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Thermal Mass Behaviour of Concrete Panels Incorporating Phase Change Materials

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Thermal mass behaviour of concrete panels incorporating phase change materials



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Summary

Phase Change Materials (PCM) have been incorporated into a range of building envelope materials with varied success. This study investigates two different methods of combining concrete and phase change materials to form PCM/concrete composite panels. The first method involves adding microencapsulated paraffin to fresh concrete during the mixing process. The second method involves vacuum impregnating butyl stearate into lightweight aggregate which is then included in the concrete mix design. The primary aim of the study is to determine which method is the most effective way to improve the thermal mass characteristics of a concrete panel in the context of a thermal energy storage system for space heating in a building. The study observes the rate at which the panels absorb and emit heat, ie, the heat flux, and also how the heat flux changes throughout the depth of the panel. The panels are heated in a controlled environment provided by a specifically designed light box. Radiation is used as the heat transfer mechanism. Surface and internal temperatures of the panels are recorded during heating and cooling periods. The data recorded, together with the determined densities and thermal conductivities, are used to compare the thermal mass behaviour of each type of panel and to determine the influence that the method of incorporating a phase change material into a concrete panel has on the effectiveness of the PCM to improve the thermal mass characteristics of the concrete panel. The study highlighted the complexity of thermal behaviour of PCM/concrete composites. 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 (PCM), PCM/concrete, thermal mass, thermal diffusivity, thermal storage

1. Introduction

As the main consumer of material resources and energy, the construction industry has great potential to develop new efficient materials that reduce energy consumption in buildings. Using the mass of a building as a heat storage system can reduce the demand on the heating and/or cooling systems of the building. Concrete is a dense building material that combines a high specific heat capacity with a thermal conductivity that is appropriate for the diurnal heating and cooling cycle of buildings. The heat storage capacity of concrete can be enhanced by adding phase change materials (PCMs) which provide a high latent heat storage capacity. A thermal energy storage system can utilize sensible heat storage, latent heat storage or a combination of both. In sensible heat storage systems energy is stored in a material 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 [1]:

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

where:

Q = quantity of heat stored, (Joules).

T_f & T_i = final temperature and initial temperature respectively ($^{\circ}\text{C}$).

m = mass of heat storage material.

C_p = specific heat capacity of material (J/kgK).

A sensible heat storage system can be provided in a building by using the mass of the building as the storage unit. The ability of a material to store heat is referred to as its *Thermal Mass*.

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

For a material to provide good thermal mass it requires three properties:

- i. A high specific heat capacity, C_p (J/kgK).
- ii. A high density, ρ (kg/m^3)
- iii. An appropriate thermal conductivity, k , that suits the required storage period (W/mK)

Another relevant thermal property of a material is thermal diffusivity, α , which relates the ability of a material to conduct heat to the ability of a material to store heat.

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

Thermal diffusivity indicates the rate at which temperature changes occur in a material. The larger the value of thermal diffusivity the quicker the material will reach temperature equilibrium with its environment.

The thermal inertia of a material denoted 'I' is a measure of the responsiveness of a material to variations in temperature. Thermal Inertia can be calculated using the following equation [2]:

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

where ρ is the density, k is the thermal conductivity and C_p is the specific heat. A high thermal inertia describes materials that characterize high thermal mass. Referring to equation (3) for thermal diffusivity, α equation (4) can also be written as follows:

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

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.

The latent heat capacity of a PCM is the heat energy absorbed when the PCM changes phase. The temperature of the PCM remains constant during phase change. The heat capacity of a PCM/concrete composite material is not constant as it varies in accordance with the amount of phase change that has occurred. As a result the thermal inertia and thermal diffusivity of a PCM composite will also vary depending on the phase state of the PCM. For PCM composites the heat capacity is a combination of specific heat capacity and latent heat capacity. For this reason this paper will refer to the overall heat capacity of the PCM/concrete composites.

