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Influence of Ground Granulated Blastfurnace Slag on the thermal properties of PCM-concrete composite panels

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Abstract

The thermal mass of concrete within a building can be used as an energy storage system and hence reduce the demand on the auxiliary heating and cooling systems in the building. The heat storage capacity of concrete can be enhanced by adding phase change materials (PCMs) which provide a high latent heat storage capacity. However the addition of PCM to concrete reduces the conductivity of the concrete due to the low conductivity of the PCMs. This hinders the efficient utilisation of the additional heat storage capacity provided by the PCM.

It is generally understood that the use of ground granulated blastfurnace slag (GGBS) as a partial cement replacement results in a denser cement paste which, for a given aggregate type, increases the conductivity of the concrete. The aim of this study was to determine if the use of GGBS influences the thermal mass behaviour of a PCM-concrete.

Two types of PCM-concrete panels were manufactured. Firstly microencapsulated paraffin was added to fresh concrete during the mixing process. Secondly butyl stearate was vacuum impregnated into lightweight aggregate which was then included in the concrete mix. Half of the samples contained 50% GGBS cement replacement and consequently the effect of GGBS on the thermal performance is reported.

Key words: Phase change materials; PCM-concrete; Thermal conductivity; GGBS; Thermal diffusivity; Thermal storage

1. Introduction

In the European Union the construction and end use of buildings consumes 40% of Europe's total energy. As the main consumer of material resources and energy, the construction industry has great potential to develop new efficient materials to reduce energy consumption in buildings. The IEA Technology Roadmap on Energy Efficient Building Envelopes states that improvements in building envelopes can reduce the sector's total energy consumption by a factor of 20% [1]. One method that can be employed to reduce the energy demand of buildings is to use the building skin to store thermal energy. The ability of a material to store and release heat is a function of the heat storage capacity of a material and is commonly referred to as *thermal mass.* An effective way to enhance the thermal storage capacity of buildings is to incorporate phase change materials (PCMs) into building materials. PCMs absorb and release high quantities of heat energy at specific temperatures as their phases change, that is from solid to liquid and from liquid to gas. When incorporating a PCM into a building material it is only feasible to consider the solid-liquid phase change. The temperature of the PCM remains constant during phase change so the PCM provides a high latent heat capacity.

Hawes et al. [2] first introduced the idea of increasing the thermal mass of concrete by combining a PCM with concrete in 1992. Several researchers have since investigated different methods of incorporating PCMs into concrete including macro-encapsulation [3-5], micro-encapsulation [6-9] and vacuum impregnation [9-11]. Studies have also been carried out to determine the properties and observe the thermal behaviour of PCM-concrete composites [7, 9-13].

For a material to provide good thermal mass it requires a high specific heat capacity, C_p (J/kgK), a high density, ρ (kg/m^3) and an appropriate thermal conductivity, k (W/mK) that suits the required storage period. The addition of PCM to concrete increases the overall heat storage capacity by adding the latent heat capacity of the PCM to the specific heat capacity of the concrete. However the organic PCMs that are suitable for combining with concrete also have a low conductivity which can hinder their activation and reduce the efficiency of their application.

GGBS is a by-product of steel manufacture which is commonly used as a partial cement replacement. It reacts with the calcium hydroxide that is produced by the reaction between Portland cement and water, to form a cementitious material. When all other variables are equal, including aggregate type, it is understood that the use of GGBS results in a denser concrete which in turn increases the thermal conductivity. This study investigates the influence of using 50% GGBS cement replacement on the overall thermal mass behaviour of PCM-concrete composite panels.

There are many different types of PCMs which can be broadly categorised as organic, inorganic and eutectic. Pasupathy et al. [14] summarised the advantages and disadvantages of each category. For a PCM-concrete composite that is to be used in a space heating/cooling application, the primary requirements for the PCM are a melting temperature within the human comfort range of 18^{o}C – 22^{o}C, chemical compatibility with concrete and timber and a low volume change during phase change. Taking these requirements into consideration organic PCMs were deemed the most suitable for use in this study.

