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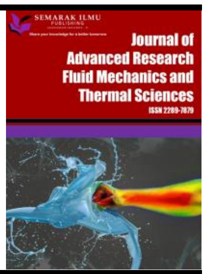

Thermal Performance Evaluation of PCM-Impregnated Aggregates in Hot Mix Asphalt: Mitigating Urban Heat Island Effects

Nasir Khan[1,*], Muslich Hartadi Sutanto[1], Bashar Sami Mohammed[1], Arsalaan Khan Yousafzai[1,2], Muhammad Imran Khan[3], Abdul Muhaimin Memon[1], Rania Al-Nawasir[4]

[1] Department of Civil & Environmental Engineering, Universiti Teknologi PETRONAS (UTP), Seri Iskandar 32610, Malaysia
[2] Department of Civil Engineering, University of Engineering & Technology Peshawar, Peshawar 25120, Pakistan
[3] Civil Engineering Department, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11564, Saudi Arabia
[4] Roads and Transportation Engineering Department, College of Engineering, University of Al-Qadisiyah, Al-Diwaniyah,58002, Iraq

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ABSTRACT

The Urban Heat Island (UHI) phenomenon, in which the temperature in urban regions is higher relative to that in surrounding rural areas, is primarily attributed to human activities and urban development. This temperature escalation poses various challenges, impacting energy consumption, human well-being, and the overall urban environment. This study explores the potential of phase change materials (PCMs) as an addition to asphaltic mixes in alleviating the UHI effect. PCMs can store and release thermal energy through phase transition and exhibit valuable thermal properties for temperature management. In the context of UHI, PCMs play a pivotal role in alleviating the surplus heat amassed in urban areas. This study evaluates the effectiveness of shape-stabilized PCM-impregnated aggregates to reduce pavement temperature. The mechanical and thermal performance of the four different bituminous mixes has been evaluated in this study. A decrease in marshall stability while an increase in marshall flow has been observed with the increase in the proportion of PCM-impregnated aggregates in the mix. Based on the thermal analysis of PCM-modified mixes, a temperature drop of 5.03 °C and 2.9 °C in core temperature was observed in the case of 70% and 35% replacement with PCM-impregnated aggregates. The introduction of PCM-impregnated aggregates into the mix lowers the rate of increase and decrease in temperature of the asphaltic mix in direct sunlight. Electrical resistivity increased by around 4% and 8.6% for 35% and 70% replacement as compared to control sample.

1. Introduction

Social and national economic development depend greatly on the development of road infrastructure. Because of the boom in the car industry, construction of roadways has significantly increased since 1950s across the globe [1]. As per the report from JKR Malaysia, approximately 119,932 km of roadways have been paved across the country by December 31st, 2022, out of which a major portion is of flexible pavements. Flexible pavements are made up of aggregates and bitumen

* *Corresponding author.*
E-mail address: nasir_22012207@utp.edu.my

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which leads to environmental pollution by releasing organic volatiles and thermal energy into the atmosphere [2]. Several approaches have been proposed to reduce the temperature of asphalt pavement by improving solar reflection, thermal resistance, and water evaporation efficiency which ultimately reduces the chances of various pavement degradation problems [3-5]. The five most common pavement degradations are thermal cracking, permanent deformation, moisture damage, aging, *and* fatigue cracking, out of which the first two are often caused by temperature. Two approaches are commonly adopted to reduce pavement degradation associated with temperature variation. The first approach is to increase the rutting resistance of the pavement by optimizing the aggregate's gradation, while the second is to enhance bitumen's performance by adding different additives to bitumen. Ji *et al.,* [6] studied the effect of gradation on the rutting resistance of asphaltic pavement and concluded that the rutting resistance increases by increasing the nominal maximum aggregate size. On the other hand, several additives like thermoplastic polymers (ethylene-vinyl acetate by Ameri *et al.,* [7]), thermoplastic elastomers (styrene by Sirin *et al.,* [8]), thermosetting polymers (resin by Bostancioğlu *et al.,* [9]), fibers (basalt fibers by Xiang *et al.,* [10]), chemical modifiers (lignin by Xu *et al.,* [11]), and waste material (ceramic waste by Hussein *et al.,* [12]) are also used. These approaches focused on tackling the mechanical problems with pavement structure without considering the surface temperature of the pavements. The surface temperature is responsible for a problem called urban heat island (UHI).