The selection of a phase change material for a given application requires consideration of the properties of the phase change materials. Depending on the application, PCMs should first be selected based on their melting temperature. For example materials that melt below 15°C are used in air conditioning systems for cooling spaces while materials that melt above 90°C are used for absorption refrigeration [3]. For a space heating application in a building, only PCMs with a melting temperature within the range of human comfort temperature (18-22°C) can be deemed suitable [4].

For this study the primary requirements for the PCM are:

- Fusion temperature around the human comfort temperature 18°C and 22°C.
- Chemical compatibility with concrete, steel and timber (formwork).
- Low volume change during phase change.

Both paraffin and butyl stearate have successfully been combined with concrete in previous research. The three predominant methods that are used for incorporating PCMs into concrete are immersion, vacuum impregnation and encapsulation. The immersion technique was used by a number of previous researchers [5], [6] and [7]. However the time required for the absorption of the PCM and evidence of leakage while in use were highlighted as problematic issues.

The vacuum impregnation method involves firstly evacuating the air from porous aggregates using a vacuum pump. The porous aggregates are then soaked in a liquid PCM under vacuum. Finally the PCM soaked aggregate is added to the concrete mix. Zhang et al [8] studied the ability of different types of porous aggregate to absorb butyl stearate. For the vacuum impregnation method it was found that an immersion time of 30 minutes at a temperature of 30° C above the melting temperature of the PCM optimises the absorption of PCM.

The most commonly used method for incorporating PCMs into concrete is micro-encapsulation, where small PCM particles (1µm to 1000µm) are encapsulated in a thin solid shell which is made from natural and synthetic polymers. These microcapsules can then be directly added to the con-

crete during the mixing process. This method provides a relatively large surface area of PCM throughout the concrete and hence it has the advantage of a high heat transfer rate per unit volume. Other advantages are that the capsules prevent leakage and resist volume change during phase change. However the microcapsules can affect the mechanical properties of concrete [9].

For this study two methods of incorporating the PCMs with concrete were selected. Firstly micro-encapsulated paraffin is added to fresh concrete during the mixing process. In the second method butyl stearate is vacuum impregnated into lightweight aggregate which is then included in the concrete mix design. This study will also investigate and compare the thermal behaviour of concrete panels that contain GGBS together with phase change materials that are incorporated using the methods noted above. This study aims to establish an optimum method of incorporating the phase change material into the structure and also an optimum depth of PCM to maximize the efficiency of the thermal storage behavior of the phase change material.

2. Methodology

The test groups of sample panels for the experimental design were selected as follows:

1. 4No. Control mix panels (2No. with 50% GGBS)
2. 4No. Concrete/microencapsulated PCM panels (2No. with 50% GGBS)
3. 4 No. Concrete + PCM lightweight aggregate panels (2No. with 50% GGBS)

Each concrete panel is 200mm x 200mm x 200mm. In order to record the temperature within the panels during testing each panel has 3No. thermocouples cast into the concrete at equal depth intervals of 50mm, together with thermocouples located on the front and rear faces. After casting the concrete panels are cured for 28 days and dried out for a further 28 days.

In order to replicate heat energy transfer from the sun while controlling the amount of heat energy that each panel is exposed to and ensuring that the panels are exposed to equal amounts of energy, 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 of the electromagnetic waves that are emitted. In order to exclude the environmental effects such as temperature variation in the test room, an insulated light box was designed and constructed as shown in Fig. 1.

