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A comprehensive review on sustainable rigid pavement materials using PCM

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ABSTRACT

Increased pavement temperatures also help in the urban heat island effect and thermal distress in pavements. Extremely low temperatures of pavements induce freeze-thaw damage and low temperature cracking. Pavement applications of phase change materials (PCMs) to mitigate temperature extremes are an emerging area of investigation. Incorporation of PCM into pavements can minimize high and low levels of temperature extremes. PCMs have the ability to store energy in the form of latent heat without rising in temperature or in volume. Encapsulated PCMs are used for pavements to minimize leakage.

Keywords—Sustainable Rigid Pavement; Phase Change Materials; Energy efficient Rigid Pavement; Sustainable Infrastructure; Thermal Energy Storage; Green Urban Planning.

1. INTRODUCTION

The growing concerns about global warming, urban overheating, and localized climate change have sparked intense study interest in recent years. As urbanization accelerates, changing rural landscapes into expansive metropolis, it is anticipated that by 2050, a considerable share of the world population will reside in urban areas up to 66% [1]. This demographic movement not only alters the physical environment, but it also exacerbates environmental concerns, particularly the Urban Heat Island (UHI) effect. This phenomenon, defined by increased temperatures in metropolitan areas relative to their rural equivalents, is becoming a crucial issue of the twenty-first century [2]. The UHI effect, a result of urbanization, is caused by causes such as industrialized materials replacing natural terrains, heat emissions from urban constructions, and the disappearance of water bodies. This environmental hazard endangers human health, increases energy consumption, and exacerbates air pollution [3]. In light of these issues, the role of artificial pavements, which cover a large section of urban landscapes, has been called into question. Due to their high thermal inertia and darker surfaces, these pavements considerably contribute to the UHI effect by absorbing and storing solar heat [4]. Among these, cool pavements have emerged as an appealing solution. These technologies, which include reflecting pavements, evaporation pavements, heat harvesting pavements, and phase change materials, provide varied approaches to mitigating urban warming [5]. The study's goal is to provide an in-depth analysis of various paving technologies, examining their effectiveness in mitigating UHI effects. Reflective pavements, for example, are known for their cost-effectiveness and ease of application, but can cause glare issues, whereas evaporation pavements offer cooling benefits but require ongoing maintenance [6, 7].

2. BACKGROUND

Building on the foundation of early paths, ancient civilizations began to appreciate the value of more lasting and strategically built highways. The Roman Empire recognized for its engineering brilliance, revolutionized road construction [8]. They built huge road networks that not only served a practical purpose but also represented the empire's might and scope. These roads were precisely designed, with layers of materials for drainage and durability, and served military, commercial, and administrative reasons. The Roman method to road construction established a standard for future civilizations. The planned location and longevity of these roads improved connectivity over enormous territory, having a considerable impact on trade and military operations. The Roman roads were so well-built that certain pieces still survive today, demonstrating their engineering skill. The move from primitive trails to build roadways was a big step forward in human civilization. Roads became an emblem of civilization, promoting economic growth, cultural interchange, and administrative control [1].

3. ENVIRONMENTAL IMPACT

Roads emit a substantial amount of carbon dioxide, both during construction and when vehicles travel on them. When assessing the global climate change scenario, this factor is critical. Roads also contribute significantly to the development of urban heat islands, with materials such as asphalt absorbing and radiating heat, raising metropolitan temperatures. These ecological aspects are critical for determining the total environmental impact of road infrastructure. Nonetheless, the concept of sustainable road design has emerged as a critical solution in response to these environmental issues [9]. This method includes the use of eco-friendly materials and construction processes to reduce environmental effect. Sustainable road design seeks to reduce carbon emissions, minimize habitat destruction, and address the problem of urban heat islands. It integrates new methods including the use of permeable materials, vegetation integration, and smart planning to protect natural environments [10]. In India, flexible pavements have a 63% greater impact on abiotic depletion of fossil resources than rigid pavements, while rigid pavements have a 47% higher impact on acidification and a 198% increase in global warming. This shift toward sustainable infrastructure reflects a growing recognition of the need to balance development with environmental stewardship. In terms of CO_2 emissions, Major District Road (MDR) rigid pavements cut CO_2 by 69.60 and 18.97 tonnes, respectively, due to albedo and carbonation. In contrast, Major District Roads with flexible pavements emit 345 tonnes of CO_2. Furthermore, the deforestation associated with these projects results in a large carbon sink loss, with 76 and 228 tons of CO_2 equivalents per kilometer for flexible and stiff pavements, respectively. An uncertainty analysis of this study highlights the trustworthiness of these findings, with a standard deviation of less than 5% [11].

