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Mechanical and Thermal Evaluation of Different Types of PCM-concrete composite panels

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Mechanical and thermal evaluation of different types of PCM-concrete composite panels

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ABSTRACT: Thermal mass indicates the ability of a material to store and release heat and is a function of the heat storage capacity of a material. The thermal mass of construction materials can be used to reduce the energy required for heating and cooling buildings. The heat storage capacity of concrete can be increased by incorporating phase change materials (PCMs) into the concrete and hence providing additional latent heat storage capacity. Research was carried out to compare the thermal behaviour of two different types of 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. This study aimed to establish which type of PCM/concrete composite material was most effective at improving the thermal mass behaviour of the panel and also to evaluate the effect that the PCM had on the relevant properties of concrete. The panels were exposed to radiative heat energy in a controlled environment for a specified time period during which the surface and internal temperatures of the panel were recorded. The temperature data together with the measured density and thermal conductivity was used to evaluate and compare the thermal mass behaviour of each type of PCM/concrete composite material. The addition of PCM to the concrete significantly increased the overall thermal storage capacity of the concrete despite reducing the density and thermal conductivity of the concrete. It was determined that the concrete containing the lightweight aggregate/PCM was more effective at increasing the thermal storage capacity up to a depth of 100mm.

KEY WORDS: Phase change materials; PCM concrete; Thermal conductivity; Thermal diffusivity; Thermal storage

1 INTRODUCTION

The use of renewable energy sources is increasing due to the drive to reduce the threat of climate change and secure energy supply. Solar energy is a major renewable heat energy source however its intermittent nature means that its effectiveness is dependent on the inclusion of an efficient thermal energy storage system. Thermal storage systems 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 its temperature. 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 mass of a building can be used to provide a sensible heat storage system and hence act as a *thermal mass.* 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. This study aimed to improve the thermal mass characteristics of concrete by adding latent heat capacity through the incorporation of phase change materials and hence increasing its overall heat storage capacity.

The latent heat capacity of a PCM is the heat energy absorbed by the PCM when it changes from one phase to another, ie from solid to liquid and from liquid to gas. For practical reasons it is only feasible to use the solid-liquid phase change of a material when incorporating a PCM into a building component. The temperature of the PCM remains constant during phase change. The heat capacity of a PCM/concrete material is not constant as it varies in accordance with the state of the phase transition. 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.

There are many different types of PCMs hence the selection of a phase change material for a given application requires consideration of the properties of the phase change materials and a weighing up of their particular advantages and disadvantages in order to reach an acceptable compromise. 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, only phase change materials with a melting temperature within the range of human comfort temperature (18-22^{o}C) can be deemed suitable [1].

Paraffin is an organic PCM with melting temperatures ranging between 20^{o}C and 70^{o}C. A number of researchers ([2], [3] and [4]) have carried out thermal energy storage studies that combined paraffin with concrete. Generally from a 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 [5].

Butyl stearate is a fatty acid with melting temperatures similar to that of paraffin. It has also successfully been combined with concrete in previous research.

There are three main methods used for incorporating PCMs into concrete - immersion, vacuum impregnation and encapsulation. The immersion technique was used by a number of previous researchers ([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^{o} C above the melting temperature of the PCM optimises the absorption of the PCM.

The most commonly used method for incorporating PCMs into construction materials is micro-encapsulation, where PCM particles (1μm to 1000μm) are encapsulated in a thin shell which is made from natural and synthetic polymers. These microcapsules are then added to the concrete during the mixing process. This method provides a large surface area of PCM throughout 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 affect the mechanical properties of concrete [9].

For this study two methods of incorporating the PCMs with concrete were selected, a microencapsulated paraffin product which was available ready made and vacuum impregnated butyl stearate which was manufactured in the laboratory. The study aimed to establish the most effective method of incorporating phase change material into concrete and also an optimum depth of PCM to maximize the efficiency of the thermal storage behaviour of the phase change material.

