Assessment of Two Methods of Enhancing Thermal Mass Performance of Concrete Through the Incorporation of Phase-Change Materials

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Abstract

According to the *IEA Technology Roadmap on Energy Efficient Building Envelopes*, buildings are responsible for more than one third of global energy consumption, with space heating and cooling consuming 33% of this energy, and increasing to 50% in cold climates. Using the mass of a building to store heat and/ or cold can reduce the demand on the auxillary heating and/or cooling systems and hence reduce the overall energy demand of the building. In this study the thermal storage capacity of concrete was actively enhanced by integrating phase-change materials (PCMs) which provide a high latent heat storage capacity. Two methods of incorporating PCMs into concrete were used to form PCM/concrete composite panels. The first type of panel was formed by adding microencapsulated paraffin to fresh concrete during the mixing process. The second panel was formed by vacuum impregnating butyl stearate into lightweight aggregate which was then included in the concrete mix. The aim of the study was to compare the thermal behaviour of both PCM/concrete composite panels to a control concrete panel and to evaluate which method of PCM incorporation is the most effective at improving thermal mass characteristics in the context of a thermal energy storage system for space heating/cooling in a building. The panels containing PCM displayed significantly greater thermal storage capacity, despite having reduced thermal conductivity and density. The study concluded that the panel containing lightweight aggregate/PCM composite is more effective at providing additional thermal storage, particularly within the first 100mm of depth of an element of structure.

Keywords:

Phase Change Materials (PCMs), PCM/concrete composite, Thermal diffusivity, Thermal storage.

1. Introduction

1.1 Background theory

The use of thermal energy storage systems (TES) is recognised as one of the most effective approaches to reducing the energy consumption of buildings. One of the main issues with renewable energy sources such as solar is that the supply is intermittent. A TES system can be used to absorb and store both solar energy and excess heat due to use and occupancy during the day, which can then be released to the internal environment when the room temperatures fall at night. In this way a TES system provides a potential for improved indoor thermal comfort for occupants by moderating internal temperature fluctuations and reducing the overall energy consumption of the building due to load reduction and shifting electricity consumption to off-peak periods (Figure 1).
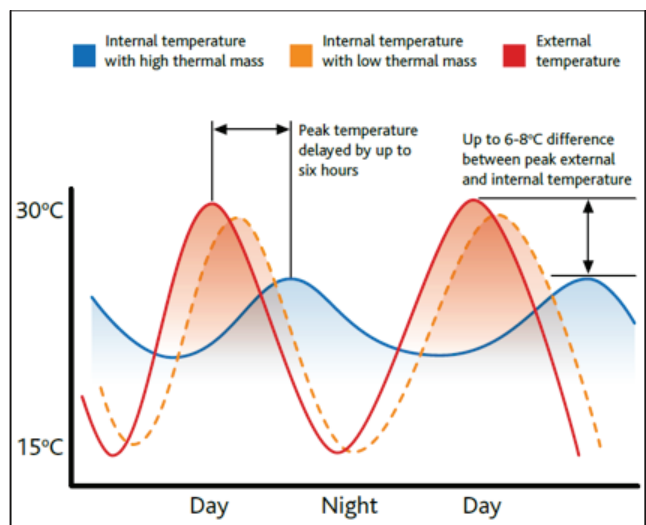

Figure 1. Stabilising effect of thermal mass on internal temperatures [1]

A TES system can include sensible heat storage, latent heat storage or a combination of both. Sensible heat storage systems store energy by increasing the temperature of the material. The capacity of a material to store energy depends on the amount of energy required to change the temperature of a unit amount of the material, ie, the specific heat capacity of the material. The storage capacity of a sensible heat system is given by[2]:

$$Q = \int_{T_i}^{T_f} mC_p dT \quad (1)$$

where

Q = quantity of thermal energy stored, (Joules).
T_f & T_i = final temperature and initial temperature respectively (°C).
m = mass of material.
C_p = specific heat capacity of material (J/kgK).

Using the mass of a building as a TES system is an established approach in the design of energy efficient buildings and is commonly referred to as *thermal mass*.

$$\text{Thermal mass} = \text{mass} \times \text{specific heat capacity} \quad (2)$$

One of the main parameters that influence thermal mass behaviour is thermal diffusivity, α, which is the ratio of the conductivity of a material to its volumetric heat storage capacity given by the equation:

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$$\alpha = \frac{k}{\rho C_p} \ (m^2/s) \quad (3)$$

where ρ is the density (kg/m³), k is the thermal conductivity(W/mK) and C_p is the specific heat capacity (J/kgK). Thermal diffusivity indicates the rate at which temperature changes occur in a material. The higher the value of thermal diffusivity the quicker the material will reach temperature equilibrium with its environment.