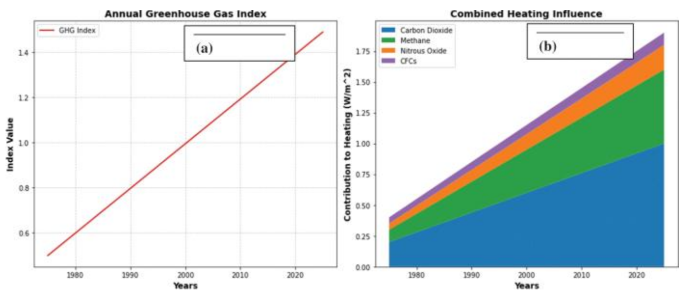

FIG. 1 ANNUAL GREENHOUSE GAS INDEX IN (A), COMBINED HEATING INFLUENCE (B) [11]

4. EFFECTS ON PAVEMENT DUE TO HEAT

The distress of rigid pavements attributed to heat effects is mostly owing to temperature and material behaviour-driven stresses. Here are the significant causes attributable to heat effects:

4.1. Warping Stress:

Concrete slabs warp or expand with higher temperatures. Lack of suitable expansion allowance in properly designed joints would result in overstress and induce warping cracks at joint edges. These cracks are worsened in areas of high day-to-night or seasonal temperature differences.

Warping stresses in rigid pavements arise due to temperature gradients across the concrete slab, primarily caused by daily temperature variations between the top and bottom surfaces. These stresses are critical in pavement design, as concrete's low tensile strength makes it vulnerable to cracking under tension. Here's a detailed breakdown:

4.1.1. Mechanism of Warping Stresses: Daily Temperature Variation

Summer Midday: The top surface heats up faster than the bottom, creating a temperature gradient. The top layer expands more but is constrained by the cooler bottom layer, inducing compressive stress at the top and tensile stress at the bottom.

Visualization: Imagine the slab curving downward (warping), with the top fibers compressed (→←) and bottom fibers stretched (←→).

Night time: The top cools faster, contracting more than the bottom. This reverses the stresses: tensile stress at the top and compressive stress at the bottom.

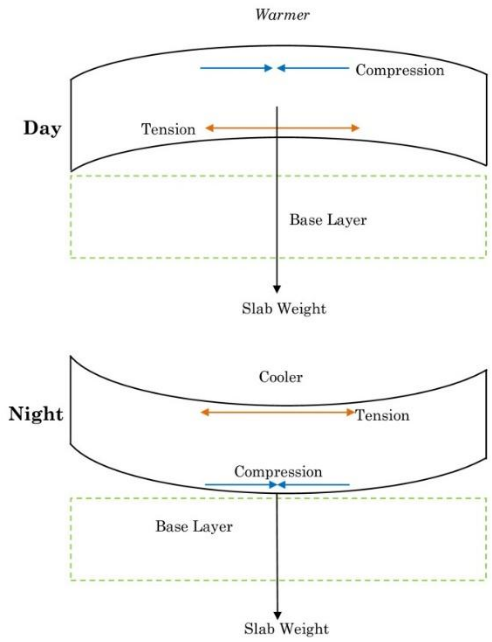

FIG. 2 WARPING STRESS [7]

Seasonal Temperature Changes: Summer Expansion: The entire slab expands longitudinally, inducing compressive frictional stresses along its length.

Winter Contraction: The slab contracts, creating tensile frictional stresses.

4.2. Thermal Gradient Stresses

Asymmetrical heating of the pavement surface induces thermal gradients, resulting in curling or warping of slabs. This may result in cracking or disconnection between the slab and the subgrade. The cyclical expansion and contraction due to daily or seasonal temperature fluctuations further degrade the pavement structure.

4.3. Shrinkage Cracks

Drying shrinkage is caused by heat accelerating evaporation of moisture from concrete, resulting in shallow, hairline cracks that compromise the pavement surface.

5. CLASSIFICATION OF RIGID PAVEMENT

5.1. Continuously reinforced concrete pavement (CRCP):

CRCP prevents transverse contraction joints through the utilization of continuous longitudinal reinforcement (typically 0.6% - 0.7% cross-sectional area). Pavement cracks randomly across, with mean spacing of 46 - 183 cm. Steel reinforcement closes fractures, permitting aggregate interlock to distribute load across crack interfaces. Grade 60 bars with minimum yield point of 420 MPa are commonly used for longitudinal steel reinforcement. Transverse steel in chairs reinforces the longitudinal steel and inhibits cracking (refer to Fig. 3). If well-constructed, CRCP provides satisfactory ride quality, can be surfaced with asphalt without reflection cracking, and has a long life. Under wet-freeze conditions, concrete pavements undergo both heat and traffic-induced strains. In addition, they are prone to freeze-thaw degradation. This renders them more vulnerable to initiation and growth of cracks in more than one direction. CRCP contain rebar in two directions. The supplied rebar effectively regulated longitudinal and transverse development of cracks, proving CRCPs to have potential performance under wet-freeze conditions. CRCP has several downsides, including expensive initial construction costs, difficulty in building, and higher repair costs compared to other pavement options. MDOT and Louisiana stopped utilizing CRCP in 1978 and 1975, respectively, due to premature failures caused by insufficient concrete slab thickness, poor base, rounded aggregate, and/or poor construction method, as well as bad subgrade conditions [12].