Paraffin is an organic PCM with melting temperatures between 20^{o}C and 70^{o}C. It is inactive in an alkaline environment, chemically stable and relatively inexpensive however it also has a relatively low conductivity [15]. Previous researchers [7-9, 12] have combined paraffin and concrete in thermal energy storage studies. In this study a microencapsulated paraffin product called Micronal (figure 1), which comes in a powder form was selected. The powder is added to the fresh concrete towards the end of the mixing process to limit any damage to the capsules. As the capsules are very small (1μm to 1000μm) this product provides a large surface area for heat transfer. The capsules also prevent leakage and resist volume change during phase change. However previous studies [7,12] concluded that 5% by mass of concrete is the optimum quantity of Micronal as higher quantities resulted in lower concrete strengths and significant reductions in density and thermal conductivity which hindered the utilisation of the additional latent heat capacity provided by the PCM.

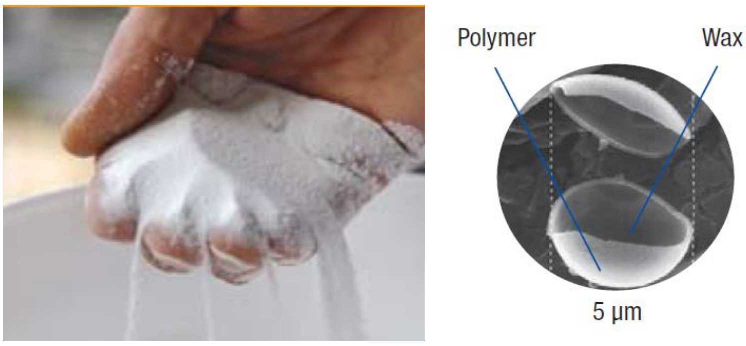

Figure 1. Images of Micronal DS 5040 X

A second organic PCM called butyl stearate was also utilised in this study. Butyl stearate is a fatty acid with melting temperatures similar to that of paraffin. In previous research that combined butyl stearate with porous lightweight aggregates (LWA) [10, 11] the composite was found to be chemically compatible, non-toxic and had a large thermal energy storage density. In this study a vacuum impregnation technique was used to incorporate the butyl stearate into a lightweight expanded clay aggregate which had a high absorption capacity. The air was evacuated from the aggregates prior to soaking the aggregates in liquid butyl stearate under a vacuum using a sealed dessicator (figure 2). The LWA/PCM composite was incorporated into the concrete mix design by replacing an equal volume of ordinary aggregate with the determined required volume of LWA/PCM.

Figure 2. Manufacture of the aggregate/PCM composite

This study aimed to investigate the influence of GGBS on the thermal mass behaviour of two types of PCM-concrete composite panels, one type containing micro-encapsulated paraffin and a second type containing a LWA/PCM composite.

2. Methodology

In order to ensure that equal amounts of additional latent heat capacity were added to each type of panel Differential Scanning Calorimetry tests (DSCs) were carried out on each of the PCMs to determine their exact melting temperature range and latent heat capacity. The summary of the results are shown in figure 3 and tabulated in table 1.

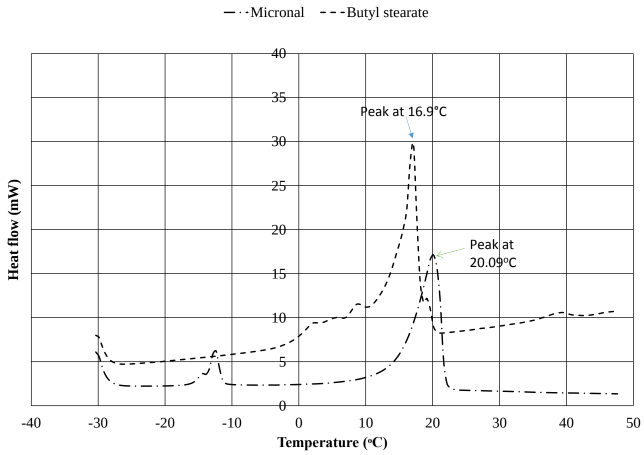

Figure 3. Heat flow V's temperature for PCMs

	Measurement	Butyl Stearate	Micronal
Heating	**Onset (°C)**	15.2	15.1
	Peak (°C)	16.9	20.1
	Latent heat (J/g)	**171.5**	**97.3**

Table 1.Results of DSC tests highlighting latent heat of fusion

From the results of the DSC tests, the latent heat capacity provided by 5% Micronal (by mass of concrete) was determined and then the required quantity of butyl stearate to provide an equal amount of latent heat capacity was calculated. This exact amount of butyl stearate was then vacuum impregnated into the lightweight aggregate.

