THERMAL PERFORMANCE OF CONCRETE WITH PCMS

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Abstract

Development of energy efficient and environmentally friendly materials to reduce energy consumption in buildings is a major concern in today's building and construction industry. Sustainable development of energy efficient materials in buildings needs to consider not only the mechanical properties such as strength and stiffness of structural materials but also thermal properties which includes heat capacity and thermal insulation. Concrete as most widely used construction material has a great potential to improve its heat storing capacity or thermal mass for their effective usage in buildings. One of the promising solutions is thermal energy storage with Phase change materials (PCM). Concrete incorporating PCM improves the thermal mass of the building which reduces the space conditioning energy consumption and extreme temperature fluctuations within the building. The heat capacity and high density of concrete coupled with latent heat storage of PCM provides a novel energy saving concepts for sustainable built environment. Microencapsulation is a latest and advanced technology for incorporation of PCM in to concrete which creates finely dispersed PCMs with high surface area for greater amount of heat transfer. Moreover PCM absorbs the excess energy during cement hydration and reduces the possibility of formation of cracks within the concrete. This paper reviews available literature on Phase change materials in concrete, its application and discusses finite element modelling of thermal performance of composite concrete.

Key Words: Sustainable Concrete, Phase Change Materials, Concrete, Thermal Energy Storage, Finite element modelling

1. Introduction

Building and construction industry is a prime consumer of world’s material and energy resources which accounts nearly for 40% of usage. Nevertheless limited conventional fossil energy sources produce harmful emissions which are accountable for environmental pollution. In an effort to conserve energy, thermal energy storage systems (TES) can be regarded as a convenient solution. Thermal energy storage is capable of storing energy for later usage with either sensible heat storage materials or latent heat storage materials. Although sensible storage has been used for centuries as a passive thermal storage, latent storage materials provides more effective storage of heat with comparatively very small amount of material. Latent heat storage materials are referred to as phase change materials (PCMs) preferably with solid liquid phase change. Integration of PCM in to building fabric can increase the thermal storage capacity of the building envelope. Cementitious materials as the most widely used construction materials in buildings has a great potential in developing high performance thermal storage material.

2. Thermal Energy Storage

Thermal energy storage (TES) system can store thermal energy for a later usage. The stored energy can assist in effective utilization of energy where there are mismatches in energy supply and demand and differential pricings are applied for peak and off-peak energy usage Zhu *et al* (2009). Sensible heat storage is the most common method of heat storage which includes stone, brick or water as the storage media. In latent heat storage, when the phase transition occurs from solid to liquid or liquid to gas or vice-versa, thermal energy is stored as latent heat of a storage material. Latent heat storage is highly attractive due to high energy density per unit mass and its ability to store heat at almost constant temperature Pasupathy *et al* (2008). Thermodynamic properties govern the selection of a PCM for a particular application. Suitable phase transition temperature or melting temperature and the melting enthalpy are the main criteria. Building materials incorporated with PCMs can store significant amount of thermal energy in building envelope with less structural mass compared with sensible heat storage Tyagi *et al* (2011). PCMs can be used to stabilize the indoor temperature in a building by reducing the temperature fluctuations due to external weather conditions. Incorporation of PCM in construction materials should be selected properly to mitigate the problems associated with the application of these materials. Some of the considerations in incorporation methods of PCM includes volume changes during melting and freezing, slow heat transfer rate, problems of leakage and adverse effects on the physical properties of the matrix. Encapsulation of a solid liquid PCM during its phase transition is crucial in most cases to hold the liquid phase of the PCM and to reduce the reactivity of PCM with the outer environment Hawlader *et al* (2003). In Microencapsulation, micronized materials (both liquids and solids) are packaged in the form of capsules, which range in size from less than 1 µm to more than 300 µm. The outer shell of the capsule can be made by using natural and synthetic polymers which provides a hard shell Hawlader *et al* (2003). The advantages of microencapsulation include reduction of the reactivity with the outside environment and improvement in heat transfer to the surrounding due to high surface to volume ratio of the microcapsules. Due to the hard shell, the core material can withstand frequent volume changes during phase change.