UHI is a condition in which the temperature of an urban area is higher than that of the surrounding area due to the increase in the application of artificial materials in urban areas. This happens because green areas are being converted into roads and buildings due to the lateral spread of construction. This movement is increasing day by day because of population growth. Hussein *et al.,* [12] claimed that South Asia and China will account for approximately 60% of the overall urban population growth between 2007 and 2025. Local climate patterns can change because of UHI, which can lead to an increase in electricity demand for cooling down living spaces using air conditioning. A study by Ang *et al.,* [13] claimed an increase of 7.8% in electricity consumption for an increase of 1 °C in atmospheric temperature in Singapore. Santamouris *et al.,* [14] concluded that the demand for electricity increases by 0.5% to 8.5% against an increase of 1 °C in different cities. These studies shows that UHI effect can increase electrical consumption, water consumption, and cause problems for natural habitats in urban areas. Therefore, researchers need to take measure to alleviate the UHI effects.

1.1 Techniques for Reducing UHI

UHI directly amplifies the negative effects on global warming and indirect effects on electricity consumption across the globe. To alleviate the increase in demand for electricity and reduce the effect on global warming, studies suggest some approaches to cut off the root cause in the form of UHI. One of the approaches for reducing the UHI is the use of porous pavement. Porous pavements can reduce the UHI, but according to Li *et al.,* [15], porous pavement may have a higher surface temperature than normal pavements in case the pavement is not exposed to significant moisture. It was concluded that the application of porous pavement can reduce the surface temperature in conditions where abundant water is available to the pavement surface [16,17]. The use of reflective pavement also reduces the surface temperature due to the increased glare (albedo) on the pavement surface. This albedo effect can be increased by painting the surface of the pavement or changing the colour of the aggregates but the glare distracts the drivers and also increase the atmospheric temperature for the nearby residents due to reflection of solar lights from the surface. Another option for reducing UHI is the use of hydronic asphalt pavements (HAP). This approach is not preferred due to the requirement of additional structures (pipes), the cooling source required to cool the pipes, and the higher chances of cracks in the pavement surface due to high stress applications.

The application of phase change material (PCM) is another approach that can be adopted for pavement surface temperature reduction, but this approach is still in the research phase. Some of the studies have successfully employed PCM to reduce UHI, but these experiments do not comply with the structural requirements of pavements. Chen *et al.,* [18] added PCM-L and PCM-Z as phase change material 5% by weight of aggregates and concluded that the indirect tensile strength, and rutting resistance decreased as a result of PCM incorporation. Wei *et al.,* [19] added PCM directly to the bitumen, which resulted in a temperature drop of 9 °C: however, it adversely affected the ductility of the binder. Another study by Ryms *et al.,* [20] concluded that the rutting depth observed in the case of mix modified with PCM-impregnated aggregates was 14.2 mm and 2.7 mm for the control sample, which is more than 5 times higher than that of conventional mixes. This study will try to use PCM to alleviate the UHI effect while fulfilling the structural requirements of the pavement.

PCM has the capability to absorb or transfer thermal energy to/from the surrounding environment when it undergoes phase transition without affecting the overall temperature. It can store and release thermal energy in the form of latent heat and sensible heat, upon the removal or introduction of a heat source. When PCMs are introduced with a heat source, they absorb the heat in the form of sensible heat. The amount of sensible heat keeps on increasing until the temperature reaches a specific point and the material is in a solid-liquid state. This state stores energy in the form of latent heat until it turns into liquid state. After this point, the PCM stores the energy in the form of sensible heat. A graphical explanation of this phenomenon can be seen in Figure 1 which is referred to as the heat absorption/storing phase of PCM.