Another key property that influences thermal mass behaviour is the thermal inertia of a material denoted 'I' which is a measure of the responsiveness of a material to variations in temperature. Thermal inertia is given by the following equation [3]:

$$I = \sqrt{\rho C_p k} \ (J/(m^2 K \sqrt{s})) \quad (4)$$

A high thermal inertia describes materials that characterise high thermal mass and high thermal conductivity. Such materials will display small changes in temperature throughout the diurnal cycle. Referring to equation (3) for thermal diffusivity, α, equation (4) can also be written as follows:

$$I = \frac{k}{\sqrt{\delta}} \ (J/(m^2\sqrt{s})) \quad (5)$$

It can be noted from equation (5) that the higher the thermal diffusivity of a material the lower the thermal inertia. Hence for a building material to provide good thermal mass it requires an appropriate balance between thermal diffusivity and thermal inertia. Concrete is a building material that combines a high specific heat capacity and high density with a thermal conductivity that is appropriate for the diurnal heating and cooling cycle of buildings and hence has good thermal mass characteristics. In this study the thermal storage capacity of concrete was enhanced by adding phase-change materials (PCMs) which provide a high latent heat storage capacity.

A PCM is a material that absorbs high amounts of thermal energy while changing phase, ie, solid to liquid and liquid to gas. The change in temperature of PCMs during phase-change is insignificant. When incorporating PCMs into construction materials it is only the liquid-solid phase-change that is utilised. As temperature increases the PCM absorbs the heat and changes phase from solid to liquid. When the temperature decreases the PCM releases the heat as it changes from liquid to solid. In this way PCMs can be used to control air temperatures within a building [4]. Kosny et al [5] carried out an overview of the potential applications of phase-change materials in building envelopes which depend largely on local climate conditions and melt temperature range of the PCM.

The overall thermal capacity of a PCM/concrete composite is a combination of the specific heat capacity of the concrete, the specific heat capacity of the PCM and the latent heat capacity of the PCM. It will vary depending on the state of the phase transition of the PCM. The total energy stored by a PCM composite, omitting a liquid to gas phase-change, can be written as:

$$\int_{T_i}^{T_f} m_c C_{pc} dT + \int_{T_i}^{T_{mi}} m_{pcm} C_{ps} dT + m_{pcm} L + \int_{T_i}^{T_f} m_{pcm} C_{pl} dT \quad (6)$$

where

$Q_{pcm\text{-}comp}$ = overall thermal capacity of PCM/concrete composite

T_{mf} & T_{mi} = final melt temperature and initial melt temperature respectively (°C).

m_c & m_{pcm} = mass of concrete and mass of PCM respectively (kg).

C_{pc} = specific heat capacity of concrete (J/kgK)

C_{ps} & C_{pl} = specific heat capacity of solid PCM and liquid PCM respectively (J/kgK)

L = latent heat capacity of PCM (J/kg)

1.2 Selection of PCM

There are many different types of PCMs which can be broadly classified into three categories based on their chemical composition – organic, inorganic and eutectics. Pasupathy et al (2008) [6] summarised the advantages and disadvantages of each category.

Organic PCMs mainly comprise paraffin and fatty acids and are compatible with most construction materials. Paraffin wax is a hydrocarbon with a chemical structure C_nH_{2n+2}. Paraffins typically have melting temperatures ranging between 20°C and 70°C. The higher the number of carbon atoms in the chain the higher the melting temperature [2]. A number of researchers, ([7], [8], [9], [10], [11] and [12]) have carried out thermal energy storage studies that combined paraffin with concrete. The paraffin is micro-encapsulated in thin polymer shells which are then added to fresh concrete towards the end of the mixing process.

The microcapsules provide a large surface area for heat transfer and also resist volume change during the phase transition. Cabeza et al.[11] constructed two full size cubicles with windows incorporated in each wall, one with ordinary concrete and the other with a concrete which contained 5% by weight micro-encapsulated paraffin. The study successfully demonstrated an increase in thermal storage capacity and increase in thermal inertia for the PCM/concrete composite. Generally from the review of studies that considered PCM/concrete composites, paraffin appears to be the most common choice of PCM as it is inactive in an alkaline medium, chemically stable and relatively inexpensive. However, paraffin has a relatively low conductivity and the capsules also adversely affect the mechanical properties of the concrete [13].