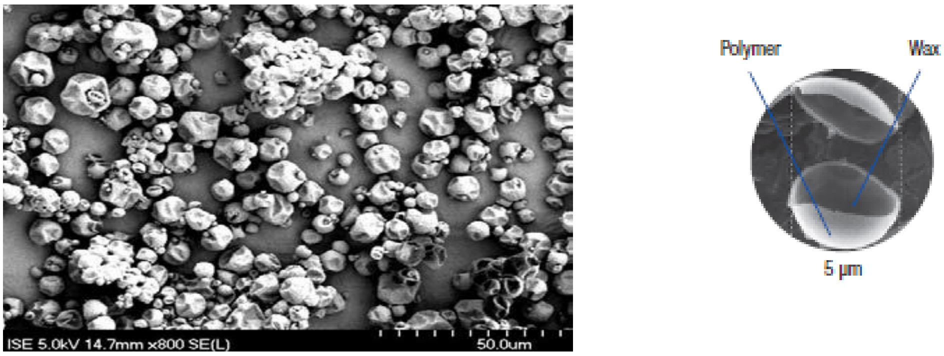

Figure1:Scanning Electron microscopic image of many capsules and an opened microcapsule (BASF)

3. Cementitious materials with Microencapsulated PCMs

Concrete is extensively used as a building material for residential and commercial buildings around the world. Thus the PCM technology has a great potential in developing an energy efficient concrete product for thermal comfort in buildings. Due to the high thermal mass of concrete, thermal energy can be stored during the day and be released at night, reducing the demand for cooling and heating. Addition of PCMs in to concrete can further enhance the thermal storage capabilities of concrete.

In early stage of development of thermal energy storage concrete, impregnation is used as the method of incorporation. Hawes et al. (1990) has studied latent heat storage of concrete with different types of PCMs in different types of concrete blocks. Incorporation of PCM in to concrete blocks was carried out through an immersion process in a liquid PCM bath. Silica fume and fly ash used as pozzolanas to reduce the alkalinity of concrete and to improve the compatibility with alkaline sensitive PCMs. Another potential application method of PCM in to concrete have been highlighted in the recent research done by Zhang et al. (2004) and Bentz and Turpin (2007). Light-weight aggregates with high porosity are used as the matrix materials to achieve adequate storage of PCM. In the constructed concrete, these porous aggregates are surrounded by dense cement based materials which avoid the leakage and pollution of PCM. Bentz and Turpin (2007) investigated the effectiveness of thermal storage mortar with light weight expanded shale aggregates with paraffin and polyethylene glycols as PCMs. It is stated that embedding PCM in more thermal conductive light weight aggregates improves the heat transfer between PCM and concrete. The results from a study of two actual size concrete building tests using microencapsulated PCM were presented by Cabeza et al.(2007) . A lower inner temperature up to 3° C was achieved with PCM. Improved thermal inertia was also observed which shows prospects for energy savings in buildings. Moreover it is stated that solidification and melting of PCMs in every cycle and night cooling is important to achieve full performance of the PCM storage.

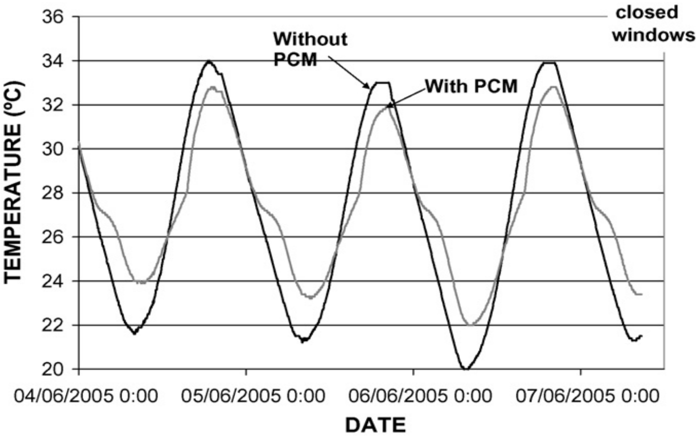

Figure 2: South wall temperatures with and without PCM (Cabeza et al. 2007)

The opportunities presented by the microencapsulation of PCM in gypsum plaster was investigated by Schossig *et al*. (2005) As the capsules are very small, the destruction of capsules is highly unlikely. The fine distribution of the PCM particles in the matrix provides larger surface area for heat transfer, so the heat transfer rate during melting and freezing cycle is enhanced significantly. It has been shown that microencapsulation of PCM results in easy application, improved heat transfer and good compatibility with conventional construction materials. The PCM walls facilitate low fluctuations in the indoor air temperature.

