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Design and manufacture of a precast PCM enhanced concrete cladding panel for full scale performance monitoring

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ABSTRACT: The overall aim of this study is to develop innovative precast cladding panels for the renovation of Europe's existing building stock thereby improving their energy performance. Using the mass of a building to store heat and/or cold can reduce the demand on the auxiliary heating and/or cooling systems and hence reduce the overall energy demand of the building. Previous laboratory research has shown that the incorporation of phase change materials (PCMs) into concrete enhances its thermal storage capacity by up to 50%. However in a real application where a PCM-concrete composite material is used in a building to store thermal energy, the effectiveness of the PCM depends on many variables including the form of construction and local climate conditions. In this research study a precast cladding panel formed with PCM enhanced concrete has been developed and manufactured. In order to observe the performance of the PCM-concrete composite panels in a full scale scenario, three demonstration huts have been constructed and instrumented to record internal thermal behaviour. Monitoring of the data is ongoing and shows that the effectiveness of the PCM varies with the seasons. Data recorded during the summer period highlighted that the internal temperature may not drop low enough during the night to solidify the PCM and discharge the stored heat. A further test in which passive ventilation was provided during the night proved to be an effective method of addressing this issue. It is expected that this long term study will enable recommendations to be made on the seasonal benefits of using PCM-concrete to enhance the energy performance of buildings located in climate conditions similar to Ireland. The results of the data analysis will inform a refinement of the panel design prior to installing the panels at a school in the UK which currently has an overheating problem.

KEY WORDS: Phase Change Materials; PCM-concrete; Thermal storage behaviour.

1 INTRODUCTION

According to the World Business Council for Sustainable Development over half of Europe's building stock –circa 80 million buildings-were constructed between 1950 and 1975[1]. In this period efficient energy performance was not a critical design factor. The IEA Technology Roadmap on Energy Efficient Building Envelopes states buildings are responsible for more than one third of global energy consumption with space heating and cooling consuming 33% of this energy, increasing to 50% in cold climates. Improving the energy performance of building envelopes can reduce the sector's total energy consumption by 20% [2].

One method that can be employed to improve the energy performance of a building envelope is to use the mass of the envelope to store thermal energy. Thermal energy storage (TES) in buildings is a building integrated renewable technology that is proposed as one of the most effective approaches to reducing energy consumption of buildings. 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).

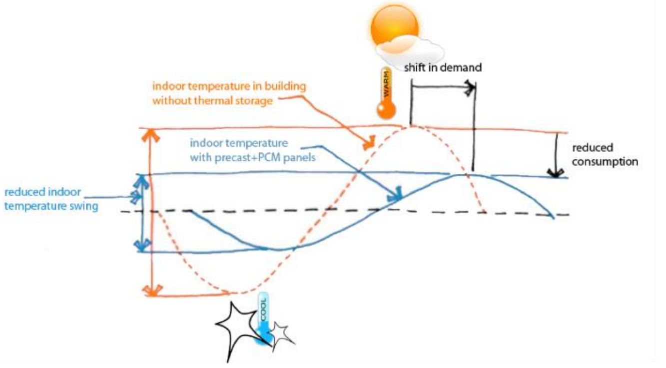

Figure 1. Impact of increased thermal mass provided by PCM-concrete panels on internal temperatures. (Adapted from image on Autodesk Sustainability Workshop)

The ability of a material to store and release heat is a function of its specific heat capacity and the mass of the material and is commonly referred to as *thermal mass.* Also materials of different conductivities will absorb and release heat at different rates back to the environment. For a building material to provide suitable thermal mass an appropriate balance between the diffusion of heat through it (its thermal diffusivity) and the inertia to temperature change (its thermal inertia) is required, *i.e.* between its heat release and storage tendencies. 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 it has good thermal mass characteristics. Previous research has shown that the thermal mass behaviour of concrete can be enhanced by incorporating phase change materials (PCMs) into the concrete which provide an additional latent heat capacity and hence increases its overall thermal storage capacity [3].

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 relatively constant during phase change where the PCM provides a high latent heat capacity. 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 [6]. For a space cooling application the appropriate melt temperature range is higher at 19 – 24^{0}C [7]. Kosny et al. [8] carried out an overview of the potential applications of phase change materials in building envelopes which depend largely on local climate conditions and the melt temperature range of the proposed PCM.