Fatty acids have melting temperatures similar to that of paraffin. They also have good melting and freezing properties. However, they are generally more expensive than paraffin [13]. Butyl stearate is a less expensive fatty acid which has also been successfully combined with concrete in previous research ([14] and [15]). Zhang et al[15] compared different methods of incorporating PCMs into porous aggregates and concluded that the vacuum impregnation method was the most effective. In the vacuum impregnation method the air was evacuated from the porous aggregate using a vacuum pump. The aggregates are then soaked in a liquid PCM under vacuum. The porous aggregate was then added to a concrete mix. The thermal energy storage capacity of the concrete samples were assessed using differential scanning calorimeter tests and it was found that the energy absorbed by the PCM/concrete composite samples increased almost linearly with the volume fraction of PCM in the concrete.

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Inorganic phase-change materials are salt hydrates. Salt hydrates are alloys of inorganic salts and water. They have high latent heats per unit mass and volume. They also have high conductivity, almost double that of paraffin [2]. However, salt hydrates have two particular problems – incongruent melting and supercooling – which reduces the efficiency of the heat transfer.

A eutectic mixture is a combination of chemical compounds or elements that , at a particular combination, will solidify at a lower temperature than any other combination. Eutectics nearly always melt and freeze without segregation since they freeze to an intimate mixture of crystals. Also on melting, both components liquefy simultaneously. However, there is only limited data available on the thermo-physical properties of eutectics as the use of these materials is still new to thermal storage applications.

Primarily, the selection of a PCM should ensure that the melt temperature range of the PCM is suitable for the intended application. For a space heating application in a building, phase-change materials with a melting temperature within the range of human comfort temperature (18-22°C) are suitable [6]. For a space cooling application the appropriate melt temperature range is higher at 19 - 24°C [16].

The phase-change material selected must also be chemically compatible with the material in which it is to be incorporated. For this study organic PCMs were deemed the most suitable for incorporating into concrete. Hence, taking into account the suitable melt temperature range for a space heating/cooling application, paraffin and butyl stearate were selected.

1.3 Objective of study

Previous research has been carried out on many types of PCM/concrete composites. However, the effectiveness and performance of the different types of composites have not been compared in previous studies. The depth of heat penetration into a PCM/concrete panel depends on the thermal conductivity of the panel, the latent heat of the PCM and the temperature of the internal environment in which the panel is located. The PCM in the panel will only be effective, that is change phase, within a particular depth which depends on these factors.

In this study two methods were used to incorporate the PCMs into concrete to form PCM/concrete composite panels.

1. microencapsulated paraffin was added to fresh concrete during the mixing process.

2. butyl stearate was vacuum impregnated into lightweight aggregate which was then included in the concrete mix design.

The main objectives of this study were to:

(i) compare the effectiveness of the two methods of incorporating phase-change materials into concrete at increasing thermal storage capacity.

(ii) compare the effective depth of each PCM within the panel in order to inform future design of PCM-concrete panels so that the efficiency of the thermal storage behavior of the PCM/concrete composite material can be optimised.

(iii) To evaluate the effects that the phase-change materials have on the thermal conductivity strength, and density, of concrete.

2. Methodology

To compare the two methods selected for combining the PCMs with concrete, six panels in total were manufactured, two panels of each type of PCM/concrete composite and two control panels with no PCM. In the following sections of this paper the panels containing the lightweight aggregate impregnated with butyl stearate are referred to as LWA/PCM and the panels containing microencapsulated paraffin are referred to as ME PCM.

Each concrete panel was 200mm x 200mm x 200mm. A panel depth of 200mm was chosen to reflect the typical thickness of an internal wall within a building. In order to record the internal temperatures within the panels during testing three thermocouples were cast into each panel at equal depth intervals of 50mm. Thermocouples were also placed on the front and rear faces. After casting, the concrete panels were cured for 28 days in accordance with IS EN 12390-2. As moisture content has a significant influence on the thermal conductivity of materials the panels were allowed to dry out for 28 days after curing. The moisture content for all panels was less than 4% prior to measuring the thermal conductivity of the panels.

