# Applications of Phase Change Materials in Concrete for Sustainable Built Environment: A Review

Amitha Jayalath, Priyan Mendis, Ranjith Gammampila and Lu Aye.
Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia.

## Abstract

The fast economic development around the globe and high standards of living imposes an ever increasing demand for energy. As a prime consumer of world's material and energy resources building and construction industry has a great potential in developing new efficient and environmentally friendly materials to reduce energy consumptions in buildings. Thermal energy storage systems (TES) with Phase change materials (PCM) offer attractive means of improving the thermal mass and the thermal comfort within a building. PCMs are latent heat thermal storage (LHTS) materials with high energy storage density compared to conventional sensible heat storage materials. 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. This paper reviews available literature on Phase change materials in concrete, its application and numerical modelling of composite concrete. However most of the existing TES systems have been explored with wallboards and plaster materials and comparatively a few researches have been done on TES systems using cementitious materials. Thus, there is a need for comprehensive experimental and analytical investigations on PCM applications with cementitious materials as the most widely used construction materials in buildings.

**Key Words:** Phase Change Materials, Concrete, Thermal Energy Storage, 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. Current TES materials employed in the building industry includes sensible heat storage materials like steel, masonry and water, where thermal energy is stored by raising the temperature of the material. 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. PCMs are capable of storing energy at constant or nearly constant temperature which is referred as the phase transition temperature of the PCM. Cementitious materials as the most widely used construction materials in buildings has a great potential in developing high performance thermal storage material. Numerical modelling of composite material with PCM is very important for optimal material selection and optimal designing of the systems. Simulation of thermal energy storage in concrete characterizes the heat transfer behaviour and thermal properties of this composite 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, Ma & Wang 2009). Physical processes for heat storage include sensible heat storage and latent heat storage. Sensible heat storage is the most common method of heat storage 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, Velraj & Seeniraj 2008) Solid-liquid systems are the most studied and commonly commercially available and referred to as latent heat storage material or Phase change Material (PCM).

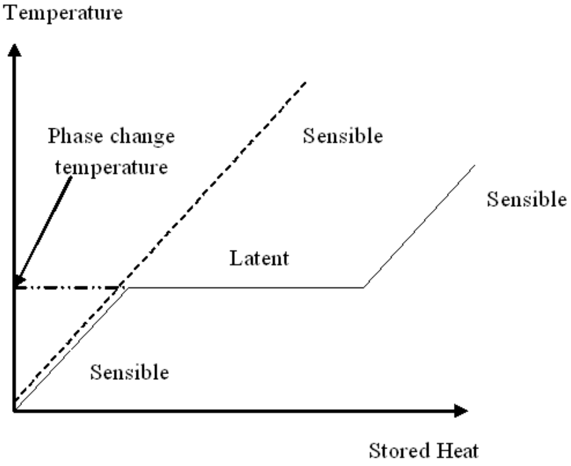

***Figure 1: Heat storage as latent heat for the case of solid-liquid phase change (Mehling & Cabeza 2008)***

The PCMs which are frequently used for the heat storage purposes have their phase conversion from solid to liquid or from liquid to solid state. PCM may be continually changed between its phases to utilize its latent heat, the heat which is absorbed during the phase change process. PCMs must exhibit certain desirable thermodynamic, kinetic and chemical properties for their application as latent heat storage materials.(Buddhi & Tyagi 2007)

*Table 1: Selection criteria for latent heat storage materials.(Pasupathy, Velraj & Seeniraj 2008)*

| | |
|---|---|
| *Thermodynamic Properties* | *Suitable phase transition temperature* |
| | *High latent heat of fusion per unit volume* |
| | *High specific heat, high density and high thermal conductivity* |
| | *Small volume changes on phase transition* |
| *Chemical Properties* | *Chemical stability* |
| | *Complete reversible freeze/melt cycle* |
| | *Long term reproducibility* |
| | *Non-toxic, non-flammable and non-corrosiveness* |
| *Economic Properties* | *Low cost* |
| | *Large scale availability* |

There are a large number of PCMs available within the required temperature range. Mainly PCMs can be categorized in to three classes, organic, inorganic and eutectics. Organic materials include paraffin and non-paraffins. They show good physical and chemical stability, good thermal behaviour, low super-cooling, good compatibility with construction materials. However paraffin is flammable and has low thermal conductivity and volume changes. Inorganic materials include salt hydrates and metallics. These have a high latent heat per unit mass, non-flammable and comparatively low in cost. Drawbacks of inorganic PCMS include phase segregation and super cooling which affects its latent heat properties. A eutectic is a combination of two or more components where each material melts and freezes congruently. This can be a mixture of Organic–Organic, Organic–Inorganic and Inorganic–Inorganic materials.

Currently organic PCMs has become quite attractive due to their advantages over inorganic materials (Khudhair & Farid 2004). Organic PCMs have little super cooling and phase segregation and they are compatible with various building materials. 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. As both aforementioned properties depend on the molecular effects, PCMs within one material class behave similarly.