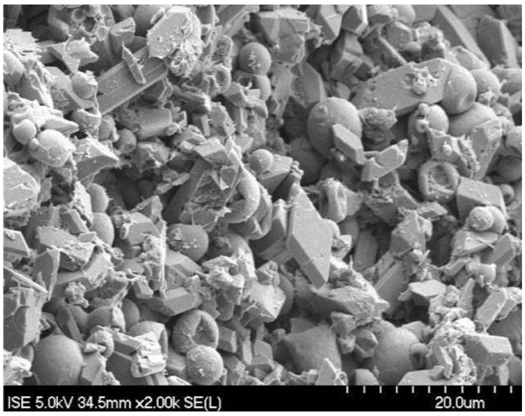

Figure 3: SEM image of PCM micro-capsules in gypsum plaster. The PCM micro-capsules with an average diameter of 8 mm are homogeneously dispersed between the gypsum crystals (Schossig et al. 2005)

A series of experiments using different percentages of PCM in self-compacting concrete mixes was studied by Hunger *et al*. (2009) Microencapsulated PCM was directly mixed with concrete and the influence on the material properties were investigated.

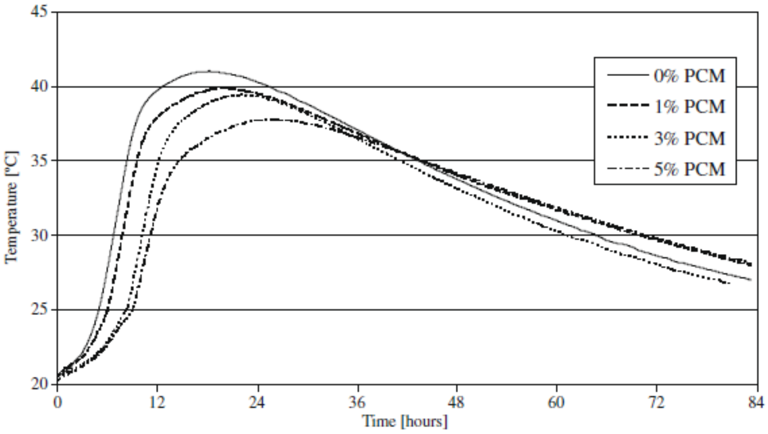

Figure 4: Temperature development of four self-compacting mixes in the kernel of the molds in a semi-adiabatic environment during the first 3.5 days after casting (Hunger et al. 2009).

Thermal properties of hardened self compacting concrete with PCM show reduction in thermal conductivity and increased heat capacity with the increase of PCM content. The increase of thermal mass due to addition of PCM improved the thermal performance of concrete. Results showed an energy savings of 12% can be achieved with 5% PCM in the mix [Hunger *et al* (2009)]. The reduced thermal conductivity and increased thermal mass of the concrete act favourably in practical applications. It improves the thermal performance of concrete and to facilitate energy savings in space conditioning. Although the increase in PCM dosage led to lower compressive strengths in the composites, 3% PCM content in the concrete accompanied compressive strengths of 35N/mm^2 which is adequate for most constructional purposes [Hunger *et al* (2009)].