To be able to accurately compare the heat transfer behaviour of the six panels, and ensure that any differences in thermal mass behaviour are due solely to the parameters of the panels, it is required that each panel is exposed to the same amount of thermal energy using the same mechanism of heat transfer. In order to replicate thermal energy transfer from the sun while controlling the amount of thermal energy that each panel is exposed to, radiation was selected as the mechanism of heat transfer. A particular artificial light source (Follow 1200 Pro lamp) was used with which it is possible to control the wavelength and intensity of the electromagnetic waves that are emitted. The lamp produces light across the three wavelengths of light – visible, infrared and ultraviolet – and mimics daylight. In order to exclude the environmental effects such as temperature variation in the test room, an insulated and airtight light box was designed and constructed as shown in Figure 2. Air temperature within the light box was recorded during all tests and the temperature difference between the internal air and the panel was monitored. Convective heat transfer from the internal air to the panel was considered to be minimal in comparison to the radiative heat from the lamp and so was omitted from consideration.

To establish the optimum size for the light box, initial tests were carried out with the lamp to determine the light intensity (Lux) and spread of light that reaches a surface positioned at particular distances from the lamp. The heat energy reaching the surface was also measured in these tests using a pyronometer. The dimensions of the light box were optimised to ensure that the thermal energy from the lamp was evenly spread across the surface of the panel and that the intensity of energy was sufficient to heat the full depth of the panel within 12 hours.

In order to ensure that an equal amount of additional latent heat capacity was added to each type of panel, the actual latent heat
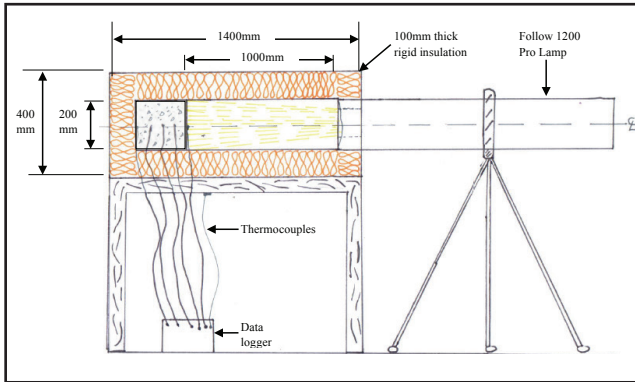
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Figure 2. Schematic of the light box design

capacity and melt temperatures of the PCMs was determined by Differential Scanning Calorimetry (DSC) tests. A scanning rate of 5°C/min was used across a temperature range of -30°C to 50°C. The tests were repeated three times on each sample. A summary of the results is shown in Figure 3. It was found that the latent heat capacities were 97J/g and 172J/g for the microencapsulated paraffin and butyl stearate respectively.
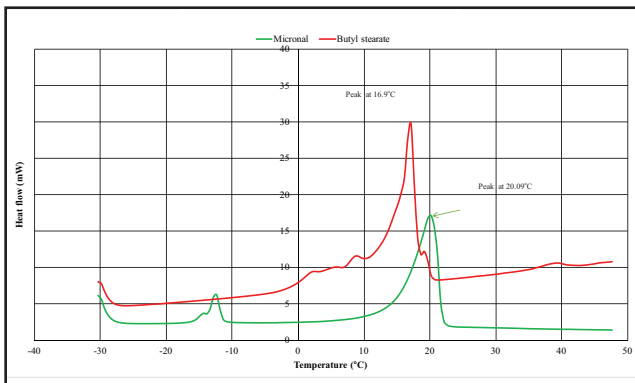

Figure 3. Heat flow V's temperature for PCM.

A microencapsulated paraffin product called Micronal was used in the microencapsulated PCM panels. Micronal is produced by BASF and comes in powder form, (Figure 4). Previous research studies, ([7] and [9]) concluded that 5% by mass of concrete is the optimum quantity of Micronal to be used in a concrete mix application. Higher quantities of Micronal yielded impractically low concrete strengths and also caused significant reduction in the thermal conductivity and density. This tended to counteract the increase in thermal storage capacity as heat flow into the panel was reduced. The latent heat capacity provided by incorporating 5% Micronal into the panels equated to 93120 joules.

Figure 4. 1.44kg of Micronal DS 5040X

The lightweight aggregate/PCM, composite was manufactured by the author in the laboratory. Preliminary tests were carried out on three types of lightweight aggregate to establish which type had the greatest absorption capacity – an expanded clay called LECA, an expanded fly ash called LYTAG, and pumice. The samples were dried in an oven. Then half of each sample was weighed and immersed in water for 24 hours. The other half of each sample was weighed and placed in a dessicator. Water was poured over the sample and a vacuum was applied for 40 minutes. The samples were subsequently surface-dried and weighed. The mass and volume of water absorbed was determined and it was established that LECA possessed the highest absorption capacity. The LWA/PCM composite was made by vacuuming the exact required quantity of butyl stearate into the LECA (Figure 5).