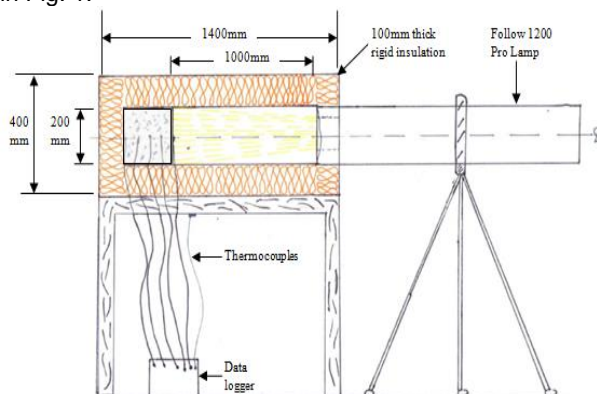


Fig.1 Schematic of the light box design

A microencapsulated PCM product called Micronal was used in the microencapsulated PCM panels. However the lightweight aggregate/PCM composite had to be manufactured. Preliminary tests were carried out on three types of lightweight aggregate to establish which type had the greatest absorption capacity. It was established that an expanded clay aggregate called LECA possessed the highest absorption capacity. The LWA/PCM composite was made by vacuuming the exact required quantity of butyl stearate (PCM) into the LECA.

The exact latent heat capacity of the PCMs was determined using Differential Scanning Calorimetry. These tests enabled the amount of latent heat capacity added to the panels to be accurately determined.

The conductivity of each of the panels was measured using an adjusted hot plate apparatus. The concrete panels were heated in the hot plate rig for 3- 4 days. When the concrete panels reached steady state the heat flux, q , (W/m^2) exiting the front face of the concrete panel was measured using a heat flux pad. The heat flux measurement is given in W/m^2 which is equivalent to J/sm^2 , ie q/At . The depth of the samples is known and hence the conductivity can be calculated from:

$$k = \frac{q}{At} \cdot \frac{d}{(T_h - T_c)} \quad (W/mK) \quad (6)$$

In order 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 while remaining in the light box. The temperature of the front and rear surfaces and at equal intervals within the concrete panel was recorded during the heating and cooling periods.

3. Results

3.1 The effect of PCMs on the properties of concrete

During the manufacture of the panels containing the LWA/PCM composite particles, the 'stickiness' of the fresh concrete suggested that some of the PCM leaked. It is likely that the heat of hydration causes the PCM to melt and as the LWA/PCM particles are not yet sealed by the hardened cement matrix the PCM can leak into the cement matrix. The leaked PCM may inhibit the migration of water and hence interfere with the hydration process and adversely affect strength development. Evidence of leakage of the butyl stearate was observed on the surface of the panels after they set (see Fig. 2).



Fig. 2. Leakage of PCM from the lightweight aggregate carrier

The addition of both the microencapsulated 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 (fig.3). The exact reason for the loss of strength requires further investigation. Notwithstanding this the strengths achieved are still suitable for some structural applications, such as non-loadbearing wall panels, low rise construction/domestic construction.

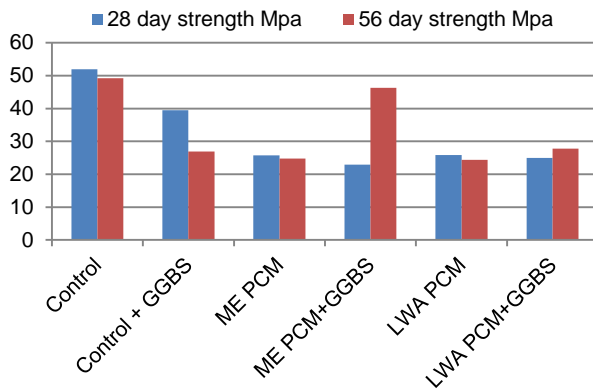


Fig. 3 Concrete strengths achieved

The thermal conductivity of each panel is a critical parameter as it directly influences the heat flux through the samples. The addition of both types of PCM resulted in a reduction in thermal conductivity of the concrete. The lower conductivity of the PCM panels resulted in reduced thermal diffusivity which in turn reduced the effectiveness of the PCM as depth increased as the heat took longer to reach the PCM.

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. The conductivity and density of the materials influence the thermal behavior however the effect that they have varies depending more on the ratio of conductivity to density of the material.