2 METHODOLOGY

Based on the two different methods selected for combining PCMs and concrete, test groups of sample panels for the experimental design were selected, two of each type (one duplicate) and two control panels without PCMs.

A panel depth of 200mm was selected to reflect the typical thickness of a wall within a building hence the panels were constructed to be 200mm x 200mm x 200mm. Each panel had 3No. thermocouples cast internally into the concrete at equal depth intervals of 50mm. Thermocouples were also located on the front and rear faces. After casting the concrete panels were cured for 28 days. As moisture content can significantly influence the thermal conductivity of concrete the panels were allowed to dry out for a further 28 days during which moisture content was monitored. All panels had a moisture content less than 4% prior to conductivity tests being carried out.

The context of this research project was to study the potential thermal storage behaviour within a pcm-concrete internal leaf of a cladding panel. In this application the internal leaf would normally have a layer of insulation on the outer face hence transmission of heat through the panel is minimal. For this reason, international standards for determining the thermal transmission properties *through* materials (ISO 8990, ASTM C1363-05) were not used. To confine the investigation to the transmission of heat into and within the pcm-concrete panel, the panels were surrounded with insulation on all but one face which was then exposed to a heat source. To exclude the environmental effects such as temperature variation in the test room, an insulated light box was designed and constructed as shown in Figure 1.

In previous research ([7], [11]) conduction and convection were used as mechanisms of heat transfer. In this study, in order to replicate a solar heat source radiation was chosen as the mechanism of heat transfer. To control the amount of heat energy that each panel is exposed to, 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.

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 results of these tests enabled the dimensions of the light box to be optimised to ensure that the heat energy is uniformly applied to the surface of the concrete panels and that the intensity of the heat energy is sufficient to heat up the panels within the selected time frame of 12 hours.

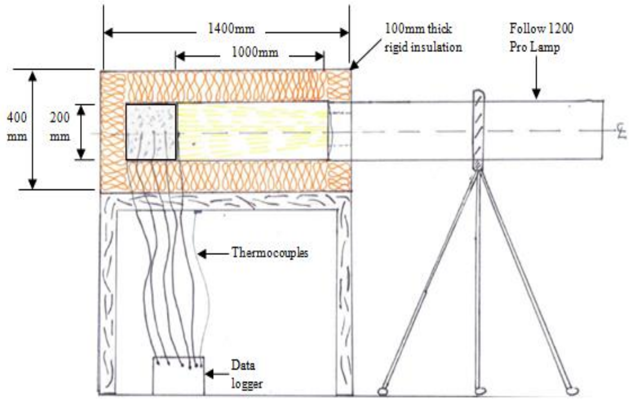

Figure 1. Schematic of the light box design

A microencapsulated PCM product called Micronal was used and came in powder form, (Figure 2). Previous research studies, ([2] and [4]) 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 which tended to counteract the increase in thermal storage capacity.

Figure 2. 1.44kg of Micronal DS 5040X

The lightweight aggregate/PCM composite was manufactured in the laboratory. Initial tests were carried out to establish the absorption capacity of three types of lightweight aggregate. 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 using a sealed dessicator, (Figure 3).

Figure 3. Manufacture of the aggregate/PCM composite

Differential Scanning Calorimetry tests were carried out on the PCMs to determine their actual latent heat capacity and melting temperature ranges. The summary results are shown in figure 4. The results of these tests enabled the amount of latent heat capacity added to the panels to be accurately determined and equalised for each type of panel.