Figure 5. Manufacture of the aggregate/PCM composite

Thermal conductivity is a key parameter in thermal mass behavior. In particular for this study once the heat is absorbed at the surface of the panel, the conductivity of the panel material will directly influence the rate of heat transfer, that is the heat flux, through the sample and hence the rate of phase change of the PCM within the panel.

To determine the thermal conductivity of the panels a hot plate apparatus was used to create a steady state temperature differential across the samples, $(T_h - T_c)$ (figure 6). T_c was typically around 20°C and T_h was typically around 40°C. The heat flux exiting the cooler surface was measured using a heat flux pad and the measurement is given in W/m^2 which is equivalent to joules/(sec m^2), that is q/At (Eq 7). The depth 'd' of the samples is known and hence the conductivity can be calculated from:

$$k = \frac{q}{At} \cdot \frac{d}{(T_h - T_c)} \text{ (W/mK)} \quad (7)$$

Figure 6. Concrete samples placed in the hot plate rig

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The mass and density of each of the panels were also recorded.

To observe and record the thermal storage behaviour of the panels, light box tests were carried out in which each panel was placed in the light box, one at a time, and heated by the lamp for 12 hours. The panel was then allowed to cool for 12 hours while remaining in the light box. The temperatures of the front and rear surfaces and at 50mm depth intervals within the concrete panel were recorded during the heating and cooling periods. The recorded temperature data, together with the measured densities and thermal conductivities, were used to determine the thermal properties of each panel and to compare the thermal storage behaviour of the panels.

3. Results and discussion

3.1 The effect of PCMs on the properties of concrete

The strength of the concrete mixes was determined by standard cube tests in accordance with I.S. EN 12390-3. The addition of both the microencapsulated PCM (ME PCM) and the LWA/PCM composite had an adverse effect on the strength of the concrete panels. Both types of PCM panels only achieved strengths in the order of 25MPa after 28 days (Figure 7). The loss of strength may be due to leaked PCM, or possibly as a result of damaged capsules, interfering with the hydration process and/or adversely affecting the bond between the cement paste and the aggregate.
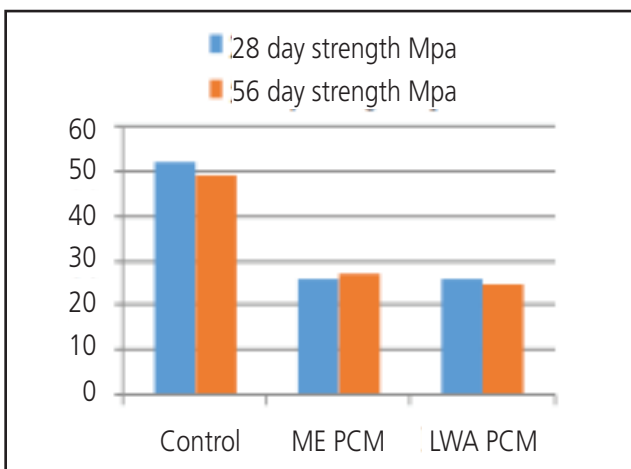

Figure 7. Concrete strengths achieved

Notwithstanding this the strengths achieved are still suitable for some structural applications, such as non-loadbearing facade panels and low-rise construction/domestic construction.

The addition of both types of PCM resulted in a reduction of 40-45% in thermal conductivity of the concrete (Table 1). This is caused by the relatively low conductivity of the PCM material. A reduced conductivity is not necessarily a problem as the desired conductivity depends on the required time frame within which the phase-change must occur – 12 hours in this study. Notwithstanding this, it is important that the conductivity of the PCM/concrete composite is sufficient to achieve a thermal diffusivity that will allow the heat to penetrate the full depth of the panel and melt all of the PCM so that the latent heat capacity provided by the PCM is fully utilised.

The density of both types of PCM/concrete composites was lower than the control concrete due to the lower density of the PCM relative to the density of cement paste (Table 1). The conductivity and density of the materials influence the thermal mass behavior. However, the effect that they have varies depending on the ratio of conductivity to density of the material (Ref Eq 3).