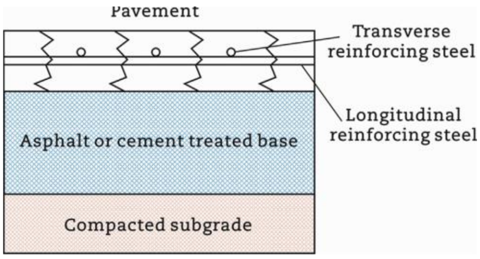

FIG. 3: CONTINUOUSLY REINFORCED CONCRETE PAVEMENT [13]

CRCP has higher initial cost because it is reinforced (usually 0.06%-0.07% longitudinally). DOTs and municipal authorities might be reluctant to adopt CRCP technology because they need to provide a higher level of care during construction compared to JPCP. Although there is less maintenance required for CRCP compared to JPCP, its maintenance strategies are more costly and demanding [14, 15]. CRCP is economically beneficial due to its excellent performance, durability, and reduced life-cycle costs. It also has good performance under wet-freeze conditions. Pavement concrete in wet-freeze areas tends to degrade as a result of repeated cycles of freeze-thaw. When water is freezing, it expands and tends to open cracks wider, with more water fitting in the next freezing cycle. Eventually, repeated cycles result in pavement failure. CRCP relies on continuous rebar to restrict cracks from getting wider [15].

5.2. Precast concrete pavement: As reported by Tayabji et al. [16], precast concrete pavement (PCP) is a widely used repair technique that enables rapid replacement of concrete damage and lengthens construction seasons. This method reduces on-site construction and curing time, and thus properly designed and well-built PCP is an expedient deployable option for new or rehabilitating high-volume road sections [17]. PCP is of two types: precast jointed concrete pavement (PJCP) and precast post-tensioned concrete pavement (PTCP). PCP uses ingredients similar to cast-in-place concrete pavements, but the composition has been tuned for precast operations. Many PCP systems employ proprietary components, such as joint load transfer systems, pre-stressing hardware, and expansion joints [16]. Recently, proprietary leveling devices were added at slab corners. PCPs are often utilized on high-traffic roads, thus they should be constructed to resist these conditions [16]. The design should consider stress and deflection, 28-day compressive strength, flexural strength, aggregate interlock, load expectancy for dowel bars at joints, and slab curling from temperature gradients [16]. PCP panels are cast at a factory and stored for 14 days before they are loaded onto a truck and transported to the site. The handling of the panels, which is otherwise done using a four-point lifting system, is an important consideration [16]. Installation is laid out by the National Precast Concrete Association [17] as requiring removal and preparation of the sub base, laying of the precast slab, levelling and grouting, backfilling load transfer slots, and sealing joints. Precast concrete slabs can potentially live longer than cast-in-place concrete as they are made and cured in a controlled setting. Employing high cementitious materials and accelerators during PCP production can improve early-age strength, which can enable bed flipping at a quicker rate and production in 24 hours. Precast panels are more costly initially compared to the conventional DOT repair practices, which means that their employment is only cost-effective whenever user delays translate to large amounts of expenses. Lane closures for extended periods are typical where high traffic volumes are experienced, contributing to higher fuel costs and productivity loss [18]. Incorrect installation of PCP may lead to damage of the adjacent concrete pavement, poor load transmission, and uneven slab support, which result in a reduced service life for the precast slabs. PCP slabs are cast at a manufacturing factory, which means the manufacturer is in charge of the materials, build, and curing process. This presents several benefits. PCP panels are cast and cured in a factory, where they achieve design strength under optimal conditions. This renders them ideal for paving in wet-freeze environments [16].

5.3. Self-consolidating concrete pavement: The research team suggests re-evaluating the use of self-consolidating concrete (SCC) for pavements as more research emerges. Wang et al. [19] report self-consolidating concrete (SCC) pavement that uses a concrete mixture consolidating through its own weight. The concrete mixture is designed to flow easily and fill gaps with minimal mechanical vibration in paving [17, 19]. The proportion of cementitious material, aggregate, and additive is chosen based on the inverse proportion between shear rate and yield stress/viscosity. Self-consolidating concrete mixtures typically have a flexural strength of around 4.55 MPa and compressive strength ranges from 32.5 to 52.5 MPa [20].

6. APPLICATION OF PCM AS PAVEMENT MATERIALS

High pavement temperatures cause thermal distresses in pavements and the urban heat island effect. Extremely low pavement temperatures lead to low temperature cracking and freeze-thaw damage. PCM can be used to limit pavements' exposure to both higher and lower temperatures. With little change in volume and no increase in temperature, PCMs can store energy as latent heat. To reduce PCM leakage, encapsulated PCMs are utilized in pavements. There has been a concerted effort worldwide to reduce the negative impacts of infrastructure development on the ecosystem and environment. The urban surface temperature has increased by roughly 10 to 21 degrees Celsius relative to the ambient air temperature as a result of the conversion of natural landscape into artificial constructions.

Additionally, the high temperature in asphalt pavement causes rutting, bleeding, and binder adhesion to tires by lowering the binder's stiffness. With every 10 degrees Celsius increase in temperature, the rate at which asphalt pavements oxidize about doubles, causing early aging, stiffening, and the emergence of premature cracks. Lowering the temperature of asphalt pavement can lower the binder's quality requirements. Transverse, longitudinal, and corner fissures are caused by repetitive temperature curling in concrete pavements. Transverse, longitudinal, and corner cracks are caused by repetitive temperature curling in concrete pavements. Reduced pavement temperature may limit the thermal strains created in concrete pavements, as higher temperature differential was identified as the primary cause of cracking.