Previous research has been carried out by the authors [3, 4 & 5] to determine the properties and observe the thermal behaviour of PCM-concrete composites. The research studies found that PCMs can add significant thermal storage capability to concrete - up to 50% - augmenting its inherent thermal mass potential. The addition of PCM to concrete reduced its strength however sufficient strength was achieved for non-load-bearing applications. For the PCM to be effective it is critical that the temperature in the environment that the PCM is located varies above and below the melt temperature range of the selected PCM within a diurnal 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 that are well insulated may hinder the performance of a PCM's thermal energy storage element. 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 air-tightness.

The research presented in this paper outlines the design, manufacture and full scale monitoring of thermal behaviour of a precast PCM enhanced concrete cladding panel. This research is part of a European funded Horizon 2020 project entitled IMPRESS (http://www.project-impress.eu). The overall aim of IMPRESS is to develop innovative precast products for the renovation of existing building stock thereby improving the performance and energy efficiency of European buildings. Partners in this project include the leading concrete cladding company, Techrete Ltd and Sirus International who provided the monitoring equipment in the huts.

2 METHODOLOGY

Previous laboratory studies had shown that a PCM-concrete composite can provide significantly enhanced thermal storage capacity [11, 12 & 13]. In a real application the effectiveness of the PCM depends on many variables including the form of construction, building use and local climate. For this reason it was decided to use the PCM-concrete to form precast concrete cladding panels and construct three demonstration huts, one control hut and two huts containing a PCM composite, in order to monitor and observe the performance of the PCM-concrete composite in a full scale scenario over a long duration that includes all seasons. The primary objective of the PCM-concrete panel design is to demonstrate the reduction in overheating effects in the huts.

2.1 PCM-concrete composite

To form the PCM-concrete composite a micro-encapsulated PCM product called Micronal was added to a self-compacting CEM 1 concrete mix, 5% by weight of concrete, during the mixing process. The thermal behaviour of this composite was investigated in previous research by the authors [3, 4, & 5]. Also 5% Micronal by weight of concrete has been shown to be the optimum quantity of Micronal to be used in a concrete mix application [9 & 10]. Higher quantities of Micronal yields impractically low concrete strengths and also causes significant reduction in the thermal conductivity and density which tends to counteract the increase in thermal storage capacity.

2.2 Design of panels

There are three different types of panels, each comprising of a 70mm thick concrete outer leaf, 120mm insulation and a 125mm thick inner leaf which varies in composition (Figure 2).

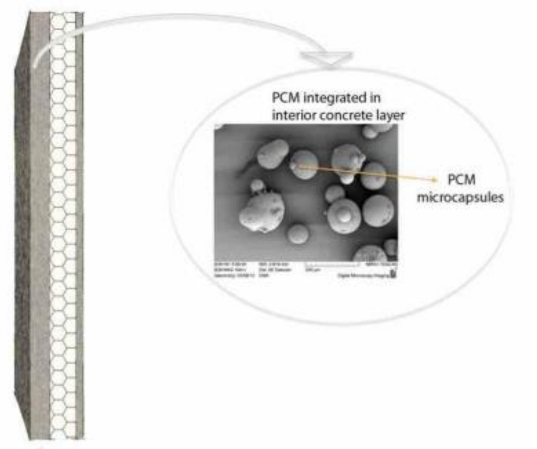

Figure 2. Precast concrete sandwich panels containing PCMs

For the Control hut, the inner leaf is constructed using a CEM I mix without any PCM. For the second hut, the inner leaf is formed using the PCM-concrete composite. This hut is referred to as the Full-PCM hut. In the third hut the inner leaf is made up of two layers. The inner 60mm comprises of the PCM-concrete composite and the outer 65mm of the inner leaf, adjacent to the insulation layer, comprises of normal concrete without any PCM content. This hut is referred to as the Partial-PCM hut. The purpose of the Partial-PCM hut is to enable the effective depth of the expensive PCM to be assessed. The amount of PCM that will melt during a diurnal period will depend on the intensity of heat in the environment where the panel is located. As the PCM absorbs heat and melts, it hinders the penetration of heat deeper into the panel so the PCM becomes less effective with increasing depth [3]. In a real building the level of exposure to a heat source depends on both local climate and the exposure of the wall surface to daylight. So the effective depth of the PCM will depend on the proposed location of the composite material.