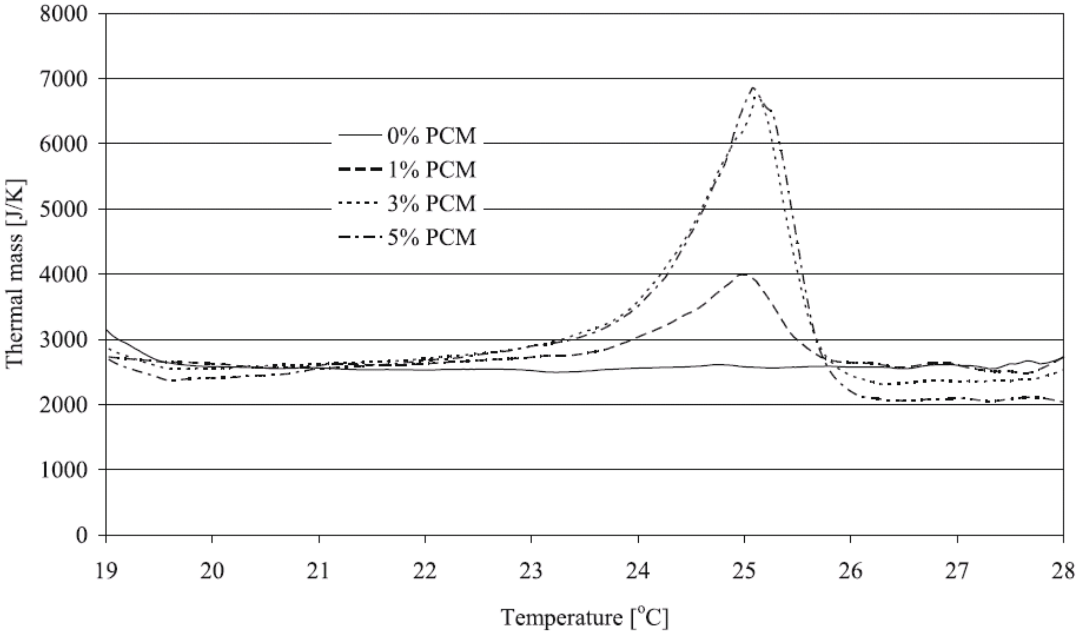

Figure 5: Thermal mass of the PCM mixes versus temperature (Hunger et al. 2009)

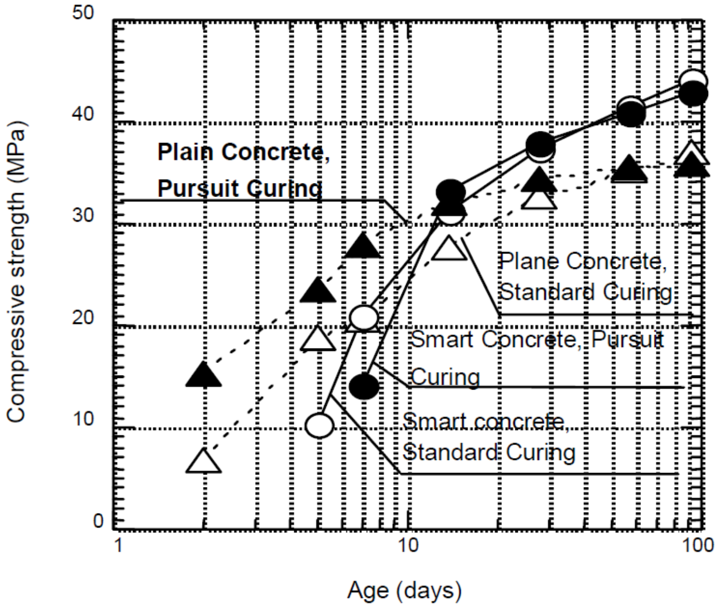

Figure 6: Development of the compressive strength of smart concrete with PCM and plain concrete. (Mihashi et al. 2002)

Mihashi *et al*. (2002) in their experimental studies showed that though the early stage compressive strength is low due to reduced hydration peaks, later stage compressive strength is higher than normal concrete. One suggestion to improve early stage compressive strength by Salyer and Sircar (1997), was to increase percentage of cement in the formulation. However increasing cement content has its own negative impacts on environment with relates to consumption of energy and CO_2 emissions and may not be considered as an effective solution.