Therefore, it was necessary to create cool pavement technologies that had as little negative environmental impact as possible. By absorbing heat energy from the pavement, PCM undergoes phase change as the pavement temperature rises above its phase change temperature, helping to lower the pavement temperature. Therefore, one potential method of attaining both greater and lower temperature regulation in pavements is the integration of PCMs. Latent heat storage materials can store relatively more energy per unit mass without much temperature variation, even though heat energy can be stored in a material by increasing its temperature (sensible heat storage), changing its phase (latent heat storage), changing the intermolecular bond (thermochemical energy storage), or a combination of these methods. So, there has been much more research on the various options for adding PCMs to pavements.

6.1. Phase change materials for pavements:

PCMs may store a significant quantity of thermal energy and have a high latent heat of fusion [21]. When compared to other heat storage media, these materials have a greater capacity to store energy per unit mass, with the least amount of temperature fluctuation possible from Figure 4. The ratio of mass to volume is known as relative mass of a substance needed to hold a specific quantity of heat the amount of energy needed to store the mass (or volume) of PCM the same quantity of thermal energy. The rise in temperature of various materials while 5000 kJ of heat energy is stored is seen in Figure 4 (b). The PCM was paraffin wax, which has a melting point of 59.9ºC and a latent heat of fusion of 190 kJ/kg [22]. Recent research by Cabeza et al. [24] suggests that the volume change during phase shift may vary up to 24%, despite the majority of earlier studies stating that it is less than 10% [23]. To improve the thermal comfort of buildings, PCMs are utilized in the civil engineering area for walls, floors, PCM-filled glass windows, ceilings, roofs, and facades. The application of PCMs in road pavements is currently the subject of extensive research. When PCM is added to road pavements, the temperature of the pavement will rise during cooling and decrease during heating.

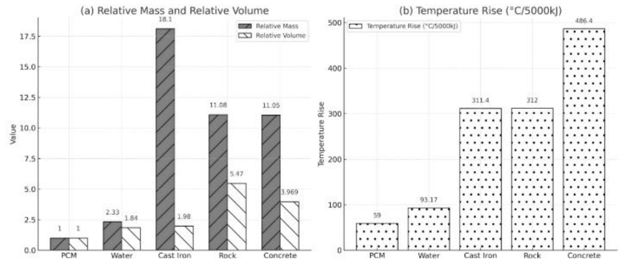

FIG. 4: (A & B): HEAT STORAGE MEDIUM COMPARISON [23]

Typically, solid-liquid PCMs are utilized to regulate the temperature of the pavement. Fig. 5 displays the phase diagram of an ideal PCM. Solidification is the term for the liquid-solid phase transition, whereas fusion is the term for the solid-liquid phase transition. The temperature at which phase transition takes place with constant atmospheric pressure is referred to as the fusion temperature (T_m). Pure PCM will be in the liquid phase above the fusion temperature and in the solid phase below it, devoid of supercooling and the hysteresis effect [25].

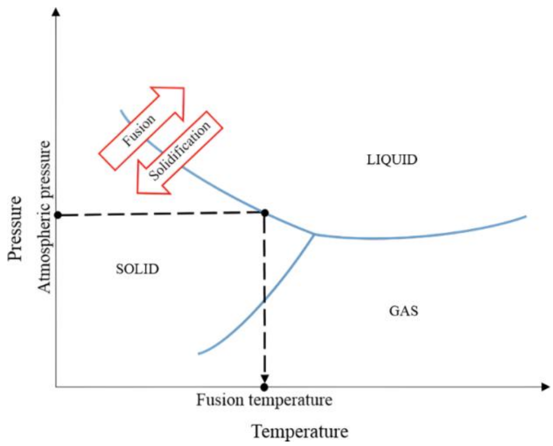

FIG. 5: PHASE DIAGRAM FOR PCMS [26]

The solidification of a PCM occurs in three phases, as shown below in Figure 6. The liquid PCM releases sensible heat during the first step until it reaches the temperature at which it fuses. The second phase then sees the release of the material's latent heat while maintaining a steady temperature. The third phase involves the sensible release of heat from the pure solid body until the temperature reaches equilibrium. The nucleation effect, which is the production of first crystals or nuclei, initiates the solidification process of PCM. The nucleation rate is the ability to form crystals when the PCM temperature drops below the fusion temperature.

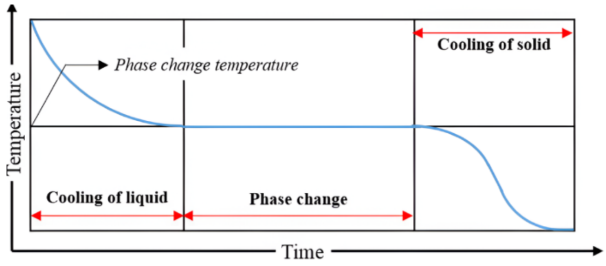

FIG. 6: SOLIDIFICATION WITHOUT SUPERCOOLING [26]

This phenomenon, known as the supercooling effect, occurs when the nucleation rate is low and the material stays in the liquid phase below the fusion temperature, as shown in Fig. 7 [26]. One significant disadvantage of using PCMs in industry is the supercooling effect. Nucleating agents such as solid nanoparticles and high melting point paraffins or alcohols can be added to PCM to accelerate nucleation [28, 29].