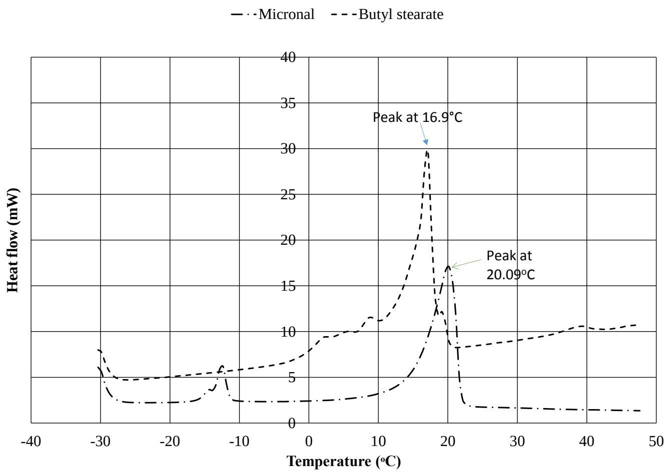

Figure 4. Heat flow V's temperature for PCMs

The thermal conductivity of each panel is a critical parameter for this study as once the heat is absorbed at the surface of the panel, the conductivity of the panel material will directly influence the heat flux through the sample and hence the thermal mass behaviour. An adjusted hot plate apparatus was used to determine the conductivity of the panels. The concrete panels were heated in the hot plate rig until a steady state condition was confirmed. 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) ie 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.

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 temperatures of the front and rear surfaces and at equal 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*

A concrete mix was designed in accordance with Teyenne et al. [10]. It was noted during the trial mix that the addition of microencapsulated PCM reduced the workability of the fresh concrete significantly. The quantity of superplasticiser had to be increased to a level normally associated with self-compacting concrete in order to obtain a workable 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 during the hydration process. It is likely that the heat of hydration caused the PCM to melt and as the LWA/PCM particles were not yet sealed by the hardened cement matrix the PCM leaked 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 (Figure 5).

Figure 5. Leakage of PCM from the lightweight aggregate

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 (Figure 6) compared to 50MPa for the control specimens. This aligns with results from previous research [2]. It is noted that two of the 56 day results are lower than the corresponding 28 day results which is unexpected however it is within the variability of the testing. One reason for the loss of strength is 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.

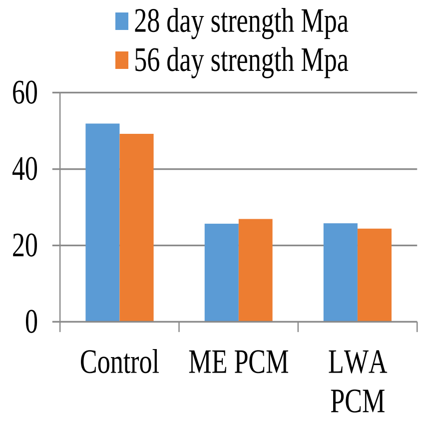

Figure 6. Concrete strengths achieved

The thermal conductivity results for the control panels were within the expected range for concrete. The addition of both types of PCM resulted in a reduction in thermal conductivity of the concrete. This is caused by the 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 ensure optimum effectiveness of the enhanced latent heat capacity provided by 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 (Table 1) influence the thermal behaviour however the effect that they have varies depending more on the ratio of conductivity to density of the material than on the absolute values of each.

Table 1. Conductivity and density of panels

Panel Type	Density (kg/m^3)	Conductivity (W/mK)
Control (C3)	2284	1.56
Control (C4)	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 Heating behaviour

The specific heat capacity of a material is given by:

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

where:

ΔQ = quantity of heat energy transferred to material, (Joules).

ΔT = change in temperature of the material (^{o}C).

m = mass of heat storage material.

For a PCM/concrete composite material the heat capacity varies during the phase transition therefore as proposed by [11], eq. (2) must be modified to include the temperature gradient over time:

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

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 (^{o}C/s).

During the light box tests each panel 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 0.04m^2. 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, varies 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 dT/dt throughout the 12 hour period was determined. The dT/dt curve was then multiplied by the mass of the relevant panel and the reciprocal of the result was calculated, ie 1/(m(dT/dt) and plotted. 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 7 shows a plot of the relative overall thermal storage, as recorded at 50mm depth throughout the 12 hour period. It can be noted that the panels containing PCM provide greater thermal storage capacity. Computing the area under each of the curves confirms that the panels containing the lightweight aggregate/PCM composite provide the highest overall thermal capacity at a depth of 50mm.