4. Numerical Investigations with PCM

The characterization of material properties of building materials with PCMs and the analysis of the thermal performance of these materials in a building are important in designing thermal storage systems with PCMs. A reliable numerical model to simulate material properties can facilitate optimal design without having time consuming full scale experiments. Heat transfer in PCM during phase change is quite complex due to the nature of nonlinearity [Lamberg et al (2004)]. Analytical solutions which have developed to solve phase change problems deal with simple geometry and boundary conditions. Stefan Problem is one of the most used analytical solution for one dimensional solid-liquid phase transition [Ogoh & Groulx (2010)].

Phase change problems are generally solved with finite difference or finite element methods. The most common numerical methods in solving non linear behavior include Enthalpy method and Heat Capacity method. The Enthalpy method utilizes total energy required during the phase change which includes both sensible and latent heat by using the enthalpy of the material. Effective heat capacity is linearly proportional to the latent heat and the specific heat of the material. Lamberg et al. (2004) have carried out finite element analysis of paraffin with FEMLAB using both enthalpy method and heat capacity method. The most accurate result was obtained from the Effective Heat Capacity method used in a narrow temperature range. Zhang et al. (2007) carried out numerical studies on thermal behavior of hypothetical solid-solid PCM using FEMLAB. The effect of varying percentages of PCM and the material thickness has been investigated with finite element modelling. Simulations indicated that fluctuations of indoor room temperature can be reduced by using PCM in cement compounds. Higher the PCM amount and higher the compound thickness, there is an increase in the amplitude of temperature fluctuations reduction. However the increase in thickness offers increased thermal resistance during discharge of the stored heat, thus an optimum value of thickness is preferred.

The improvement in thermal behavior in a building due to integration of PCM depends on number of factors. This includes the amount and properties of PCM, climate conditions, design of the building. Therefore a complete simulation of thermal effects in a building with PCMs is necessary to evaluate the benefits. Ibanez et al.(2005) developed a simple model with TRNSYS to simulate the thermal behavior of buildings including elements with PCMs. TRNSYS15 was used in modelling using the active layers for radioactive heating and cooling of the Type 56 ‘Multi-Zone Building’. The material properties were first characterised by the experiments and then the thermal behavior of these materials in the building was analysed. The simulation showed reduction in temperature fluctuations with PCM and results can be evaluated by altering phase change temperature, heat capacity of PCM and its place of application within the building.

4.1 Case study

Finite element modeling was carried out on thermal behavior of hypothetical solid-solid PCM using COMSOL. The integrated PCM and cement compound was treated as a homogenous mixture which was subjected to solar radiation. . The material properties for the model were obtained from studies carried out by Dahai *et al*. (2007). The effect of varying percentages of PCM and the comparison with different type of concrete mixtures were simulated with finite element modelling. A wide range of numerical methods are available to solve PCM integrated problems. The most common methods are enthalpy method and heat capacity method. The main equations for solid liquid phase change are composed of the Navier-Stokes (momentum) equations, the continuity equations and the energy equations [Lamberg *et al* (2004)]. In a solid-solid phase change, convective heat transfer can be neglected and both momentum and continuity equations can be disregarded. The simplified form using energy equation is as follows.

$$\rho C_P \left[\frac{\partial T}{\partial t}\right] = \nabla(k\nabla T)$$

Where ρ = Density
C_p= Specific heat
k = Thermal conductivity.

The Enthalpy method utilizes total energy required during the phase change which includes both sensible and latent heat by using the enthalpy of the material. For the solid-solid PCM, energy equation can be written as follows.

$$\rho \frac{\partial \mathrm{H}(\mathrm{T})}{\partial \mathrm{t}} = \nabla(\mathrm{k}\nabla T)$$

With the effective heat capacity method, non-isothermal phase transition of the PCM can be solved. Effective heat capacity of the material (C_{eff}) is linearly proportional to the latent heat and the specific heat of the material. It is inversely proportional to the melting or solidification temperature range Lamberg *et al* (2004). The effective heat capacity of the PCM during a phase change can be given as;

$$\mathrm{C}_{\mathrm{eff}} = \frac{\mathrm{L}}{T_{\mathrm{e}}\text{-}T_{\mathrm{o}}} + \mathrm{C}_{\mathrm{p}}$$

Where L = Latent heat of fusion
T_o = Onset temperature of phase transition
Te= End temperature of phase transition.