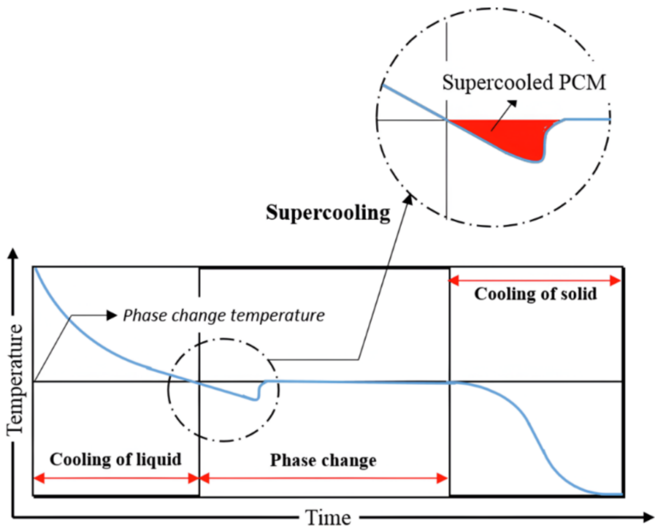

FIG. 7: SUPERCOOLING EFFECT [26]

6.2. Performance of PCM incorporated pavements: Both concrete and asphalt pavements are protected against temperature extremes by the addition of PCMs. When the pavement's temperature rises over the phase transition at midday in the summer, the PCM's temperature goes through absorb heat during its fusion to undergo a phase transition from solid to liquid temperature and stop the pavement's temperature from rising. At night, as the temperature of the pavement decreases, by altering its phase, the PCM releases the heat energy that has been accumulated. Once more, at its fusing temperature, from liquid to solid PCMs of for low temperatures, a lower melting temperature can be employed thermoregulation. These PCMs will be liquid at room temperature and solidify when the temperature falls below the temperature at which they fuse. It is possible to raise the pavement's temperature by using the latent heat that is released during the liquid-solid phase transition.

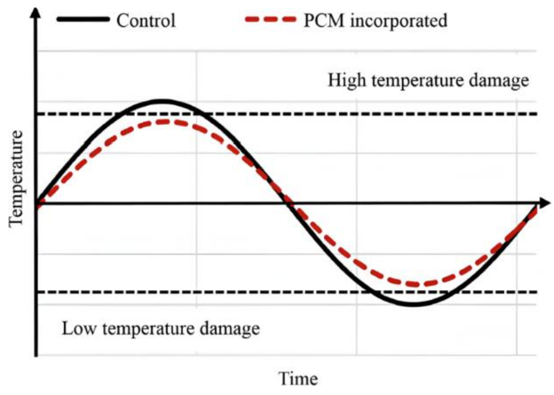

FIG. 8: THERMAL PERFORMANCE OF PCM INCORPORATED PAVEMENT [27]

For low temperature thermoregulation, PCMs with a high latent heat of fusion and a melting temperature that is marginally above 0°C are appropriate [30, 31]. Figure 8 illustrates the function of PCMs in pavement thermoregulation schematically.

6.3. PCM classification: Solid-liquid PCMs are the most cost-effective option for pavement applications due to their intermediate melting temperature and minimum volume change [32]. Compounds can be classed as organic, inorganic, or eutectic, as illustrated in Figure 9.

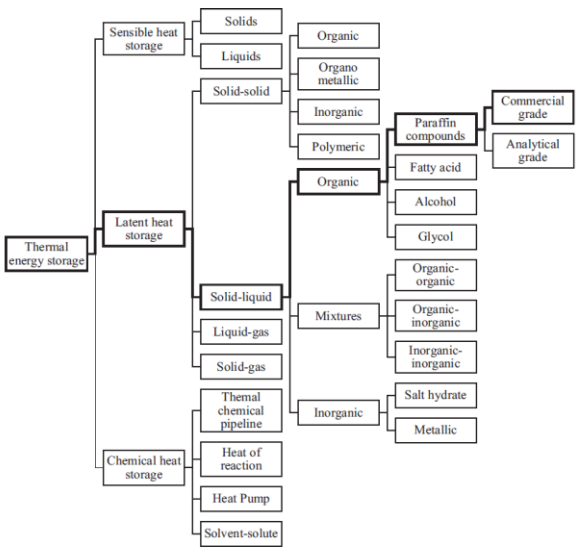

FIGURE 9: CLASSIFICATION OF PCMS [32]

6.3.1. Organic PCM: Organic PCMs require no supercooling during phase change and possess good corrosion resistance [33, 34]. Organic PCMs are characterized by improved cyclic chemical and thermal stability with no phase segregation [35]. Organic compounds may be classified as paraffin and non-paraffin compounds. Paraffin compounds are hydrocarbons with the general formulae CnH2n+2 and the phase change temperature of these compounds highly depends on hydrocarbon chain length. The paraffin compounds' melting point variation with chain length of hydrocarbons is shown in Fig. 10. Paraffins are available commercially and in great use since they are cheap, safe, dependable and non-corrosive [34, 36].