Table 1. Conductivity and density of panels

Panel Type	Density (kg/m³)	Conductivity (W/mK)
Control	2284	1.56
Control	2295	2.10
ME PCM 1	2075	1.20
ME PCM 2	2112	0.98
LWA/PCM 1	2076	0.82
LWA/PCM 2	2010	1.18

3.2 Thermal storage behaviour

The specific heat capacity of a material is given by:

$$Cp = \frac{\Delta Q}{m\Delta T} \quad \text{(J/kgK)} \quad (8)$$

where:
ΔQ = quantity of thermal energy transferred to material, (Joules)
ΔT = change in temperature of the material (°C).

However, for a PCM/concrete composite material the heat capacity varies during the phase transition and therefore as proposed by[17], eq. (8) must be modified to include the temperature gradient over time:

$$Cp = \frac{A.q}{m\frac{dt}{di}} \text{(J/kgK)} \quad (9)$$

where 'A' is the area of the sample (m²), q is the thermal energy supplied to the sample (W/m²), m is the mass (kg), dT/dt = increase in sample temperature in a given time step (°C/s).

In the light box tests carried out as part of this research each of the panels was exposed to equal amounts of thermal energy from the lamp over an equal time period of 12 hours hence the 'q' value is the same for each panel. Also the area exposed to the light is the same for each panel at 0.2m². Hence the overall thermal storage capacity of the panels can be compared by evaluating the mass x dT/dt value for each panel.

The heat flux, that is the rate of heat transfer through the PCM/concrete composite material, will vary throughout the depth of the material as the PCM changes phase. As a result, the heat flux transferred to the surface of the sample is overestimated with respect to the internal temperature gradient over time which leads to an overestimate of the overall thermal storage capacity. To overcome this issue the applied heat flux 'q' is left in the equation as a constant and only the data from the three internal thermocouples at 50mm, 100mm and 150mm is considered.
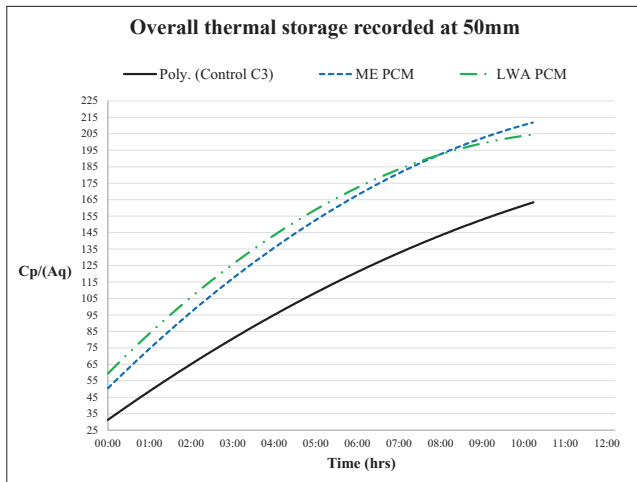
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Figure 8. Curves showing relative overall thermal capacity at 50mm

The temperature data for each panel was analysed and the time taken for each 1°C increase in temperature throughout the 12 hour period was determined, ie dT/dt over time. Each dT/dt value is then multiplied by the mass of the relevant panel and the reciprocal of the result is calculated, ie, 1/(m(dT/dt). This value is then plotted against time to observe how it varies over the 12 hour heating period. The higher the value of 1/(m(dT/dt) the higher the thermal storage capacity. The overall area under the resulting curves is indicative of the overall thermal capacity and a comparison of the thermal storage capacity of the panels was made

Figure 8 shows a plot of the relative overall thermal storage, as recorded at 50mm depth throughout the 12-hour heating period. It is clear that the panels containing PCM provide greater thermal storage capacity. As confirmed by computing the area under each of the curves, the lightweight aggregate panels (LWA/PCM) provide the highest additional overall thermal capacity measured at a depth of 50mm.

**Table 2. Additional thermal storage provided
by PCM panels measured at 50mm depth**

Panel Type	ΔT in Panel(°C)	% Overall thermal storage relative to control panel
Control	25	100.0
ME PCM	19	157.5
LWA PCM	18	161.7

The percentage of additional thermal storage and thermal mass provided by the PCM panels was determined and the results are shown in Table 2. It is noted that the LWA/PCM panel provides the largest increase in thermal storage of 61.7%. The panel with microencapsulated PCM (ME PCM) also provides a significant increase in thermal storage of 57.5%.

Table 3 and Table 4 show the equivalent results computed from the data recorded at 100mm depth and 150mm depth.