Thus the governing energy equation can be expressed as;

$$\rho \mathrm{C}_{\mathrm{p}}(T)\left[\frac{\partial T}{\partial t}\right] = \nabla(\mathrm{k}\nabla T)$$

$$C_{\mathrm{p}} = \begin{cases} C_{\mathrm{p}} & T < T_{\mathrm{o}} \\ \dfrac{\mathrm{L}}{T_{\mathrm{e}}\text{-}T_{\mathrm{o}}} + C_{\mathrm{p}} & T_{\mathrm{o}} \leq T \leq T_{\mathrm{e}} \\ C_{\mathrm{p}} & T > T_{\mathrm{e}} \end{cases}$$

The PCM integrated cement compound is considered as a uniform mass with average thermal and physical properties. The hypothetical PCM has solid-solid phase transition, thus the mode of heat transfer has been considered only as by conduction and any convective terms were neglected. A two dimensional transient FE analysis was carried out under conduction heat transfer with COMSOL Multiphysics module. Phase transition temperature range of $23^{o}C$-$25^{o}C$ has been taken for both heating and cooling phases. The model dimensions were taken as 20mmx10mm rectangular block and transient analysis was carried out for 9000s. The upper surface of the rectangular block was supplied with time dependent variable temperature to represent the outdoor temperature fluctuations while keeping other boundaries insulated. The specimen was modeled with finer mesh of quadrilateral elements where it was solved for 404 elements and 447 degrees of freedom.

The thermo physical properties of the PCM were obtained from the literature as follows.

Table 1: Thermo physical properties of the solid-solid PCM

Property	Value
Density(ρ) kg.m^{-3}	800
Thermal conductivity(k) W.m^{-1} K^{-1}	0.3
Specific Heat(C_p) Jg^{-1}K^{-1}	1.6
Onset temperature of phase transition(T_0) K	296
End temperature of phase transition(T_e) K	298
Latent heat of fusion on heating/cooling (L) J.kg^{-1}	8000

Phase transition temperature range of 23°C-25°C has been taken for both heating and cooling phases. Using effective heat capacity method, the heat capacity for different PCM percentages during the phase transition was obtained as follows.

Table 2: Specific heat of PCM cement compound during phase change

Weight % of PCM			
0%	10%	20%	30%
C_p= 1300	$C_p = \begin{cases} 1330 & T < 296K \\ 5330 & 296K \leq T \leq 298K \\ 1330 & T > 298K \end{cases}$	$C_p = \begin{cases} 1360 & T < 296K \\ 9360 & 296K \leq T \leq 298K \\ 1360 & T > 298K \end{cases}$	$C_p = \begin{cases} 1390 & T < 296K \\ 13390 & 296K \leq T \leq 298K \\ 1390 & T > 298K \end{cases}$

The discontinuity of C_p during the phase transition was integrated in to FE modelling using smoothed switch functions. A smoothed Heaviside function with a continuous second derivative without overshoot: flc2hs was used in the simulation as follows.

$$H = \mathrm{flc2hs}\left((T - T\_trans)[1/K], dT\ [1/K]\right)$$

Where H= Heaviside function

T_trans = Transition temperature

dT = Transition Interval.

The proper simulation of the phase change with the Heaviside function was assured with small time steps (with maximum of 60 seconds) during the transient simulation. The density and the thermal conductivity of the compound material were assumed to be as constant during the modelling. Concrete with two different densities were compared to evaluate their effect on improving the thermal performance in a building with PCM.

4.1.1 Results and discussion

Surface temperatures were plotted with different percentages of PCM and comparison was made with two types of concrete. The input temperature profile consists of a temperature curve fluctuating from 293K to a maximum temperature of 312K.