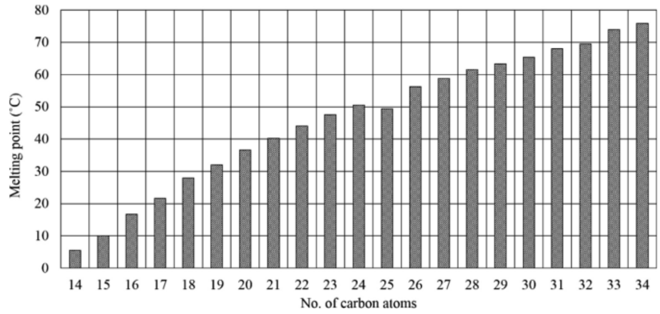

FIG. 10: RELATIONSHIP BETWEEN MELTING POINT AND LENGTH OF HYDROCARBON CHAIN OF PARAFFINS [34]

The addition of materials with higher thermal conductivity, including aluminum powder, graphite, and metal foams, can improve the low thermal conductivity of paraffin materials [37]. Utilization of metallic fillers, metallic matrix structures, finned tubes and aluminum scraps can also be used to improve the heat conductivity of paraffins [38]. Organic PCMs have latent heat of fusion between 170 kJ/kg and 270 kJ/kg at temperatures between 5°C and 80°C, making them appropriate for use in buildings [34]. As indicated by Figure 10, as the length of the hydrocarbon chain increases, the melting point of paraffin compounds rises. Non-paraffin substances are mainly fatty acids, alcohols, esters and glycols. Unlike paraffin compounds having comparable properties, non-paraffin compounds have different properties [33]. Non-paraffin PCMs exhibit higher latent heat of fusion, reduced thermal conductivity, toxicity, and instability at high temperatures. They are slightly caustic and combustible at higher temperatures [33,34]. Non-paraffin-based PCMs are 2 to 2.25 times more expensive than commercial grade paraffins [33]. Fatty acids, with the general formula $C_mH_nO_2$, are a popular nonparaffin-based PCM for construction applications.

6.3.2. Inorganic PCMs: Inorganic PCMs are divided into salt hydrates and metallic PCMs. Salt hydrates are crystals composed of inorganic salts and water, while metallic PCMs are metals and alloys with low melting points. Inorganic PCMs have significantly higher energy storage density and thermal conductivity compared to organic PCMs.

6.3.4. Salt hydrates: Salt hydrates are crystalline solids generated by the interaction of inorganic salts with water, with the typical formula ABnH2O. During phase shift, salt hydrate crystals break down into anhydrate or lower hydrate salts and water. Salt hydrates exhibit increased latent heat of fusion, higher thermal conductivity, cheap cost, and minimal volume change after phase change. Salt hydrates are chemically and thermally unstable [39,40], corrode metal components [41], and have low nucleating ability, leading to supercooling [42]. Adding nucleating chemicals can enhance salt hydrate supercooling [43, 44]. Another problem linked with salt hydrate is incongruent melting. In rare circumstances the degraded water may not be sufficient to dissolve the solid phase. Lower hydrates may settle down due to density variations. Incongruent melting causes permanent melting-freezing of salt hydrate [33, 36]. To address incongruent melting, consider using thickening agents [43], encapsulation to decrease separation [45], mechanical agitation [46], or adding excess water [47].

7. EFFECT OF PCMS ON THE MECHANICAL STRENGTH OF CONCRETE:

Recent studies show that including PCMs reduces the mechanical strength of concrete. PCM microcapsules' intrinsic softness contributes to their lower mechanical strength [48]. Concrete with slower cement hydration and more porosity has lower mechanical strength [49]. The PCM leakage in concrete may hinder the contact between cement particles and water [50]. Moreover, researches indicate that the hydration reactions are delayed in concrete with PCM leakage concerning that with no leakage [51]. The key reasons behind the strength reduction of PCM incorporated concrete, as summarized by Marani and Nehdi [52], are illustrated in Fig. 10. Further, the PCM incorporation tends to decrease the density of concrete due to the lower density of PCM microcapsules [48, 52].

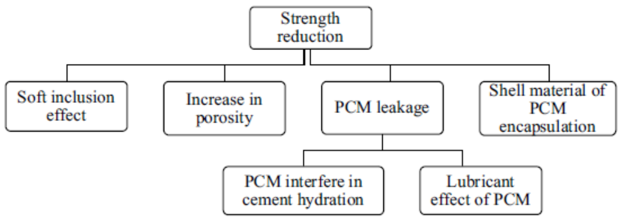

FIG. 11: REASONS FOR STRENGTH REDUCTION IN PCM INCORPORATED CONCRETE PAVEMENTS [52]

8. SELECTION OF SUITABLE PCM:

Selecting the appropriate PCM and encapsulation technology are essential for increasing the performance of PCM-included pavements. Organic PCMs are usually suggested for paving. They are ideal for non-corrosive use and do not need supercooling. Commercial-grade paraffins are most commonly used PCM all over the globe because they have a broad range of melting temperatures and greater latent heat of fusion [53]. In addition, the melting point of paraffins, as presented in Fig. 12, is appropriate for pavement use. While non-paraffin-based PCMs are 2 to 2.25 times pricier than paraffins, unsaturated organic acids and polyethylene glycol have also been researched as PCMs for pavements.