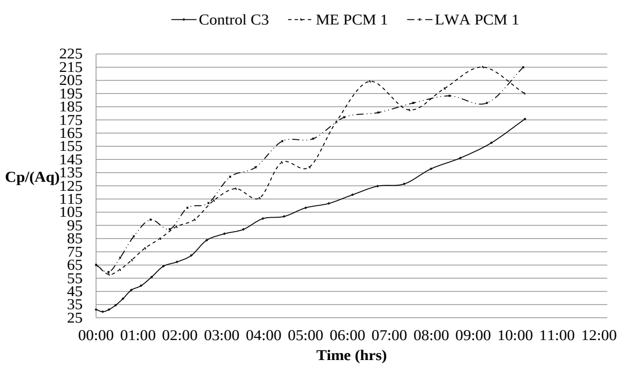

Figure 7. Curves showing relative overall thermal capacity at 50mm

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 greatest 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 2. Additional thermal storage provided by PCM panels at 50mm

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

Tables 3 and 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 at 100mm

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 at 150mm

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. Part of the reason for this is that the overall thermal storage for the control panel increases. However another thermal property that contributes to this 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. The lower conductivity and higher heat storage capacity 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. As shown in Figure 8, 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 a heat source 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.

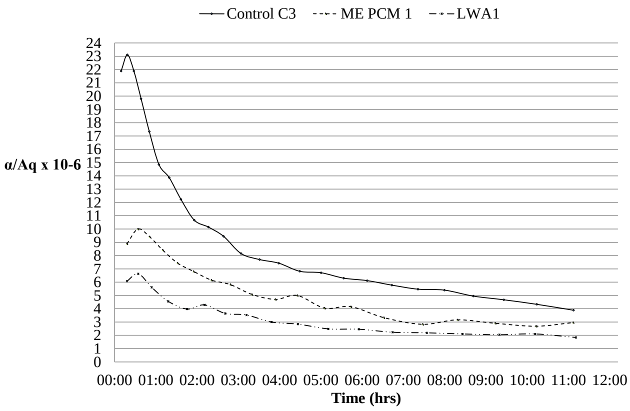

Figure 8. Relative thermal diffusivity recorded at 50mm

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: [12]:

$$I = \sqrt{\rho\, C_p k} \quad (J/(m^2K\sqrt{s}\,) \qquad (5)$$

where ρ is the density, k is the thermal conductivity and C_p is the specific heat. 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 (4) for thermal diffusivity, α, equation (5) can also be written as follows:

$$I = \frac{k}{\sqrt{\alpha}} \quad (J/(m^2K\sqrt{s}\,) \qquad (6)$$

It can be noted from equation (6) 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.

Figure 9 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.

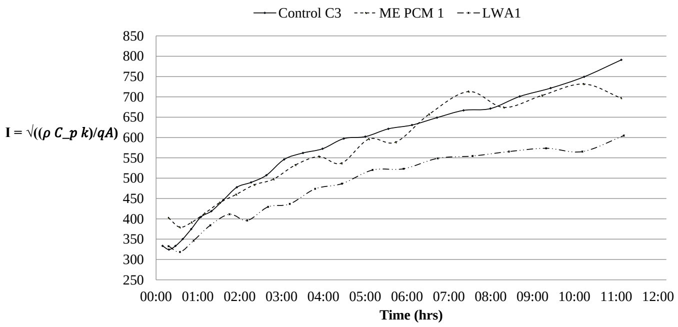

Figure 9. Relative thermal inertia recorded at 50mm

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 the greatest increase in thermal storage capacity compared to the control panel.
- The LWA/PCM panel displayed the lowest increase in temperature throughout the 12 hour heating period.
- 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 reach 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.

5. FURTHER RESEARCH

Further research is currently being carried out to investigate the influence of ground granulated blast furnace slag (GGBS) on the thermal properties of PCM/concrete. Methods of improving the thermal conductivity of concrete containing lightweight aggregate/PCM composite are also being explored.

ACKNOWLEDGMENTS

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

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