3.2 Heating behaviour

Eq. (1) can be rearranged to give:

$$C_p = \frac{\Delta Q}{m\Delta T} \quad (\text{J/kgK}) \quad (6)$$

However for a PCM/concrete composite material the heat capacity varies during the phase transition therefore as proposed by [11], eq. (6) must be modified to include the temperature gradient over time:

$$C_p = \frac{A \cdot q}{m \frac{dT}{dt}} \quad (\text{J/kgK}). \quad (7)$$

where 'A' is the area of the sample (m^2), q is the heat energy supplied to the sample (W/m^2), m is the mass (kg), dT/dt = increase in sample temperature in a given time step ($^{\circ}\text{C/s}$).

In the light box tests carried out as part of this research each of the panels was exposed to equal amounts of heat 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 $m \frac{dT}{dt}$ value for each panel.

As noted previously the heat flux ie rate of heat transfer through the 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 are considered.

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 $\frac{dT}{dt}$ over time. Each $\frac{dT}{dt}$ value is then multiplied by the mass of the relevant panel and the reciprocal of the result is calculated, ie $1/m \frac{dT}{dt}$. This value is then plotted against time to observe how it varies over the 12 hour heating period. The higher the value of $1/m \frac{dT}{dt}$ 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.

Fig. 4 shows a plot of the relative overall thermal storage, as recorded at 50mm depth. 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 provide the highest overall thermal capacity at a depth of 50mm.

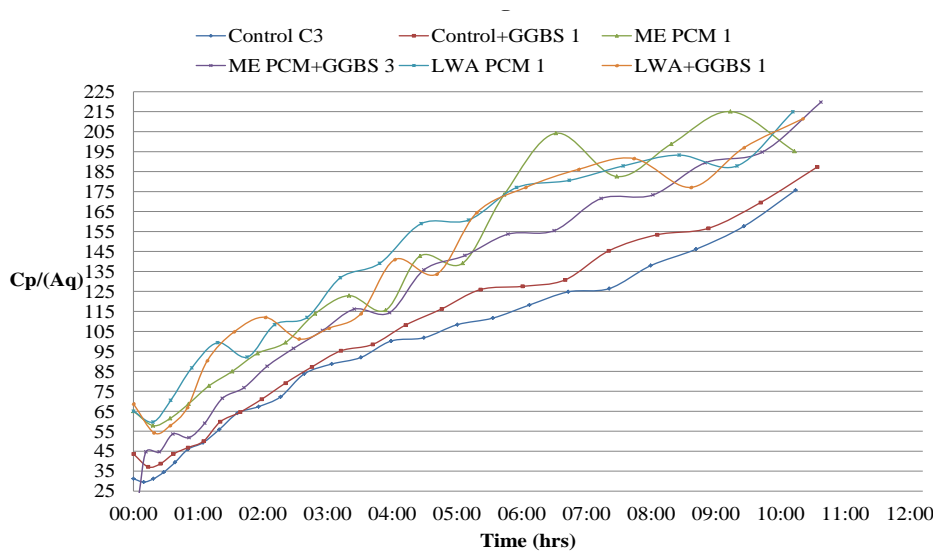


Fig.4 Curves showing relative overall thermal capacity at 50mm

The percentage of additional thermal storage and thermal mass provided by the PCM panels was determined by calculating the area under each curve and setting the value for the control curve at

100%. The results are shown in table 1. It is noted that the LWA PCM panel and the LWA PCM+GGBS panel provide the greatest increase in thermal storage of 61.7% and 59.4% respectively. The panel with microencapsulated PCM (ME PCM) panel and ME PCM+GGBS panel also provide a significant increase in thermal storage of 57.5% and 54.6% respectively.