2.3 Manufacture of panels

The panels were manufactured in the Techrete Ltd manufacturing facility in Dublin and the demonstration huts are also located at this facility. The fresh PCM-concrete was sufficiently workable although a self-compacting mix was not achieved. The strength of the PCM-concrete composite was sufficient to facilitate striking of the formwork and lifting of the panels after 20 hours of curing. The manufacture of the panels and erection of the huts proceeded without any problems and proved that the PCM-concrete composite can successfully be scaled up from a laboratory environment to a real building scenario (Figure 3).

Figure 3. PCM-concrete composite panel under construction

2.4 Design of huts

In order to ensure that the data from each of the huts is comparable, all of the huts had identical design parameters including dimensions, level of insulation, air tightness, glazing and orientation. The huts were positioned in an open area on the site to mitigate any overshadowing. All the huts are orientated with the glazed elevation facing south (Figure 4).

Figure 4. Demonstration huts located in Techrete Ltd

2.5 Instrumentation of huts

Each hut is fully instrumented for collection of temperature data and internal and external environmental data (Figure 5) There are 30No. type K thermocouples in each hut to record the temperature of the wall panels. Thermocouples were cast into the internal leaves of the panels, located at depths of 30mm, 60mm and 90mm. Thermocouples are also located on the internal and external surfaces of the inner leaf and also on the outer face of the insulation layer. These thermocouples enable the varying temperature profile throughout the depth of the wall to be determined at any point in time. Also the rate of heat penetration into the wall and through the wall can be determined.

A heat flux pad is located on the internal face of the north wall in each hut. The data from the heat flux pad indicates the heat flow into and out of the wall at the surface. A type K thermocouple records internal air temperature and a HOIKI Z200 also records internal air temperature and relative humidity in each hut. The external temperature and relative humidity are also recorded and an EKO MS-802 pyranometer is used to record solar irradiance at the site.

A 2kW heater is installed in each hut. The purpose of the heaters is to enable a heat load pattern to be applied that replicates a particular scenario, for example, the heat load pattern of a classroom that has an overheating problem. All the heaters are linked so that they turn on and off in unison. The heater in the Control hut determines when all the heaters switch on and off. A programmable thermostat is connected to the Control hut heater and hence any programmed heat load pattern will be applied equally to all huts. Each heater is monitored for power use using split current transformers.

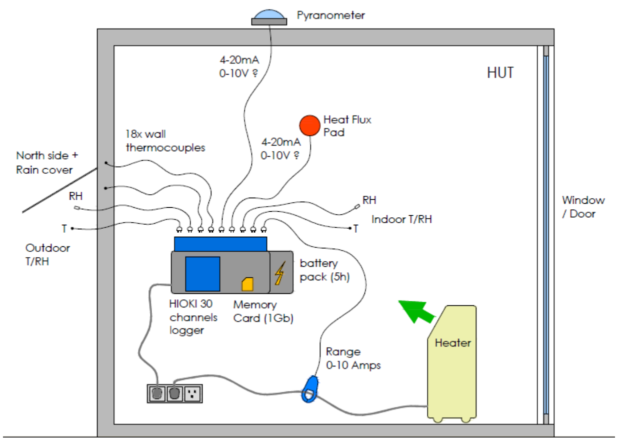

Figure 5. Schematic layout of instrumentation of each hut (Courtesy of Sirus)

All the data from the thermocouples and instruments is recorded on HOIKI portable data loggers, with one logger located in each hut. The data is collected on a regular basis and analysed to assess the performance of the PCM-concrete composite. The objective for using the PCM-concrete composite is to provide additional thermal storage to enable excess heat to be absorbed and hence reduce overheating. It is expected that when the internal air temperatures in the huts increase due to solar gain and the heating regime, the rate of increase of the internal air temperatures will be lower in the PCM than in the Control hut. It is also expected that the peak internal air temperature in the Control hut will be higher than in the PCM huts.

3 RESULTS AND DISCUSSION

Data collection and analysis is an ongoing process which at the time of writing has been progressing for just over 12 months. Various phases of data have been analysed including winter and spring with heaters, and summer and autumn without heaters (‘Passive’). The effectiveness of the PCM varies with the seasons and applied heat load. For example, in the winter season with a relatively low applied heat load, due to lower solar gains, the temperature of the internal wall does not increase sufficiently to cause the PCM to melt hence the PCM remains inactive. When the heat load is sufficient to increase the internal air temperature in the huts to greater than circa 25^{O}C generally the temperature of the wall increases above 20^{0}C and the effect of the PCM can be observed. The rate of increase of air temperature in both PCM huts is lower than in the Control hut. Also the peak air temperature in the Control hut is consistently higher than the peak temperatures in the PCM huts, generally in the order of 1^{o}C. A thermal inertia effect can also be observed in both the PCM huts as it takes longer to reach the peak temperature, in the order of 1 – 2 hours. It can also be observed that during the cooling phase the PCM huts are slower to cool down due to the fact that the PCM-concrete holds on to the heat within the wall until the temperature drops sufficiently (below 20^{o}C) to cause the PCM to start solidifying and releasing the heat to the internal air.