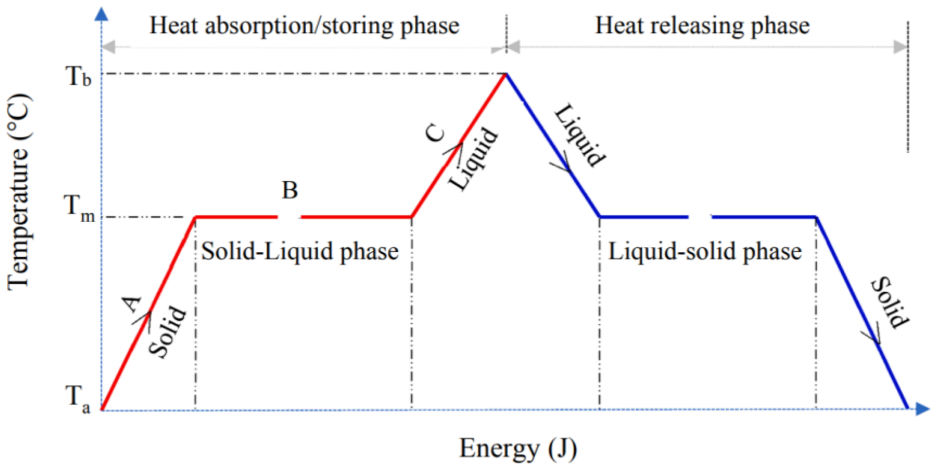

Fig. 1. Heat absorbing and releasing mechanism of PCM

Now, to release the stored energy, the whole procedure is followed in the reverse direction, starting with releasing the energy in sensible form. This energy release lowers the temperature and keeps on decreasing until it reaches the phase change temperature. The material is now in the liquid-solid state and will release significant energy in the form of latent heat with zero temperature change until it is completely converted into solid form. From this point onwards, it releases sensible energy and keeps on reducing the temperature until it reaches the initial temperature. This phenomenon is termed as the heat-releasing phase of PCM.

1.2 Effect of PCM on Temperature Regulation

The bituminous mixtures accumulate heat and increase the heating rate, which leads to an increase in the temperature of the pavement due to its black color, which is why it absorbs more solar radiation [21]. PCM application can reduce this effect by reducing the thermal sensitivity of asphaltic mixtures [22]. PCM-modified mixes show lower peak temperatures by absorbing some part of the solar energy without letting the temperature increase when it reaches the phase change temperature of the PCM. The effectiveness of PCM varies with the type and proportion of PCM along with other factors. Ma *et al.,* [23] concluded that PCM of up to 2.4% by weight have little effect on the temperature of bituminous mixtures. In addition, the effectiveness of PCM is also influenced by the method of application.

1.3 Methods of PCM Application

Methods for the application of PCM have been broadly divided into direct and indirect application. The indirect method is further divided into encapsulation and impregnation. Furthermore, the indirect encapsulation method can be divided into two categories based on the size of capsule. The first is microencapsulation where the PCMs are contained into small (diameter less than 1mm) capsules made of a thin layer of polymers [24]. The second is microencapsulation where PCMs are contained into packets like pouches, tubes, or panels with size greater than 1 cm in diameter [25]. Microencapsulation works better than microencapsulation because it offers a higher interaction between the capsule and the mix due to the higher surface area of the capsule. Due to this higher interaction, it offers higher heat transfer and can spread in a more even pattern as compared to microencapsulation while in the other hand, impregnation technique utilizes lightweight/porous aggregates as a medium of PCM. Porous aggregates are saturated with melted PCM and then covered with a leak proofing material before adding into the bituminous mix. The efficiency of PCM application is hugely affected by the approach adopted for PCM application and type of PCM selected for a specific use.

1.4 Types of PCM

The capacity of PCM to store energy depends on several factors like phase change transition temperature, environmental conditions, and type of PCM etc. [26]. PCMs are mainly divided into three main categories. They could be organic, inorganic, or eutectic. Organic PCMs have been further divided into paraffins and non-paraffins, and similarly inorganic PCMs can be divided into metallic and salt hydrates. Eutectic could be a combination of inorganic-inorganic, inorganic-organic and organic-organic materials.

1.4.1 Organic PCMs

Organic PCMs offer a lot of benefits like cost-effectiveness, wide range of phase change temperature, and non-toxic nature, which boosted its popularity in recent years. However, these materials have the limitation of offering lower thermal conductivity, which reduces the speed of heat transfer mechanisms. Paraffins are the most common PCMs with a general chemical formula as C_nH_{2n+2} where length of hydrocarbon chain defines the phase change temperature [27].