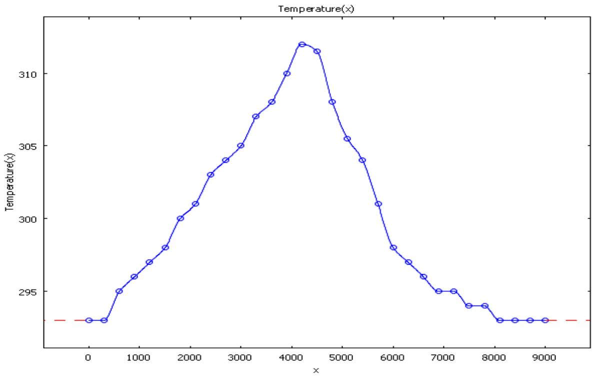

Fig 7: Plot of time dependent variable temperature input on the upper surface.

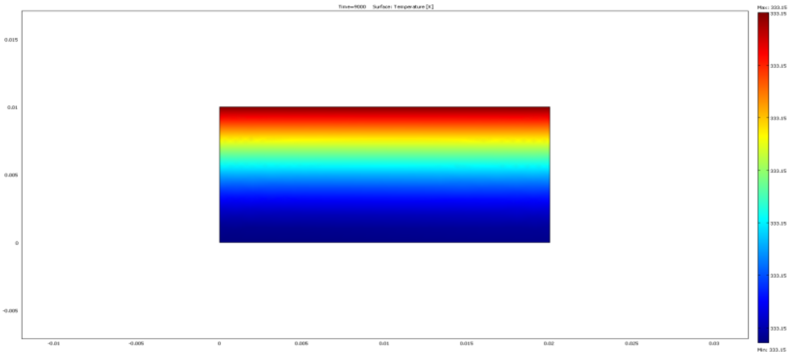

Fig 8: Surface plot for temperature at t= 9000s.

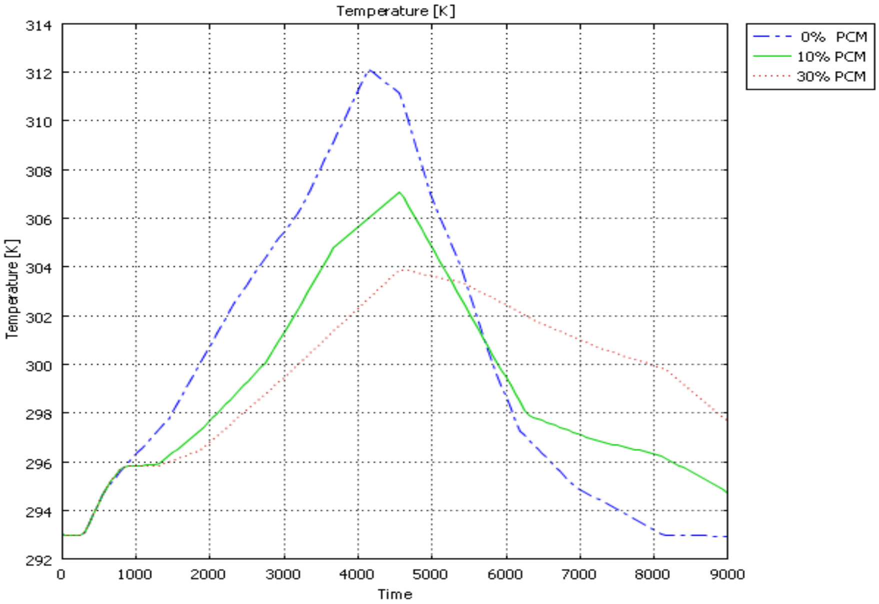

Fig 9: Temperature variation on the upper surface with different % of PCM.

As can be seen in Figure 9, the addition of PCM in to cement can reduce the temperature fluctuation on the surface. Addition of 10% of PCM reduces the peak temperature by about $5^0$and further addition of PCM can flatten the temperature fluctuation further. The temperature fluctuations on the upper surface vary mainly in amplitude with minor time delay with different PCM percentages. During the heating cycle of the PCM cement compound a plateau region in the temperature curve can be identified around 296K which represent the phase transition of the PCM. Higher the amount of PCM presents in the compound, higher the resultant heat capacity of the compound. The increase in heat capacity of the material provides a thermal buffering effect for the cement compound.