One issue that was highlighted by the analysis, in particular during the summer season, is that during the periods where the huts were heated sufficiently for the PCM to melt the temperature did not always drop low enough during the cooling phase (overnight) to cause the PCM to solidify. This means that the following day the additional latent heat storage provided by the PCM is not available as the PCM was already in a liquid state. This issue is most likely due to the high level of insulation and air tightness in the huts which minimises heat loss.

A test was set up to investigate mitigating this issue during which the huts were heated during the day by the radiators and passive ventilation was provided overnight to facilitate the purge of heat from the huts. Figure 6 shows a plot of an extract of 24 hours of data from this investigation.

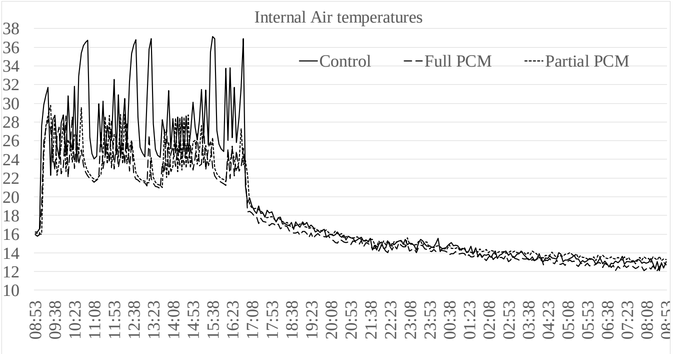

Figure 6. Internal air temperatures with night time passive ventilation

It can be observed from Figure 6 that the air temperatures in all three huts fluctuate up and down as the heaters turn on and off about the programmed set point. However the PCM huts are consistently cooler during the heating period (9am to 5pm). The Full PCM hut is an average of 4.7 ^{o}C cooler than the Control hut and the Partial PCM hut is 4.2^{o}C cooler than the Control hut during the heating period. The average internal air temperatures during the heating period are 28.7^{o}C for the Control hut, 23.9^{o}C for the Full PCM hut and 24.4^{o}C for the Partial PCM hut. There appears to be very little difference in the rate of decrease of air temperature during the cooling period. This is to be expected as the passive ventilation provided will allow heat to be purged from the huts at an equal rate.

Figure 7 shows a comparison of the temperatures at the surface of the north wall in each hut. The wall surface temperature increases by 8.0^{o}C in the Control hut, 4.6^{o}C in the Full PCM hut and by 5.0^{o}C in the Partial PCM hut during the heating period. The peak temperatures reached were 25.6^{o}C in the Control hut, 21.7^{o}C in the Full PCM hut and 22.4^{o}C in the Partial PCM hut. It can be observed that for the first 2 hours of heating, all the walls heat up at approximately the same rate however when the wall surface temperature reach 20 ^{o}C the rate of temperature increase on the walls containing PCM decreases relative to the Control hut wall. As the corresponding internal air temperatures in the PCM huts are also lower this indicates that the PCM is melting and absorbing the heat from the hut however the temperature of the PCM-concrete wall increases at a slower rate than the Control hut wall as the PCM does not increase in temperature as it melts. It is also clear from the plot that the Control hut wall surface cools down at a faster rate than the PCM huts and that there is little difference in the rate of cooling between the two PCM huts. This is to be expected as the temperature differential between the wall and the internal air is lower in the huts with PCM and also the presence of PCM increases the thermal inertia effect.

