, and fatigue should be severe. Therefore, the behavior of PCMs should be evaluated under loaded conditions.

B.3) Solidification's latent heat can increase the PCM concrete pavement's temperature. Thus, more evaluation must limit the UHI effect during nighttime for a region with warm nights.

C. Energy and environment:

C.1) One of the main reasons for using PCMs in concrete pavement is to reduce city energy consumption. It is suggested to design studies to evaluate the effect of PCM concrete pavement on the city's temperature and the annual energy consumption of buildings.

C.2) The environmental impacts of PCM concrete pavement should be considered for different regions. Scanty studies regarding PCM concrete pavements' life cycle assessment (LCA) exist.

9. Conclusion

The current review discussed the importance of phase change materials (PCMs) in the concrete pavement to increase anti-freezing capability and mitigate urban heat islands (UHI). The prior literature revealed that PCMs could increase the surface temperature for anti-freezing purposes and reduce the maximum surface temperature for cooling pavement applications. Researchers used PCMs (most studies used paraffin-based PCM) with different phase change temperatures from -0.5°C up to 51 °C with different latent heat in 122 to 240.5 J/g. Based on limited results from available literature, PCMs with phase transition temperatures around the freezing point can decrease the number of freezing events in concrete. However, the usage of PCMs in concrete pavement areas with a long snowy and long sub-zero temperature period (like Nordic countries) is unknown. Thus, we developed a simplified heat transfer simulation in Python script to simulate the effect of PCM in these regions. One of the most significant future trends in concrete pavement is the unfreezing application of PCM in icy areas where knowledge is currently lacking.

Regarding UHI mitigation, PCMs in the concrete pavement can reduce the maximum surface temperature by up to 15%. However, it should be noted that the PCMs have several drawbacks in concrete pavements. The results indicated that incorporating PCMs into the concrete pavement reduces mechanical properties such as compressive strength. Also, the leakage of microencapsulation is another drawback. Therefore, the authors suggested investigating several research areas, including using different types of PCMs (excluding paraffin), developing multilayer concrete pavement with and **without PCMs** incorporated into the layers, and assessing the environmental impact and energy efficiency of PCM-concrete pavement.