1.4.2 Inorganic PCMs

Salt and water are the constituents of salt hydrates in which the chemical bond between salt and water molecules can store thermal energy which are known as inorganic PCMs. Salt hydrates are desirable for use because of their low cost, low volumetric change, and high thermal energy storage capacity. However, according to Guo *et al.,* [28], these materials are toxic in nature and have a narrow temperature range which is why these materials are not kept at the first place while selecting PCMs. Furthermore, these materials may react differently to different cooling and heating rates, which can be mitigated using mechanical agitation, thickening agents, and water which mean the behaviour of inorganic PCM is not predictive which decreases the chances of selection of inorganic PCMs at the first place.

1.4.3 Eutectic PCMs

Because a single PCM's phase transition temperature and latent heat are often constant, researchers have investigated the possibilities of eutectic PCMs, which are made up of two or more different substances. Eutectic PCMs may provide varied phase change temperatures and latent heat capacities by altering the number of various components, which makes them more appropriate for applications. The classification of eutectic PCMs can be divided into three groups: organic, inorganic, and hybrid eutectic PCMs [29]. The Al-Si eutectic alloy and the BHO (barium hydroxide octa hydrate)-KNO3 eutectic mixture are two examples of mixtures of two or more inorganic components that make up the inorganic eutectic PCMs [30,31]. When these materials are combined, their melting points are lower than when they are separate, and they also have positive properties like excellent thermal conductivity and stability.

1.4.4 Research significance

Buildings and highways construction are converting green areas into artificial materials which results in the increase of environmental temperature. It causes heat stress affecting the biotic world and increases electricity and water consumption. Beside this it reduces the services life of pavements by increasing the chances of permanent deformation and thermal cracks in the surface. This study explores the potential of PCM to reduce the pavement's surface and core temperature by using PCM-impregnated aggregates.

2. Methodology

2.1 PCM Selection

The effectiveness of PCM depends on several factors like type, application method, quantity of PCM, and application conditions. In this study, PCM was used to reduce the surface temperature and UHI effect through flexible pavement. Organic paraffin wax was selected as the PCM for this study because it is non-corrosive, non-toxic, cheap, and easily available. The properties of adopted PCM can be seen in Table 1. This PCM was used as a solution for immersing the lightweight aggregate so that the aggregates are saturated with PCM which can be used as a replacement in hot mix asphalt (HMA).

Table 1
Properties of the phase change material

Melting Temperature	Latent Heat Capacity	Thermal Conductivity
55 - 60 °C	140 - 200 kJ/kg	0.2-0.35 W/mK

2.2 Palm Oil Clinker Absorption

Malaysia is a tropical country and is the second largest palm oil producer in the world, accounting for around 26% of global palm oil production [32]. As per the report from 2020 by Jamaludin *et al.,* [33], 457 mills with gross production of 1.16 million tons per year were operational. To operate the heavy machinery, waste materials such as palm fibres and shells are burned to produce steam to generate electricity in the palm oil mills. Due to this combustion, POCs are produced as a byproduct that are lightweight, irregular in shape, porous, and light black in colour and are dumped into landfills. Production of 1 kg crude palm oil results in 4 kg of waste such as palm oil shells, POC, and palm oil fuel ash [34]. Researchers have used these wastes as coarse and fine aggregates based on their particle size, but still a major proportion of these wastes are dumped into landfills. Karim *et al.,* [35] used palm oil clinker powder (POCP) as a supplementary cementitious material (SCMs). Ahmmad *et al.,* [36] found that the addition of POCP in concrete as SCMs can increase the 28-days compressive strength by 29 %. This study is focusing on the absorption capacity of porous aggregates and will be using them as a PCM carrier medium. As per the literature Mohammed *et al.,* [37], POC has a water absorption of 26.45 %, making it suitable for this study.