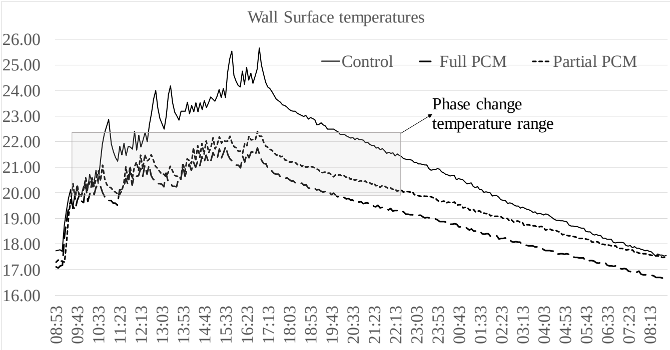

Figure 7. Wall surface temperature with night time passive ventilation

Figure 8 shows the internal wall temperature at a depth of 30mm in each hut. It can be noted from Figure 8 that the temperature of both PCM huts, at 30mm deep just increases above 20^{o}C - the start of the PCM melt temperature range – increasing up to 21^{o}C at the end of the heating phase. The wall temperature at 30mm depth increases by circa 6.0^{o}C in the Control hut, 3.5^{o}C in the Full PCM hut and by 3.7deg in the Partial PCM hut during the heating period. The peak temperatures reached were 23.3 ^{o}C in the Control hut, 20.6 ^{o}C in the Full PCM hut and 20.8 ^{o}C in the Partial PCM hut, so the PCM-concrete composite walls only exceeded the melt temperature of the PCM by less than 1^{o}C at a depth of 30mm. This highlights the issue of the effective depth of PCM and this data is indicating that, with the applied heat load, only the PCM located in the first 30mm of the wall will be effective. It can be observed that at first the PCM walls heat up at approximately the same rate however the rate of temperature increase is lower than that in the Control hut. This is to be expected as the PCM within the first 30mm of the wall will absorb the heat as it melts and hinder the transmission of heat deeper into the wall. Analysis of the temperature data collected at 60mm, 90mm and on the back surface of the wall confirms that the PCM is not activated at these depths.

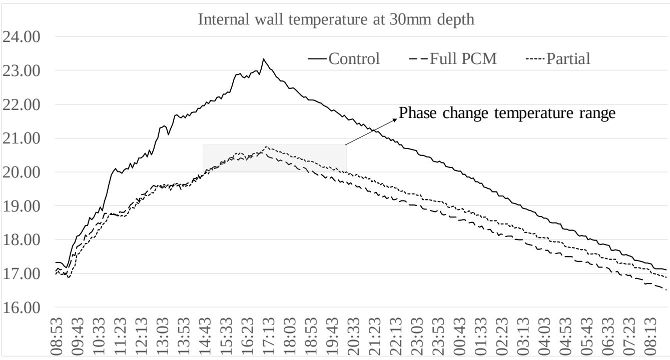

Figure 8. Internal wall temperatures at a depth of 30mm with night time passive ventilation

In the same test period as discussed above, temperature versus depth plots were produced for each hut for a 12 hour period, 9:00am to 21:00pm (Figures 9, 10 & 11). During this period the internal air temperatures were rising for the first 8 hours and then the heaters were switched off at 5pm and passive ventilation was introduced. The dashed lines indicate the cooling period**.** It can be noted that the back face of the control hut increases by 5.3^{o}C while the back face of both the PCM huts increase (by 3.1^{o}C in the Full PCM wall and 3.6^{o}C in the Partial PCM hut) hence there is less heat loss through the PCM-concrete composite walls. Although the main aim of developing the PCM-concrete panel is to reduce the overheating in a building it is interesting to observe and quantify the insulating effect of the PCM-concrete composite.

It can be also be noted from a comparison of the plots that the overall temperature increase of both the Partial PCM wall and Full PCM wall is significantly lower than the Control hut wall. This is despite the fact that, as observed from the comparison of internal air temperatures, the walls containing PCM clearly absorbed more heat from the internal air. This thermal behaviour is indicative of the latent heat stored by the PCM.