A total of 12 concrete panels were manufactured, grouped as shown in figure 4. Six panels were made using 50% GGBS. The depth of each panel was 200mm to reflect a typical wall thickness and both the width and length of the panels were 200mm. Three thermocouples were cast into the panels at equal depth intervals of 50mm and thermocouples were also located on the front and rear faces of the panels. Each panel was cured for 28 days and then allowed to dry out for a further 28 days. As moisture content can significantly influence thermal conductivity the moisture content was monitored regularly during the drying out period to ensure that it was less than 4% prior to carrying out the thermal conductivity tests.

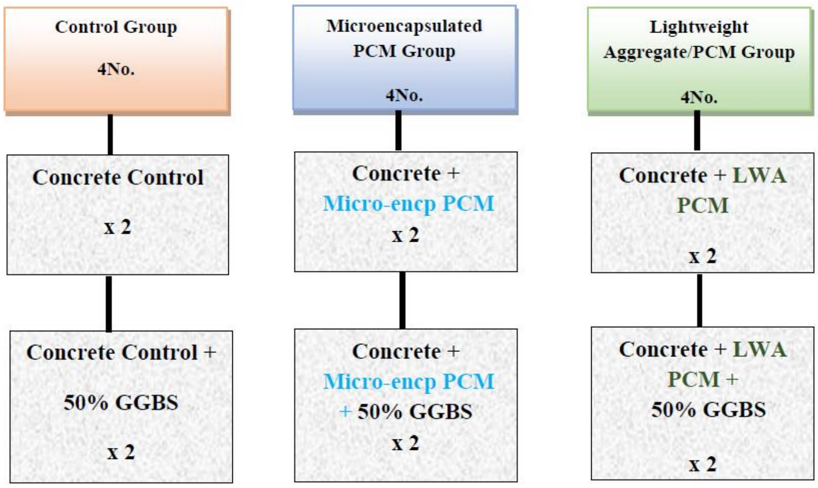

Figure 4 Panel test groups for experimental design

The thermal conductivity of each panel was a key parameter for this study. Once the heat is absorbed at the surface of the panel, the conductivity of the panel material directly influences the heat flux through the sample and hence the rate of activation of the PCM. To determine the conductivity of the panels an adjusted hot plate apparatus was used (figure 5). The concrete panels were heated in the hot plate rig until a steady state condition was confirmed, that is deviations between successive temperatures over a period of 4 hours have diminished to less than 0.5^{o}C [16]. The heat flux, q, (W/m^2) exiting the front face of the concrete panel was then measured by placing a heat flux pad, of area A, on the surface of the concrete. The measurement is given in W/m^2 which is equivalent to Joules/(sec m^2) that is q/At. The depth of the samples, d, is known and hence the conductivity can be calculated from:

$$k = \frac{q}{At} \cdot \frac{d}{(T_h - T_c)} \quad (W/mK) \qquad (1)$$

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

Figure 5. Concrete samples placed in the hot plate rig

To observe thermal mass behaviour the panels were heated for a 12 hour period and then allowed to cool for a further 12 hours. The heating and cooling curves were recorded throughout the depth of each panel. In order to replicate solar heat energy transfer, radiation was selected as the mechanism of heat transfer. An artificial light source was used (Follow 1200 Pro Lamp) with which it was possible to control the wavelength of the electromagnetic waves that are emitted and hence the amount of heat energy that each panel is exposed to. Tests were carried out on the lamp to determine the optimum distance between the light source and the front surface of the concrete panel that ensures that the light intensity (Lux) is evenly spread across the entire surface while maximising the heat energy received by the front of the concrete panel (Watts). The results of these tests informed the design and construction of an insulated light box within which the panels could be heated and cooled while environmental effects were excluded (figure 6).

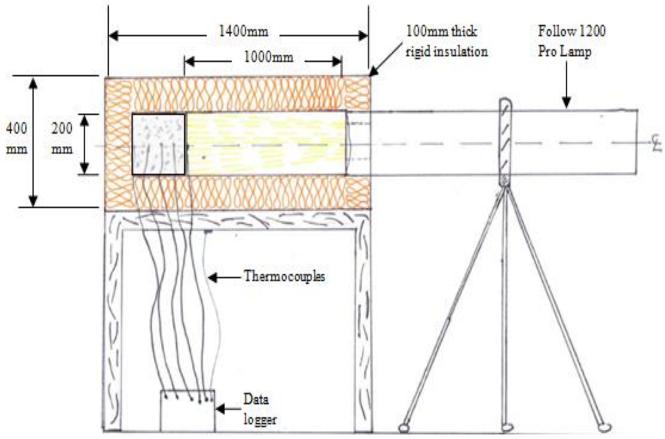

Figure 6. Schematic of the light box design

Each panel was placed one at a time into the light box and heated by the lamp for 12 hours. The thermocouples recorded the temperatures every 30 seconds at the front and rear surface and at 50mm depth intervals internally. 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 Influence of GGBS on properties of PCM-concrete composite