Palm oil clinkers (POC) collected from a palm oil company were used as PCM carriers. As the lightweight aggregates cannot sustain too much load, it was decided to use smaller sizes of aggregates as a replacement. Three different sizes of aggregates, i.e., 3.35, 2.00, and 1.18 mm, were used as carriers of PCM in the first phase. A considerable quantity of each aggregate size was immersed into melted PCM and placed in oven for 24 hrs at 65°C with periodic stirring for the whole period. Excess PCM was stained out from the aggregates, and the saturated POC was kept in open air at room temperature for 2hr. The absorption capacity of all three sizes of aggregates was compared, and it was concluded that the absorption capacity of all the aggregates is almost the same as absorption in case of 3.35 mm aggregates was 20.6%, 20.7% and, 21.2 % in case of 2 mm and 1.18 mm respectively. It was decided to use 3.35 mm aggregates as they are easy to cover with leakproof material.

2.3 POC Coating

After immersion, the aggregates were coated with cement slurry and placed in an oven at 60 °C for drying. The coated aggregates were kept under observation to check for any weight loss upon heating, but no significant reduction was observed. A total of four different percentages 0% or control, 35%, 70%, and 100% of PCM-impregnated aggregates were replaced with 3.35 mm aggregates in the gradation. These mixes were tested by Marshall testing, and then the thermal performance of the mix was evaluated.

2.4 Thermal Performance Evaluation

To assess the thermal performance of the PCM-impregnated mix, slabs of dimensions 300 x 300 x 50 mm with 35% and 70% replacement of PCM-impregnated aggregates were cast and compared with control slab with 0% PCM impregnated aggregate for 6 days in direct sunlight. The temperature was measured at the surface and the core of the sample using a laser thermometer and thermocouple.

2.5 Electrical Conductivity

Electrical and thermal conductivity highly affects the efficiency of PCM in terms reducing the temperature of the surrounding area. Electrical conductivity was evaluated with the help of an electronic multi-meter by placing the electrodes attached to steel plates on both top and bottom of the samples. The general mechanism of measuring electrical conductivity, surface temperature and core temperature can be seen in the Figure 2.

Fig. 2. General setup for undergoing thermal and electrical analysis

3. Results

3.1 Marshall Testing

Marshall testing was performed using optimum binder content (OBC) with varying percentages of PCM-modified aggregates. Four Marshall samples were tested for every combination in Marshall testing machine following ASTM D6927 while replacing 0, 35, 70, and 100% of 3.35 mm aggregates with PCM-impregnated lightweight aggregates. A total of 16 samples were tested to assess the effect of PCM-impregnated aggregates on Marshall stability and flow. The results of the conducted test are shown in Table 2.

Table 2
Marshall testing results

PCM (%)	Flow (mm) (3-5mm)	Cor. Stability (KN) (>8KN)
0 % Control	3.847	13.714
35 %	3.362	11.822
70 %	4.422	10.004
100 %	4.955	7.212

3.2 Thermal Performance

From Marshall testing, it was observed that samples with 0 % PCM impregnated aggregates had the maximum stability while samples with 100 % replacement had the minimal stability. Samples with 35% and 70% replacement showed marshall stability of 11.8 KN and 10 KN respectively which were within the acceptable JKR limits (>8.0 KN) for marshall stability of flexible pavements. Therefore, it was decided to assess the thermal performance of mix with 35% and 70 % PCM impregnated aggregates. Slabs having dimensions 300 x 300 x 50 mm with 0%, 35%, and 70% PCM impregnated aggregates were cast. The slabs were compacted using manual mechanical compactor. Slabs were placed in direct sunlight for six days and the temperature was observed at a minimum of three locations at the surface and core of the samples every hour from 11 am to 5 pm. The average surface and core temperature for 35% and 70% can be seen Figure 3 and Figure 4 respectively. Figure 3 compares the surface temperature of control and PCM modified (35%) samples under direct sunlight. Maximum reduction in core temperature can be seen between 1400 to 1500 hrs. Moreover, the rate of increase in temperature in case of modified sample is lesser than control sample.