Two different concrete types were compared with different densities to understand its effect on thermal performance of concrete with PCM. Light-weight concrete and normal concrete with 10% PCM were used for comparison and the thermal conductivity was kept as constant. Figure 10 shows that normal concrete has a better thermal performance compared to light-weight concrete, thus denser the material, higher the thermal buffering effect. Moreover it can be seen that amplitude of temperature fluctuations can be reduced with PCM. Normal concrete without PCM has an amplitude of 19^0C for temperature variation while addition of PCM reduces it to nearly 10^0C. Thus in practice addition of PCM in to concrete can lead to better thermal performance and energy savings in building applications.

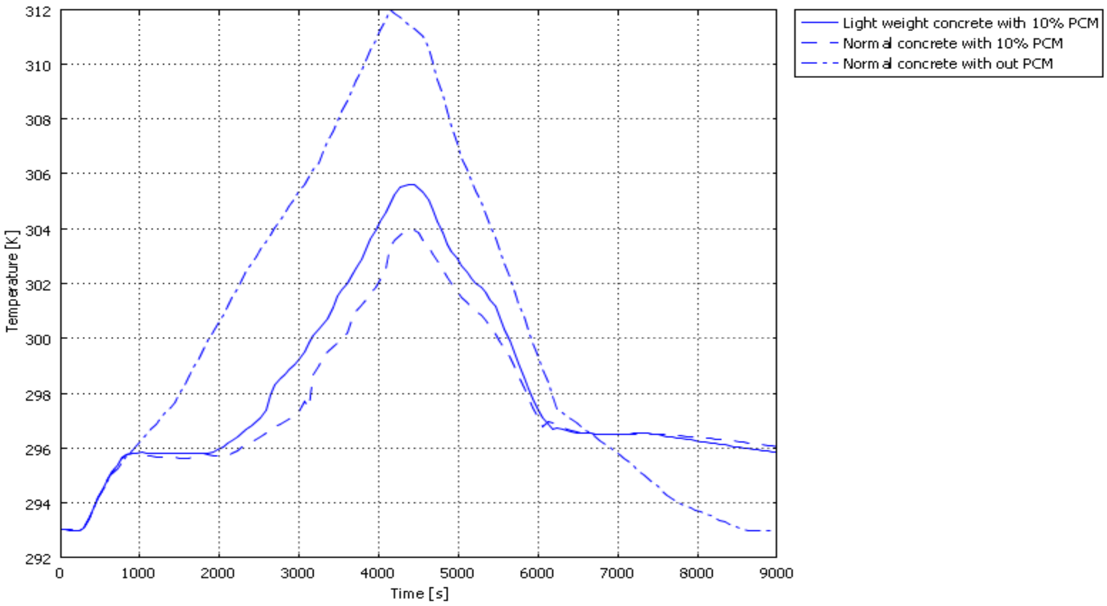

Fig 10: Temperature variation on the upper surface with different concrete densities.

5. Conclusions

Latent heat storage materials with solid liquid phase change or Phase Change Materials (PCMs) provide a promising solution in developing efficient thermal storage systems for buildings. Their inherent ability to store large amount of heat at almost constant temperature can increase the thermal mass of building materials. The high thermal mass of concrete can be further enhanced by the addition of PCM and it will act positively on reducing peak temperatures during cement hydration.

A finite element modeling was carried out with PCM cement composite to understand the thermal performance of the material with addition of PCM. The simulation results shows that peak temperatures can be lowered with addition of PCM and reduction of peak temperatures shows a linear relationship. A Comparison of two different concrete types shows that thermal performance of normal concrete with PCM is better than light-weight concrete due to its high density. Moreover addition of PCM in to concrete reduces the amplitude of temperature fluctuations. Thus the addition of PCM in to concrete improves the thermal performance of concrete which enhances the occupants comfort and reduces the consumption of energy for space conditioning. While improving the thermal properties of concrete with the addition of PCM, its effect on mechanical properties should also be considered. As only a few research projects have been conducted on thermal energy storage systems (TES) using cementitious materials, there is an urgent necessity for comprehensive experimental and numerical investigations on microencapsulated PCM applications with concrete.

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