The strength test results for the control and PCM-concrete mixes are given in table 2. The addition of both types of PCM had an adverse effect on the strength of the concrete regardless of the presence of GGBS. This reduction in strength aligns with results from previous research [7]. In all cases - except the 56 day strength of the LWA PCM panel – the strength of the panels containing GGBS is lower. This is not unexpected as the reaction of the GGBS with calcium hydroxide is relatively slow when compared to the hydration of Portland cement hence the rate of strength gain is typically slower in concrete containing GGBS.

Cube type	**28day MPa**		**56day MPa**	
	100% OPC	**50% GGBS**	**100% OPC**	**50% GGBS**
Control	**51.9**	**39.5**	**49.2**	**46.3**
+ME PCM	**25.7**	**22.9**	**26.9**	**24.8**
LWA PCM	**25.8**	**25.0**	**24.4**	**27.8**

Table 2. Compression strength of concrete cubes.

It can be concluded from the strength tests that the presence of PCM is the determining factor in the strength of the PCM-concrete composite and it overrides any effect that GGBS may have on the strength of the cement matrix. It can also be noted that there is little difference between the strength of the ME PCM-concrete and the LWA PCM- concrete indicating that the presence of LWA is not a determining factor in the strength of the LWA PCM-concrete mix however further research is required to confirm this.

The density of the control and PCM-concrete mixes are given in table 3. The densities of the panels containing PCM are lower than the control panels. This can be attributed to the lower density of the PCMs relative to the other constituents of concrete. The panels with 50% GGBS show a small increase in density however it cannot be considered significant given the variability of concrete.

Panel Type	**Density (kg/m^3)**	
	100% OPC	**50% GGBS**
Control	2284	2322
Control	2295	2350
ME PCM	2075	2086
ME PCM	2112	2099
LWA/PCM	2076	2095
LWA/PCM	2010	2075

Table 3. Densities of panels

The thermal conductivity of each of the panels is given in table 4. As expected the presence of PCM reduces the conductivity of the concrete. The reduction aligns with findings of previous research studies ([7] [12]). Although the panels containing 50% GGBS generally show a slight increase in thermal conductivity the increase cannot be considered significant given the variability of both concrete and the testing method.

Panel Type	**Thermal conductivity (W/mK)**	
	100% OPC	**50% GGBS**
Control	1.56	1.59
Control	1.21	1.21
ME PCM	1.20	1.28
ME PCM	0.98	1.03
LWA/PCM	0.82	0.91
LWA/PCM	1.18	1.16

Table 4. Thermal conductivity of panels

3.2 Influence of GGBS on thermal mass behaviour of PCM-concrete composite

An analysis was carried out to obtain comparative values for the overall thermal capacity of the panels. The general equation for the specific heat capacity of a material is as follows:

$$C_p = \frac{\Delta Q}{m \Delta T} \quad \text{(J/kgK)} \tag{2}$$

where: ΔQ = increase in internal heat energy of material (Joules).

ΔT = change in temperature of the material (^oC).

m = mass of heat storage material.

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

However for a PCM/concrete composite material the overall heat capacity varies during the phase transition due to the variation in the latent heat capacity provided by the PCM. Therefore as proposed by Pomianowski et al. [13], equation (2) must be modified to include the temperature gradient over time:

$$C_p = \frac{A.q}{m\frac{dT}{dt}} \quad \text{(J/kgK).} \tag{3}$$

where:

- A = heated sample area (m^2)
- q = heat energy supplied to the sample (W/m^2)
- m = mass of sample (kg)
- dT/dt = increase in sample temperature in a given time step ($^oC/s$)

During the light box tests each of the panels were 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 0.2m x 0.2m. 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 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^{o}C increase in temperature throughout the 12 hour period was determined, that is 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, that is 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 of the panels and a comparison of this thermal storage capacity was made.

Figures 7, 8 and 9 show plots of the overall thermal storage of the panels with GGBS relative to the panels without GGBS for each panel type, as recorded at 50mm depth. Table 5 gives a summary of the percentage increase in the thermal storage provided by each panel relative to the control panel with no GGBS. These values were determined by computing the areas under the curves and setting the value for the control panel to 100%.