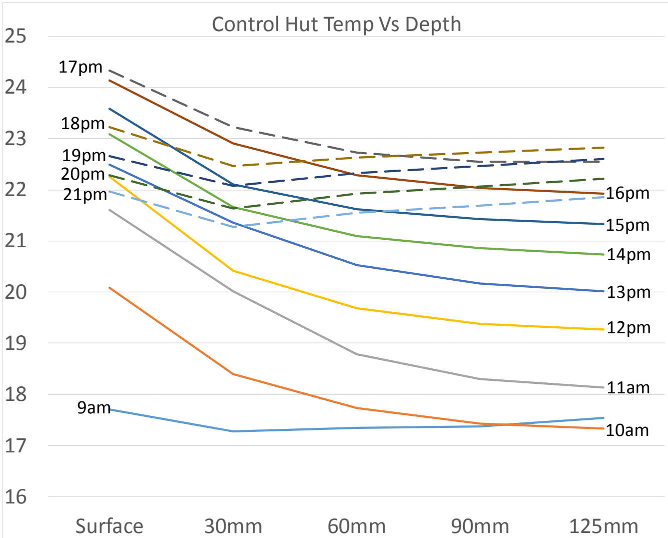

Figure 9. Temperature versus depth in Control hut

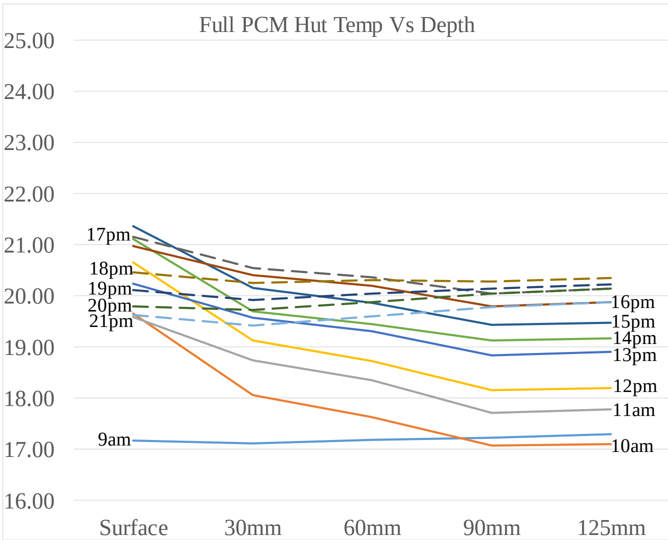

Figure 10. Temperature versus depth in the Full PCM hut

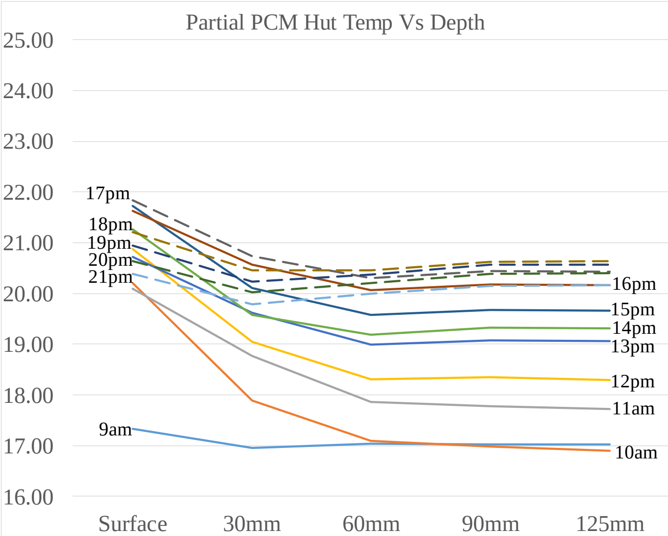

Figure 11. Temperature versus depth in the Partial PCM hut

4. CONCLUSIONS

The manufacture of the panels and erection of the huts proceeded without any problems and proved that the PCM-concrete composite can successfully be scaled up from a laboratory environment to a real building scenario.

One issue that was highlighted during the analysis of the recorded data is that during the summer season when the solar gain within the huts was sufficient to cause the PCM to melt, the internal air temperature did not always drop low enough during the night to enable the PCM to solidify. As a result, the following day the additional latent heat storage provided by the PCM was not available as the PCM was already in a liquid state. Further testing demonstrated that the introduction of night time passive ventilation is a viable method of addressing this issue.

Study of the temperature profiles though the depth of the inner walls of the panels showed that there is less heat loss through the PCM-concrete composite walls. Although the main aim of developing the PCM-concrete panel is to reduce the overheating in a building, it is interesting to observe and quantify the insulating effect of the PCM-concrete composite.

5. FURTHER RESEARCH

The on-going research described in this paper is developing the proof of technology for the PCM-concrete composite panel in a full scale scenario. The panels are going to be used to re-clad a school in the UK (Figure 12).


Figure 12. School in UK to be re-clad.

The school building has no insulation and joints and seals are damaged. It has a poor energy performance including heat loss and overheating. Prior to installation of the panels at the school, a full suite of structural tests will be carried out on the panels including flexural tests, buckling tests and racking shear tests.

ACKNOWLEDGMENTS

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