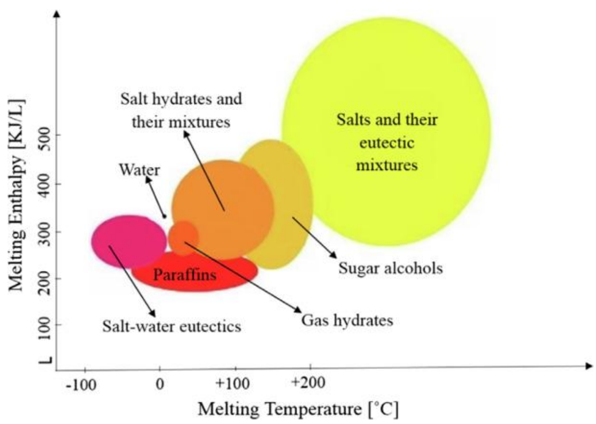

FIG. 12. MELTING POINT AND PHASE CHANGE ENTHALPY OF PCMS [51]

Si et al. [54] proposed three thermoregulation zones for pavements based on climatic circumstances, shown in Table 1. The experiment on asphalt pavement used tetradecane (melting point 5.5°C) and paraffin 58 (melting point 58°C) as PCM. Tetradecane and paraffin 58 were mixed with liquid paraffin in varying proportions for high and low temperature thermoregulation, respectively. Tetradecane, paraffin 58, and liquid paraffin were combined to achieve mixed thermoregulation. Liquid paraffin was employed for regulation as it does not alter its phase among -60°C to 60°C. Moreover, the study offers composite mass proportions for required thermoregulation type and associated enthalpy values.

TABLE 1 DETAILS OF THERMOREGULATION TYPES [54]

Thermoregulation type	Climatic condition	Distresses addressed	Suggested PCM melting point
High temperature thermoregulation	Long summer and short winter	Rutting and Upheaval	35°C–50 °C
Low temperature thermoregulation	Long winter and short summer	Freeze and thaw, Cracking, Frost boiling, etc	-5°C to 5 °C
Mixing thermoregulation	Summer and winter almost same	Defects due to continues high and low temperatures	5 °C–35°C

9. PCMS FOR COOLER CONCRETE PAVEMENTS:

Dehdezi et al. [55] examined the thermal, mechanical, and microstructural properties of PCM-based concrete pavements. PCM was made up of micro-encapsulated paraffin wax particles with sizes between 20 and 80 mm. Microstructure analysis showed little damage to PCM during curing and mixing but particles failed due to bursting under load. Bursting of PCM can increase the porosity of concrete by a large amount, lowering its mechanical strength. While the thermal performance of this concrete with incorporated PCM was good, its low mechanical strength is a disadvantage for pavement use.

10. PCMS FOR LOW TEMPERATURE THERMOREGULATION IN CONCRETE PAVEMENTS:

Ma et al. [11] engineered CS-PCM for low-temperature thermoregulation. Tetradecane (C14H30), whose phase transition temperature is comparable to low temperature pavement distresses, is used as PCM. Ethyl cellulose was used to prepare the membrane, while activated carbon and silica were used as carrier components. CS-PCM with silica possesses a greater theoretical enthalpy and is thus a better carrier than activated carbon. A dispersion agent was prepared in the lab to disperse the carrier material, which enhanced heat storage capacity and inhibited cluster formation of CS-PCM particles. The best ratio of tetradecane, silica, EC, and dispersant was found to be 1:1:0.1:0.1.

Farnam et al. [33] suggested the incorporation of LWA and embedded tubes to incorporate PCM in concrete pavements. Plastic pipes with the following dimensions were used: The embedding tubes had diameters of 10 mm. PCM was made from petroleum-derived paraffin oil and vegetable-derived methyl laurate. The addition of paraffin oil to LWA gave a heat release value of 11,000 kJ/m^3 of mortar at 3.0°C upon freezing. There was no heat release following the chemical interaction of methyl laurate with cementitious material. Methyl laurate-added mortar and paraffin oil generated heat releases of 7500 kJ/m^3 at ~3.0 °C and 12000 kJ/m^3 at ~1.2°C, respectively. The incorporation of PCM in buried pipes was not accompanied by any chemical reactions. Farnam et al. [33] replaced plastic pipes with metal pipes (22.4 mm inner diameter) made of 0.5% carbon steel with a thermal conductivity of 45 W/mK. To accommodate the maximum aggregate size of 19 mm, pipes were spaced 25 mm apart. The PCM-incorporated concrete slab melted 136.9 mm of snow within the first 24 hours.

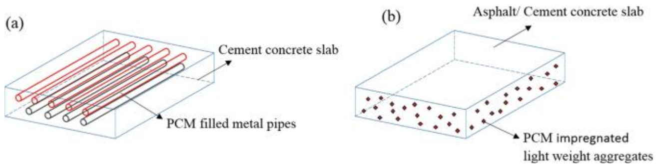

FIG. 13: (A) CORE-SHELL ENCAPSULATION IN PAVEMENTS; (B) SHAPE-STABILIZED PCM IN PAVEMENTS [33, 56]

In research by Yeon and Kim [56], PCM microencapsulated with melamine-formaldehyde resin was emulsified to avoid freeze-thaw deterioration in concrete roads. To limit the cost of microencapsulated PCM, its slurry form was used in place of powder. The liquid content of the PCM slurry can be used as free water, therefore adjust the water content in all mix proportions accordingly. Incorporation of PCM into concrete enhances its durability against freeze and thaw attack, as revealed by the findings of the research. The impact of PCM reduced notably when the temperature in the surrounding was below its phase change temperature for a considerable period of time. The PCM is completely solidified and in equilibrium with the ambient temperature. A lower phase change temperature PCM is recommended in this case.