**Table 3. Additional thermal storage provided
by PCM panels measured at 100mm depth**

Panel Type	ΔT in Panel(°C)	% Overall thermal storage relative to control panel
Control	23	100.0
ME PCM	17	147.0
LWA PCM	15	143.0

**Table 4. Additional thermal storage provided
by PCM panels measured at 150mm depth**

Panel Type	ΔT in Panel(°C)	% Overall thermal storage relative to control panel
Control	23	100.0
ME PCM	17	152.0
LWA PCM	15	147.0

At each thermocouple location the LWA/PCM panel displays the lowest change in temperature over the 12-hour period. It can be noted that the overall thermal storage of the PCM panels reduces with depth relative to the control panel. This behavior is due to the lower conductivity and higher thermal storage capacity of the PCM panels which resulted in reduced thermal diffusivity and, in turn, reduced the effectiveness of the PCM as depth increased as the heat took longer to reach the PCM. As shown in Figure 9, the LWA/PCM panels displayed the lowest diffusivity. This means that the heat took longer to penetrate 100mm in the LWA/PCM panels, so over the 12-hour period the overall heat reaching 100mm depth in the LWA/PCM panels is less than that in the control panel and also the ME PCM panels. Hence the PCM becomes less effective with increasing depth.

In a real application the level of exposure to solar energy depends on both local climate and the position of the concrete element within the building, ie, exposure to daylight. Although not considered in this research, other sources of heat within a building arise from occupancy, equipment and lighting that depends on building use. Also, the build-up of heat within a building will depend on the level of insulation provided and the airtightness of the construction. Ultimately, in a real life scenario the effective depth of the PCM will depend on all these variables. Building energy performance software would be required to analyse the thermal behavior of a particular building taking into account all the relevant variables. This study has shown that in applications where the heat energy is reaching up to a depth of 100mm into the composite PCM/concrete walls, the LWA/PCM composite is more efficient at providing greater thermal storage capacity.
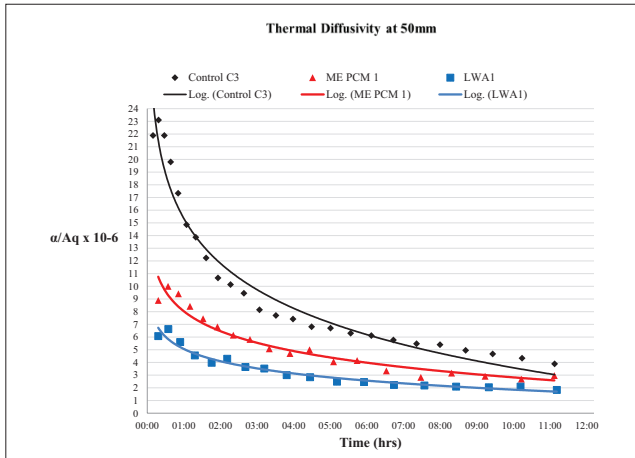
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Figure 9. Relative thermal diffusivity recorded at 50mm

Figure 10 shows the relative thermal inertia recorded at a depth of 50mm. It is noted that despite having the lowest thermal diffusivity, the LWA/PCM panel displays the lowest thermal inertia. This is caused by the low conductivity and density of the LWA/PCM panels.
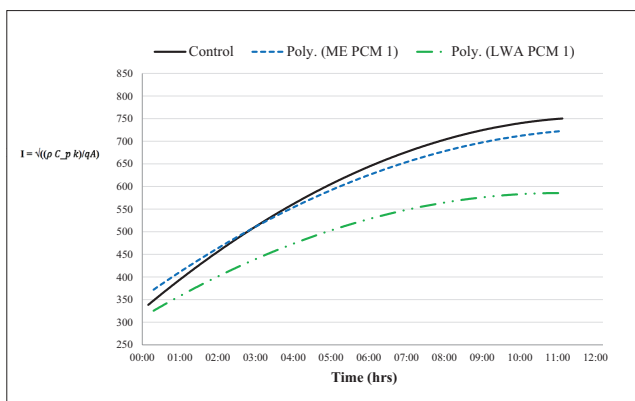

Figure 10. Relative thermal inertia recorded at 50mm

3.3 Cooling behavior

After the 12-hour heating period the Follow Pro 1200 lamp was switched off and the panels remained in the light box for a further 12 hours to cool down naturally while the temperature data was recorded. The panels did not cool down sufficiently within this time period to induce a solidification phase-change of the PCM within the panels. However, some observations and comparisons can be made regarding the rate of cooling of the front surface of the panels. In order to induce a solidifying phase-change the panels were also cooled in a fridge. In these tests all faces of the panel are exposed and the rate of temperature decrease is high.