Table 1. Additional thermal storage provided by PCM panels at 50mm, 100mm and 150mm depth

| Panel Type | % Overall thermal storage relative to control panel at: | | |
|---------------|---|-------|-------|
| | 50mm | 100mm | 150mm |
| Control | 100.0 | 100.0 | 100.0 |
| Control +GGBS | 129.9 | 112.0 | 105.0 |
| ME PCM | 157.5 | 147.0 | 152.0 |
| ME PCM + GGBS | 154.6 | 136.8 | 125.8 |
| LWA PCM | 161.7 | 143.0 | 147.0 |
| LWA PCM+GGBS | 159.4 | 147.0 | 154.0 |

It can be noted that the overall thermal storage of the PCM panels reduces relative to the control panel. Part of the reason for this is that the overall thermal storage for the control panel increases. However another factor that contributes to this behaviour is that the diffusivity of the control panels is higher than the PCM panels and the LWA panels have the lowest diffusivity as shown in fig. 6. This means that the heat is taking longer to reach 100mm in the LWA PCM panels, so over the 12 hours 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. These panels were subjected to a high level of heat energy for 12 hours. In a real application, a concrete floor or wall would not be exposed to such high levels of heat. The level of exposure depends on both local climate and position of the concrete element within the building, ie exposure to daylight. So the effective depth of the PCM will depend on the proposed location of the composite material. In applications where the heat energy is reaching up to a depth of 100mm into the composite PCM material the LWA PCM panels provide a greater thermal storage capacity.

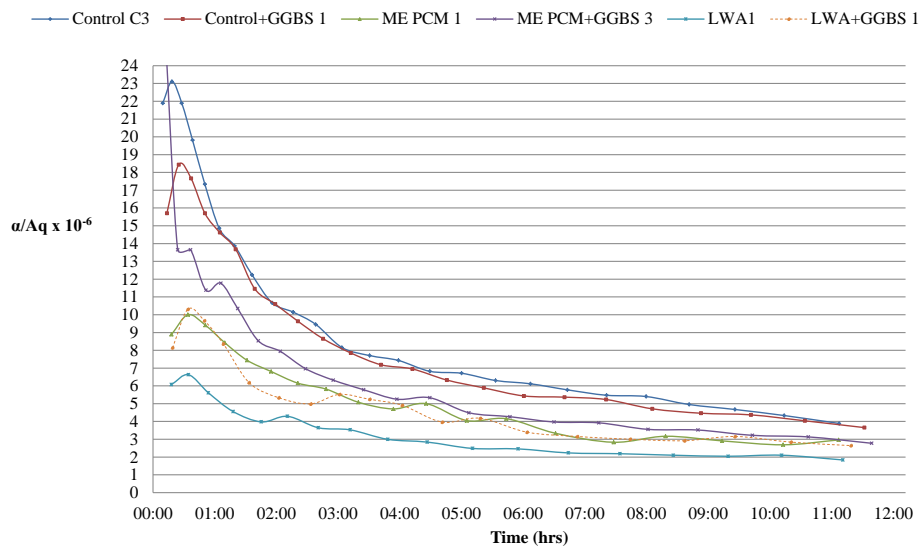


Fig. 6. Relative thermal diffusivity recorded at 50m

3.3 Cooling behaviour

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.

A study of the data recorded showed that there was no notable difference between the cooling behaviour of the panels containing GGBS and the panels without GGBS.

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 and this is leading 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.

4. Conclusion

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

- At a depth of 50mm the LWA PCM and LWA PCM+GGBS panels provide the greatest increase in thermal storage capacity over and above the control panel.
- The overall thermal storage of the PCM panels reduces relative to the control panel as depth increases due to the fact that the diffusivity of the control panels is higher than the PCM panels. Hence the heat will take longer to reach a depth of 100mm in the LWA PCM and ME PCM panels. As a result the PCM becomes less effective with increasing depth.
- 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. This means that for a 100mm thick wall panel or floor slab, the incorporation of a LWA/PCM composite is a more effective and efficient means of achieving a significant increase in the thermal energy stored.
- 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 overall thermal storage of a panel will increase as the amount of heat energy transferred to the panel increases. In a real application where a PCM/concrete composite material is used in a building to store thermal energy, the effective depth of the PCM will depend on the local climate at the proposed location of the building.
- 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 however high levels of insulation may hinder the performance of a PCM thermal energy storage element within a building.

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