11. RESULTS AND DISCUSSIONS

PCMs can control low-temperature and high-temperature thermal distresses in asphalt pavements and concrete pavements. Phase change temperature and latent heat of fusion are critical parameters that need to be taken into consideration while choosing a PCM for application in pavements [57]. PCMs having a melting point just above 0°C are generally employed for controlling low-temperature thermal distresses, and PCMs having a phase change temperature greater than 0°C are employed for high-temperature thermoregulation. The evolution of temperature of PCM embedded pavements greatly relies on measurement depth. When there is temperature difference at various depths available in the literature, data at the location closest to the pavement surface are presented in Table 3. Paraffin compounds are used in the majority of earlier studies because of its appropriate melting temperature and cost-effectiveness. Despite their higher prices, some of the unsaturated organic acids and the poly ethylene glycol have also been tested as pavement PCMs. The maximum reduction in asphalt pavement temperature observed was 19.7°C in laboratory when a PCM of melting temperature 8–25°C was incorporated with silicon powder as carrier material by 20% mass of asphalt binder. Maximum reduction in asphalt pavement temperature at the field was 7°C when Ceresin impregnated in LWA, with 18% – 20% PCM absorption, was used as 100% replacement to coarse aggregate. The thermal behaviour of PCM integrated pavements is based on the PCM properties utilized, particularly the melting point and latent heat of fusion. It is advisable to maintain the latent heat of fusion as much as possible while the melting temperature of the PCM must be chosen judiciously based on climatic condition. Since most of the earlier studies are aimed at the formulation of numerical models for the prediction of thermal behaviour of PCM integrated pavements, more comprehensive studies are required on the choice of PCM for a specific climatic condition in location. More research in this field must be done in this regard. Pavement samples made of various PCMs can be cast and subjected to various climatic conditions to develop a correlation between climatic condition and melting temperature of PCM to be chosen for that climate.

TABLE 2: PCMS FOR LOW-TEMPERATURE THERMOREGULATION.

PCM details	Melting temperature (°C)	Latent heat of fusion(J/g)	Pavement Type	Encapsulation
Tetradecane [11]	5.8	178	Concrete	Carbon and silica carrier
Paraffin oil and methyl laurate [28]	2–3	130–170	Concrete	LWA and embedded plastic pipes
Paraffin oil [29]	5.7	157.8	Concrete	LWA and embedded metal pipes
N-Tetradecane [24]	4.5	224.5	Concrete	Microencapsulated with melamine–formaldehyde resin

PCMs efficiently moderate excess temperatures of concrete and asphalt road surfaces. Application of PCM in pavements reduce the heating and cooling rate, limit the peak temperatures and slow the onset of high temperatures. This review discusses the influence of incorporating PCM on thermal behavior in pavements. This paper gives an overview of the current state of the art concerning PCMs, emphasizing their applicability in pavement projects. Shape-stabilized and encapsulated PCMs are suitable for use in pavements. Further studies are needed to increase the amount of PCM that can be incorporated without significantly affecting the mechanical strength of these pavements. The selection of suitable PCM depends on environmental conditions, while the method of encapsulation is entirely up to the engineer, taking into account the construction process and traffic loads.

12. FUTURE SCOPE OF THE STUDY

Application in rigid pavements is still at a developing stage, and although some very promising laboratory and limited field-scale results are available, gaps such as those mentioned above need further research. Translating laboratory-scale findings to large-scale, long-term field applications for diverse climatic and traffic conditions should be the goal of future studies. For that, longer periods of field monitoring will be required to establish real-life thermal performance, durability, and functional reliability during their total service life.

One of the key difficulties identified in this literature review is that of the reduction in mechanical strength that results from incorporating PCMs into the concrete. There needs to be more research conducted on advanced methods of encapsulating PCMs that will reduce any potential leakage of the PCMs while also being utilized to enhance the mechanical strength of pavement concrete. There needs to be more balance between the thermal conductivity and the mechanical strength.

So, further research work needs to be carried out to determine the requirements of PCMs in various climatic conditions. As the efficiency of PCM largely depends on the melting temperature and latent heat capacity of the PCM used, region-specific databases relating to the climatic requirements and properties of PCM needs to be generated. Until now, little work has been conducted on the long-term durability of the pavement incorporated with PCMs due to repeated traffic loading, freeze-thaw cycles, moisture ingress, and chemical exposure. In any case, the fatigue performance, crack propagation behaviour, and resistance against environmental degradation will have to be assessed to ensure safe and reliable applications in pavements. Moreover, life-cycle assessment and cost-benefit analyses are necessary to provide a quantification of environmental and economic viability for the PCMs-based pavements against conventional rigid pavements.

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