An unexpected observation from the natural cooling data is that the front face of the ME PCM panel cooled at a higher rate than the control panel, despite having a lower conductivity and lower density. However, calculations showed that the ME PCM material has a lower overall thermal capacity C_p than the control panel outside of the phase-change period. As there was no phase-change taking place during this cooling period, it can be assumed that the C_p value for the ME PCM panel is lower than C_p for the control. This leads to a higher thermal diffusivity in the ME PCM panel, facilitating the release of heat from the front of the panel.

It is also observed that the rate of decrease in temperature is similar for the control panel and the LWA/PCM panel with the LWA/PCM panel showing a slightly higher rate of heat loss at the surface. Calculation showed that outside of the phase-change period, the control panel and the LWA/PCM panel have a similar heat storage capacity. The higher conductivity and density of the control panel is contributing to the slightly higher thermal inertia of the control panel.

A notable observation from the fridge cooling tests is that the LWA/PCM panel loses heat at a slightly slower rate, displaying a higher thermal inertia. The thermal capacity of the concrete matrix in the LWA/PCM panel is the same as the thermal storage capacity of the control panel. However, the heat released by the solidifying PCM slows down the cooling of the LWA/PCM panel. It was generally noted that the ME PCM and LWA/PCM panels have similar cooling rates and both panels display thermal inertia relative to the control panel. This is due to the release of heat from the PCM as it solidifies which slows down the rate of cooling.

The study of the data collected during the natural cooling of the panels within the light box highlighted a critical issue with the use of PCM/concrete composites in buildings, which is that the indoor temperature must fluctuate above the melting temperature and below the freezing temperature of the PCM within a 24-hour period. If this range of temperature fluctuation does not occur then the PCM will not discharge latent heat energy and will not have the capacity to absorb more heat the following day. The fluctuation in the indoor temperature depends on both the local climate and the level of insulation in a building. Modern buildings tend to be highly-insulated to prevent loss of heat energy though high levels of insulation may hinder the performance of a PCM thermal energy storage element within a building.

For this reason the use of PCM/concrete composites for enhanced thermal mass behaviour is more suitable for the refurbishment of buildings that have poor levels of insulation and airtightness. For example, in an analysis carried out by the World Business Council for Sustainable Development [18], it was stated that there is currently a stock of more than 80 million buildings in Europe that were constructed between 1950 and 1975 in an era when energy performance was not included in the design criteria. Rather than demolish these buildings it may be argued that a more sustainable solution would be to refurbish the façade of the building using panels with enhanced thermal mass properties that would improve the energy efficiency of these buildings.

4. Conclusions

Based on the results of the analysis presented in this paper the following conclusions can be made:

- Up to a depth of 100mm the concrete panels containing the LWA/PCM composite provided a greater increase in thermal storage capacity compared to the control panels and ME PCM panels;

- The LWA/PCM panel displayed the lowest increase in temperature throughout the 12-hour heating period;

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- The addition of both types of PCM caused a reduction in thermal conductivity and density. This resulted in lower thermal diffusivity in the panels containing PCM;

- As depth increases the level of thermal storage provided by the ME PCM panel approaches the storage provided by the LWA/PCM panel and, at a depth of 100mm, the storage provided by the ME PCM panel was slightly greater than the LWA/PCM panel. Hence if the local conditions allow the heat energy to penetrate deeper than 100mm, the ME PCM composite material will provide a greater increase in thermal storage capacity;

- The effectiveness of both types of PCM in increasing the overall thermal storage of the concrete panels relative to the control panel reduces with depth. This is due to the fact that the thermal diffusivity of the PCM panels is lower than the control panels, hence the heat takes longer to penetrate to a depth of 100mm in the LWA/PCM and ME PCM panels;

- As thermal diffusivity is the parameter that is hindering the effectiveness of the LWA/PCM composite, improving the conductivity of the LWA/PCM panels would further enhance the thermal performance of the material;

- The design of PCM/concrete composite applications in buildings requires careful consideration of local climate, building use and construction details. For the PCM to be effective it is critical that the temperature in the area that the PCM is located varies above and below the melt temperature range of the selected PCM within a diurnal period.

5. Further research

Further research is currently being carried out to investigate methods of improving the thermal conductivity of concrete containing light-weight aggregate/PCM composite. It is also planned to construct a number of full-scale huts using cladding panels containing an inner leaf wall constructed with PCM/concrete composite. These huts will be used to record thermal data to enable an assessment of thermal mass behaviour of the PCM/concrete inner wall under real conditions.

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