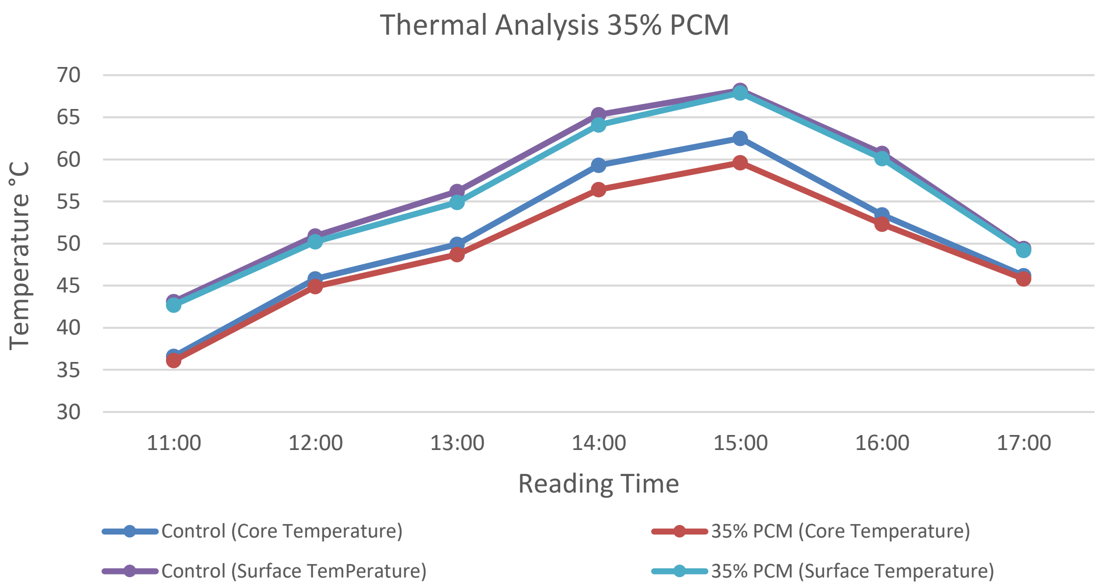

Fig. 3. Thermal performance of mix having 35% PCM-impregnated aggregates

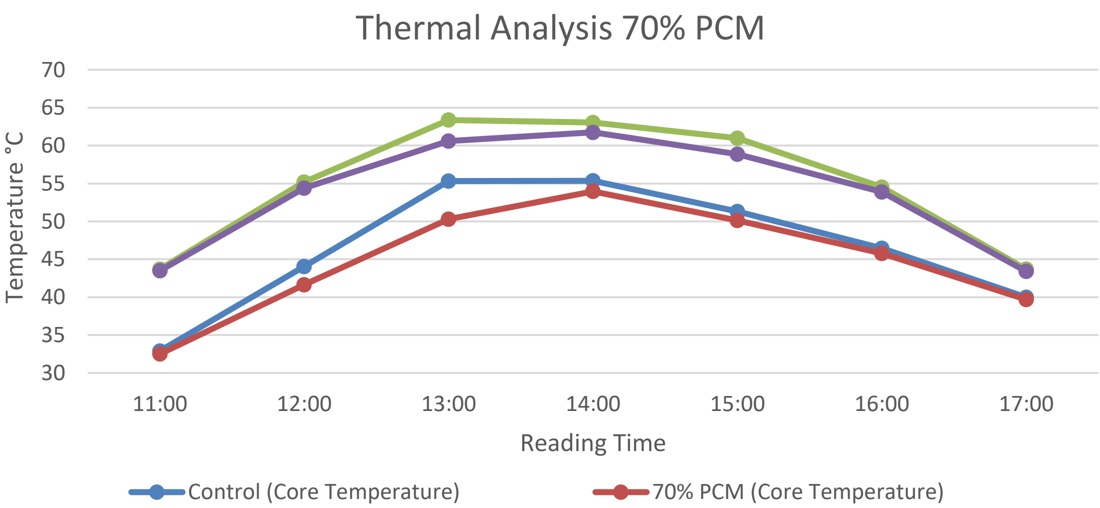

Fig. 4. Thermal performance of mix having 70% PCM-impregnated aggregates

Figure 4 draw a comparison of core and surface temperature between control and samples modified with 70% PCM-impregnated aggregates. The temperature difference between control and modified sample is maximum 1300 hrs. and minimal at 1100 and 1700 hrs. Average temperature difference between control and modified samples has been presented in Table 3 where it can be seen that the PCM effectively reduces the core and surface temperatures of the mix. A maximum average core temperature difference of 5.033 °C was observed at 1300 hrs. and a drop of 2.767 °C in surface temperature was observed at the same time for 70% PCM introduction. In the case of 35% replacement, the maximum drop in surface temperature was 1.3°C and core temperature was 2.9 °C. The temperature difference between the control and PCM modified mix was maximum when the core temperature was the closest to the phase change temperature of the PCM. Beside this, from Figure 3 and Figure 4, it can be observed that the rate of heating in the case of control sample is steeper as compared to PCM-modified sample, but on the other hand, cooling rate of the control sample is faster than the PCM-modified sample under direct sun. The reason behind this phenomenon is, that the PCM releases the stored thermal energy upon the reduction in overall temperature beyond its phase change temperature. Cooling rates of both the samples were also analyzed for six days under shade at room temperature, and it was concluded that the average core temperature of the control sample drops from 39.97 °C to 35.43 °C and 39.70 °C to 36.24 °C in one hour. A detailed analysis can be seen in Table 4.

Table 3
Difference between temperature of control and modified samples (°C)

PCM %	35 %		70 %	
Reading Time	Surface °C	Core °C	Surface °C	Core °C
11:00	0.4	0.5	0.2	0.4
12:00	0.7	0.9	0.8	2.4
13:00	1.3	1.2	2.7	5.0
14:00	1.2	2.9	1.3	1.4
15:00	0.3	2.9	2.1	1.2
16:00	0.6	1.1	0.6	0.7
17:00	0.2	0.4	0.3	0.3

Table 4
Cooling rate of the control and PCM modified mix

Reading Time	Core Temperature °C		Surface Temperature °C	
	Control	PCM	Control	PCM
17:00	39.97	39.70	43.70	43.40
18:00	35.43	36.24	35.62	36.14

3.3 Electrical Conductivity