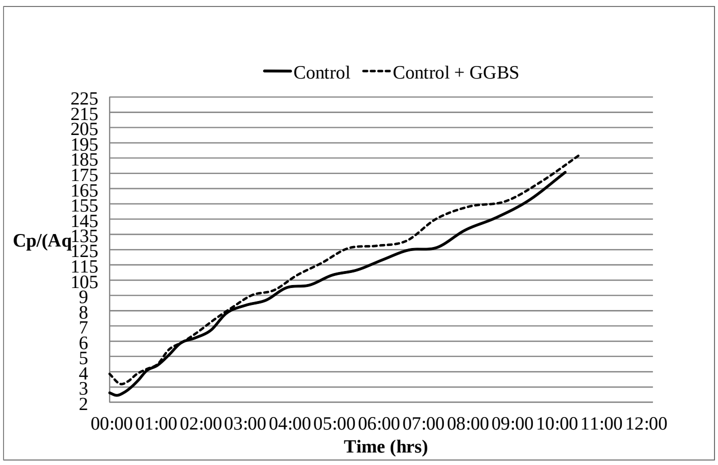

Figure 7. Overall thermal storage capacity in control panels at 50mm

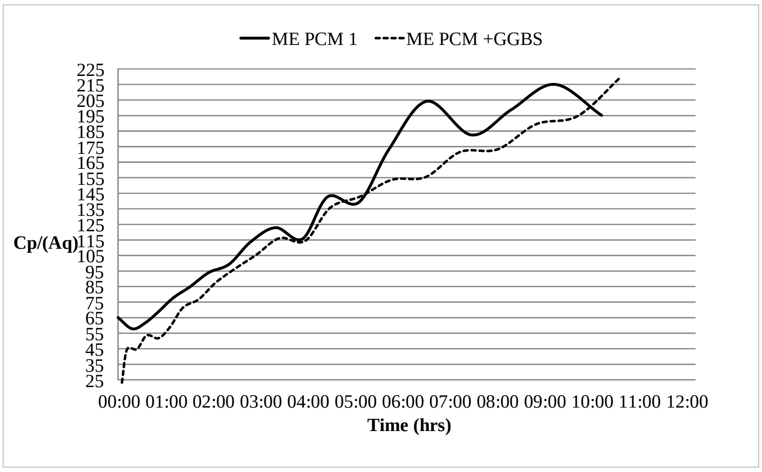

Figure 8. Overall thermal storage capacity in ME PCM panels at 50mm

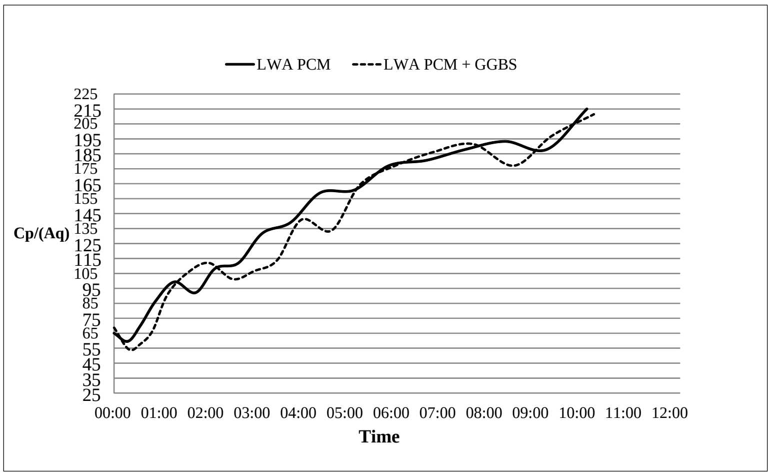

Figure 9. Overall thermal storage capacity in LWA PCM panels at 50mm

Panel Type	**ΔT in panel (^{o}C)**	**% Overall thermal storage relative to control panel**	**ΔT in panel (^{o}C)**	**% Overall thermal storage relative to control panel**	**ΔT in panel (^{o}C)**	**% Overall thermal storage relative to control panel**
	@ 50mm depth		**@ 100mm depth**		**@ 150mm depth**	
Control	25	100.0	23	100.0	21	100.0
Control +GGBS	23	129.9	21	112.0	19	105.0
ME PCM	19	157.5	17	147.0	15	152.0
ME PCM + GGBS	22	154.6	18	136.8	16	125.8
LWA PCM	18	161.7	16	143.0	14	147.0
LWA PCM+GGBS	19	159.4	18	147.0	16	154.0