Appendix A

Appendix A.1. Python code

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```
import numpy as np
W = 0.2  # Thickness of pavement (m),
A = 1.0  # Surface area of pavement (m^2) ,
rho_c = 2400  # Density of concrete (kg/m^3)
C_c = 880 # Specific heat of concrete (J/kg-K) ,
k_c = 2.3  # Thermal conductivity of concrete (W/m-K) ,
rho_p = 700  # Density of PCM (kg/m^3) ,
C_p = 1640  # Specific heat of PCM (J/kg-K) ,
k_p = 0.4  # Thermal conductivity of PCM (W/m-K) ,
h_p = 190000 # latent heat of fusion (j/kg)
f =   # Fraction of volume occupied by PCM,
dTm = 0.5  # Temperature range of melting process (C),
T_min =  # Minimum air temperature (C),
T_max = # Maximum air temperature (C),
Tav=(T_max +T_min)/ 2
Tsk= (Tav+ 273)+3*((Tav+273)/100)**0.5
h_conv = 36  # Heat transfer coefficient for convection (W/m^2-K) ,
epsilon = 0.9  # Emissivity of pavement,
sigma = 5.67e-8  # Stefan-Boltzmann constant,
tmax = 24 * 3600  # Maximum simulation time (s)
dt = 3600  # Time step (s),
t = np.arange(0, tmax, dt)  # Time grid (s) ,
N = len(t)  # Number of time steps
Tinf = ((T_max - T_min) / 2) * np.sin((2 * np.pi * t / tmax) + np.pi) + ((T_max + T_min) / 2)
Tm_list = [, , ]
Ts = np.zeros(N)
Ts[0] = Tav
Tsw = np.zeros(N)
Tsw[0] = Tav
Tsky = np.zeros(N)+Tsk
Tc = np.zeros(N)
Tb = np.zeros(N)
for i in range(1, N-1):
   VHC_eff = rho_c*C_c
   qcond =  (k_c *A * ((Tsw[i-1])-(Tb[i-1])))/W
   qrad = epsilon * sigma * A * ((Tsky[i-1] ** 4)-(Tsw[i-1]+273.15 ** 4))
   qconv = h_conv * A * (Tinf[i-1] - Tsw[i-1])
   qtotal = qrad + qconv + qcond
   dTsdt = qtotal / ( VHC_eff* A * W)
   Tsw[i] = Tsw[i-1] + dTsdt * dt
   Tb[i] = Tb[i-1] + qcond / ( VHC_eff* A * W)* dt
for Tm in Tm_list:
   print("Running simulation for Tm = ", Tm)
   for i in range(1, N-1):
      rho_eff = rho_c * (1 - f) + f * rho_p
      if Tc[i-1] < Tm - dTm or Tc[i-1] > Tm + dTm:
         C_eff = C_c* (1 - f) + (f * C_p)
         VHC_eff = rho_eff * C_eff
      else:
         C_eff = C_c * (1 - f) + (f * C_p)
         VHC_eff = rho_eff * C_eff+ ((f*rho_p*h_p)/dTm)
      k_eff = (k_c * (1 - f) + (k_p * f * ((3 * k_c) / (2 * k_c + k_p)))) / (
               (1 - f) + (f * (3 * k_c) / (2 * k_c + k_p)))
      qcond1 = k_eff * A * ((Ts[i-1] - Tb[i-1])) / W
      qrad1 = epsilon * sigma * A * ((Tsky[i-1] ** 4)-(Ts[i-1]+273.15 ** 4))
      qconv1 = h_conv * A * (Tinf[i-1] - Ts[i-1])
      qtotal1 = qrad1 + qconv1 + qcond1
      dTsdt = qtotal1 / (VHC_eff * A * W)
      Ts[i]=  Ts[i-1]  + dTsdt * dt
      Tb[i]=  Tb[i-1] + qcond / (VHC_eff * A * W) * dt
      Tc[i] = (Ts[i] + Tb[i]) / 2
   max_diff = max([t1 - t2 for t1, t2 in zip(Ts, Tsw)])
   print(max_diff)
   import matplotlib.pyplot as plt
   fig, ax = plt.subplots()
   plt.plot(t[:22]/3600, Ts[:22]-Tsw [:22], label='Difference in Surface temperature')
```

Appendix B Difference surface temperature for various phase changing temperature

Appendix B.1. Trondheim

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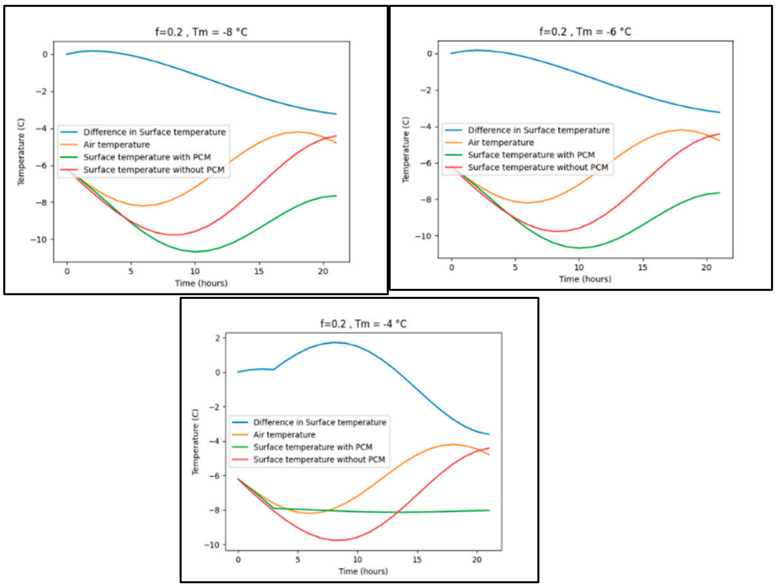
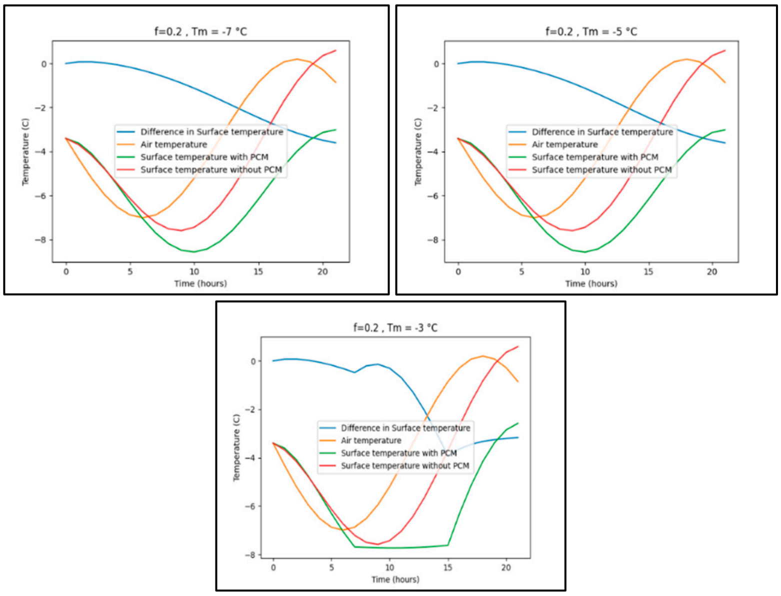


Appendix B.2. Beijing



Appendix B.3. Zanjan

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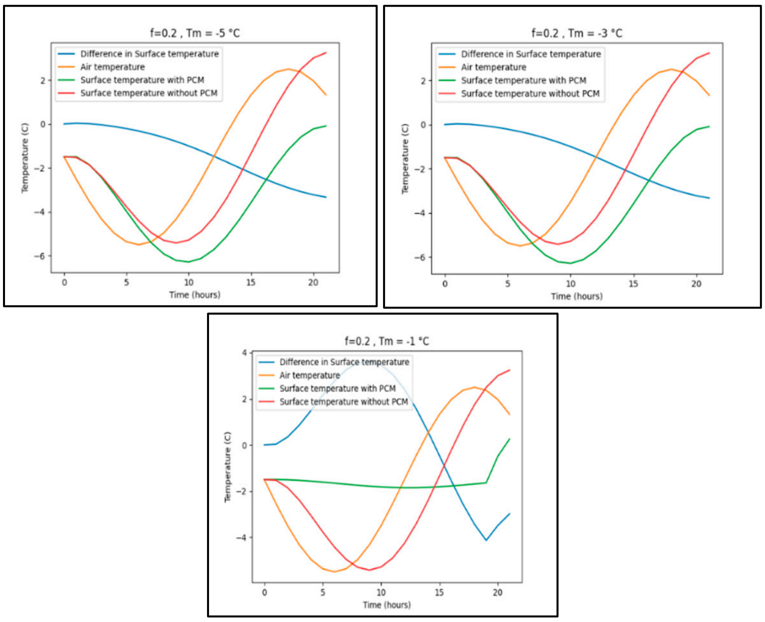
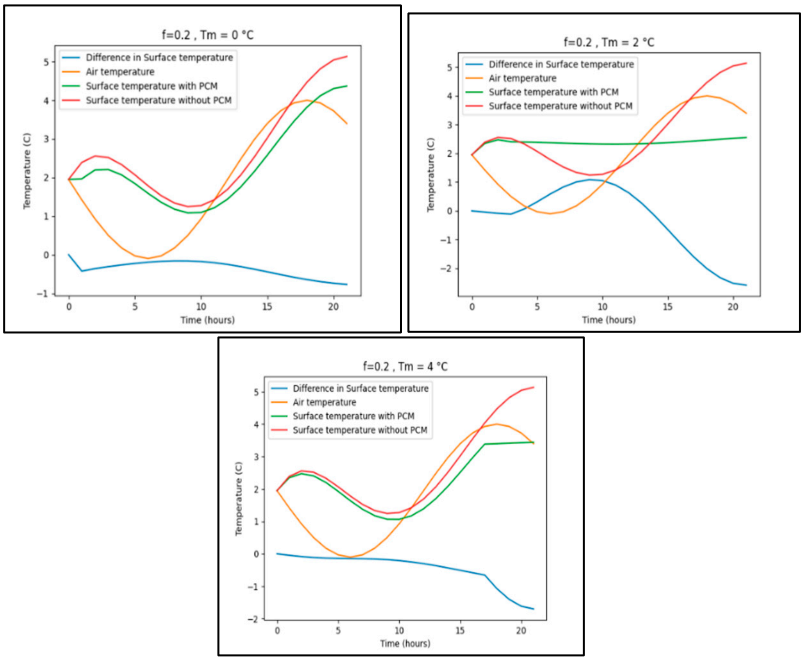
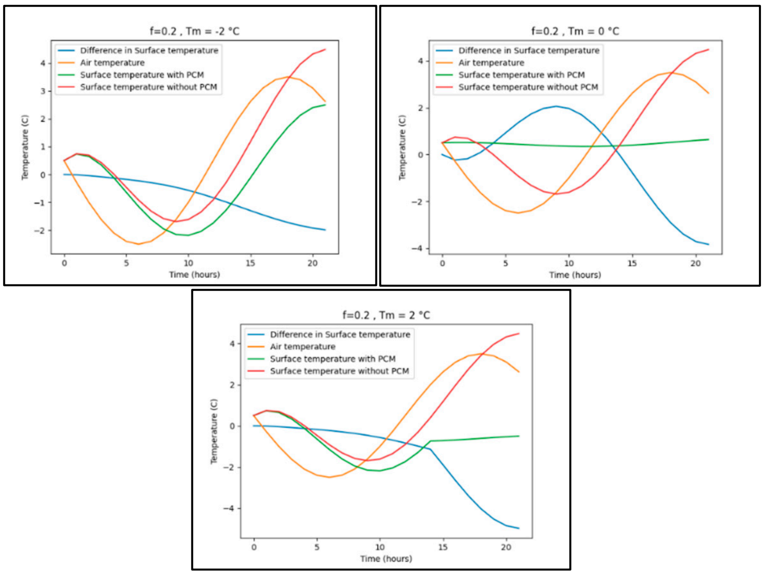


Appendix B.4. Berlin



Appendix B.5. New York



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