Performance of PCM change material is highly influenced by thermal and electrical conductivity of the environment. This study assessed the electrical conductivity of both control and modified samples against different percentages of PCM in the mix. Increasing the quantity of PCM-impregnated aggregates in the mix increases the quantity of cement in the mix. This increase reduces the electrical conductivity and increases the electrical resistivity. Electrical conductivity of the samples was measured with the help of an electronic multimeter by measuring the flow of current across the samples. The electrodes of the multimeter were attached to steel plates on both top and bottom of the sample to measure the electrical resistivity of the sample as shown in Figure 2. Control sample showed the least electrical resistivity whereas sample with 100% PCM showed the maximum electrical resistivity. Overall comparison of the samples can be seen in Table 5.

Table 5
Effect of PCM-impregnated aggregates on electrical conductivity

Sample	Resistivity (Ωm)	Increment (%)
Control	36530333	Control
35% PCM	37975000	3.95
70% PCM	39685400	8.63
100% PCM	42728900	16.9

4. Conclusions

PCMs are effective in storing latent heat, but selection of PCM requires due care because the requirement for PCM selection changes with changes in environmental temperature. However, in this study, the average higher surface temperature ranges around 60°C so PCMs having a melting temperature between 55°C and 60°C are ideal. A slight temperature drop was observed in every observation, but the temperature difference between the control and modified samples was higher between 1200 hrs. and 1500 hrs. or when the core temperature was observed to be closer to the phase change temperature of PCM. The heating rate of PCM modified sample was slower than the control sample but on the other hand the cooling rate of the PCM-modified sample was also slower than that of the control sample. The surface temperature of the control sample dropped from 43.70°C to 35.62°C while for PCM-modified sample, this temperature dropped from 43.40°C to 36.14 °C in one hour at room temperature. The same behavior was observed for the core temperature drop, where temperature dropped from 39.97 °C to 35.43 °C and from 39.70 °C to 36.24 °C for the control and PCM-modified samples, respectively. Beside this, the increase in PCM-impregnated aggregates results in the reduction of electrical conductivity of the samples. This is why researchers should focus on evaluating the effect of variations in thermal and electrical conductivity on the efficiency of PCM.

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