Table 5. Percentage increase in thermal storage relative to the control panel with no GGBS at depths of 50mm, 100mm and 150mm in each panel

As expected the panels containing PCM provide a significantly greater thermal storage capacity. The control + GGBS panel displayed a notable increase in thermal storage of 30% at a depth of 50mm. This increase reduces with depth indicating that the heat is progressing into the GGBS panel at a slower rate. A thermal property that contributes significantly to thermal mass behaviour is thermal diffusivity, α which is the ratio of the conductivity of a material to its volumetric heat storage capacity.

$$\alpha = \frac{k}{\rho C_p} \quad (m^2/s) \qquad (4)$$

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. As noted in section 3.1, there is no significant difference between the thermal conductivity and density of the control and the control+GGBS panels. This indicates that the specific heat capacity, C_p of the control panel with GGBS is greater than the C_p of the Portland cement control panel, that is more heat energy is required to increase the temperature of the GGBS panel. This is demonstrated further by the lower temperature change in the control+GGBS panel over the 12 hour heating period. Given that the concrete mix for both types of panels was identical other than the use of GGBS, the increase in specific heat capacity of the GGBS panel can be attributed to the presence of GGBS in the cement paste.

In the ME PCM panels, the panel with GGBS provides slightly less thermal storage at a depth of 50mm however this difference increases with depth again indicating that the thermal diffusivity is lower in the panel containing GGBS. Hence as the rate of heat penetration into the panel reduces, less PCM is melting and the effective depth of the PCM reduces. The change in temperature in the panels with GGBS is greater indicating that the contribution of the specific heat capacity of the concrete matrix to the overall thermal storage capacity is slightly greater in these panels.

The LWA PCM panels provide the greatest increase in overall thermal energy storage, up to a depth of 150mm, despite having the lowest conductivity and density. The reason for this can be noted from the results of the DSC tests which show that butyl stearate has a narrow melting temperature range (15-17^{o}C) enabling it to melt efficiently. However as the PCM absorbs heat and melts it hinders the penetration of heat deeper into the panel and the thermal diffusivity reduces at a higher rate in the LWA PCM panels. Hence the PCM becomes less effective with increasing depth. The LWA PCM+GGBS panel provides greater thermal storage than the LWA PCM panel without GGBS as depth increases. The reason for this may be that the influence of the higher specific heat capacity of the GGBS cement matrix on the overall heat capacity increases as the effectiveness of the PCM (latent heat capacity) decreases.

4. Conclusions

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

- The presence of PCM is the determining factor in the strength of the PCM-concrete composite and it overrides any effect that GGBS may have on the strength of the cement matrix.
- The panels containing 50% GGBS showed a slight increase in thermal conductivity but the increase cannot be considered significant given the variability of both concrete and the testing method.
- The control panel containing 50% GGBS displayed a notable increase in thermal storage capacity relative to the control panel without GGBS. This increase in thermal conductivity decreased with depth indicating that the panel with GGBS has a lower thermal diffusivity.
- As there was no significant difference between the density and conductivity values for both control panels, the lower thermal diffusivity of the control panel with GGBS can be attributed to a higher specific heat capacity. The higher specific heat capacity of the control+GGBS panel is also indicated by the lower temperature increase in the panel over the twelve hour heating period. As the concrete mixes for the two control panels are identical except for the presence of GGBS the higher specific heat capacity of the GGBS panel can be attributed to the presence of GGBS in the cement paste.
- The ME PCM panels containing GGBS displayed lower thermal diffusivity relative to the ME PCM panel without GGBS. The lower thermal diffusivity reduced the effective depth of the PCM. The change in temperature in the panels with GGBS is greater indicating that the contribution of the specific heat capacity of the concrete matrix to the overall thermal storage capacity is greater in these panels.
- The LWA PCM panel containing GGBS provided greater thermal storage than the LWA PCM panel without GGBS with increased depth. The reason for this may be that the influence of the higher specific heat capacity of the GGBS cement matrix on the overall heat capacity increases as the effectiveness of the PCM (latent heat capacity) decreases.

- Further research is required to quantify the relationship between GGBS content and specific heat capacity of cement pastes.

5. Further research

Further research is currently being carried out to investigate methods of improving the thermal conductivity of concrete containing lightweight aggregate/PCM composite.

Acknowledgements

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[1]http://www.project-impress.eu

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