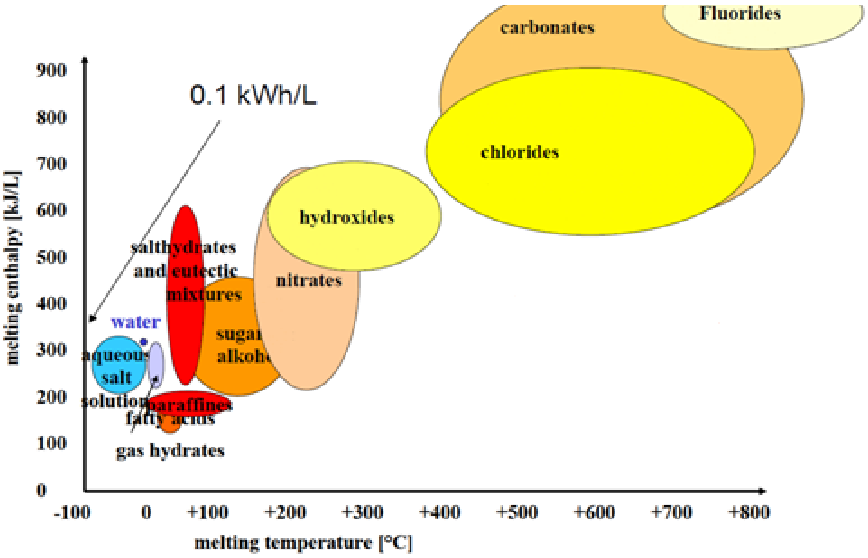

*Figure 2: Different classes of known PCMs(Mehling & Cabeza 2008)*

Compared with conventional sensible storage materials, PCMs provide high energy storage densities at a constant temperature. These unique properties of PCM provoke their application into temperature control and as a thermal storage with high storage density. One of the main areas of application is to enhance energy efficiency and thermal comfort in buildings. 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.

# 3. PCM containment

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. The simplest method consists of impregnation of the concrete block with PCM in a constant volume liquid PCM (Lee et al. 2000). This is a flexible method which can be applied to different PCM transition temperatures. Concrete blocks can be impregnated as a part of continuous process of manufacturing. It may have drawbacks of interacting with building structure and change the material matrix, possible leakage over the life time *etc*. (Schossig et al. 2005)

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, Uddin & Khin 2003). Means of encapsulation can be classified depending on their size; macroencapsulation and microencapsulation.

## 3.1 Macroencapsulation

PCMs are enclosed in a macroscopic containment like pouches, bags, bottles, pipes and similar structures made of plastic or metal. Macroencapsulation hold the PCM in liquid state and prevent it from contact with the outer environment. Some disadvantages of macroencapsulation include poor heat transfer, potential leakage and flammability. The macro encapsulation of PCM need to be protected against destruction during usage of the building and failed due to poor heat conductivity during solidification process. It requires much work to be done at the site to integrate with the building fabric.

## 3.2 Microencapsulation

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, Uddin & Khin 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. The cycling stability of the PCM has also improved as the phase separation is only limited to the microscopic distances.

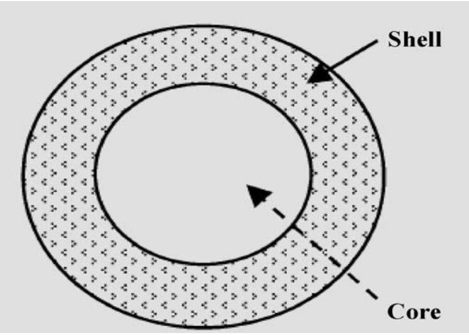

***Figure 3: Description of Microcapsule (Tyagi et al. 2011)***

When encapsulating PCM, several factors need to be considered. The material of the container must be compatible with the PCM and the wall material has to be sufficiently thick to assure necessary diffusion tightness. High resistance to mechanical and thermal stresses is a prerequisite of a microencapsulated PCM which is intended to use with construction materials. To become a PCM with good cycle stability over numerous phase transition cycles, it needs to be remained encapsulated within impermeable microcapsule for the whole product life.

Commercial products of microencapsulation use paraffin. Micronal is an example commercial product produced by BASF.

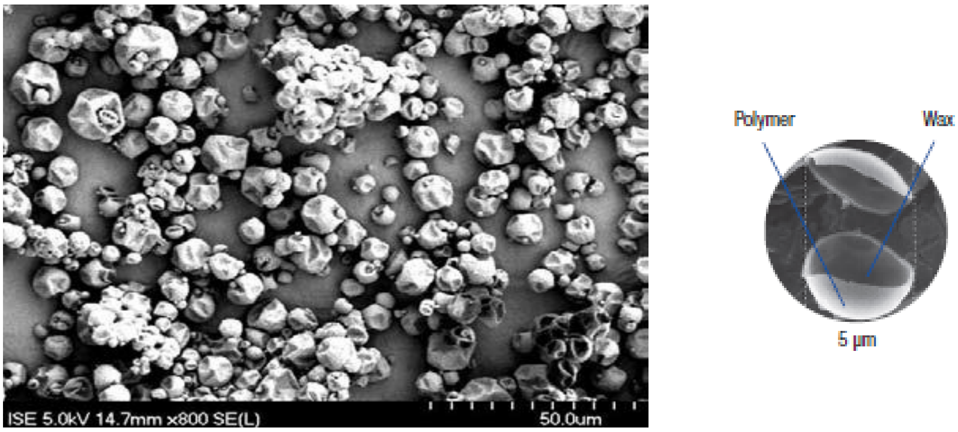

***Figure4:Scanning Electron microscopic image of many capsules and an opened microcapsule (BASF)***

## 4. Cementitious materials with Phase change Materials

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. The experiments covered the process variations including concrete alkalinity, temperature, PCM temperature, immersion time and number of immersions. Silica fume and fly ash is 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 is 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 on 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. A secondary application of PCM has also explored in this research, the reductions in peak temperature during first few days of hydration. During hydration PCM absorbs the energy and reduces the temperature rise.

New methods of PCM containment in hollow-core building blocks were studied by Salyer *et al*. (1995) which included; 1) PCM contained in pellets of cross linked high density polyethylene (HDPE); 2) PCM absorbed into high surface area of Silica in the form of “Dry powder”; 3) Imbibing of liquid PCM in to porous materials. One significant technical discovery from this research was finding of new PCM composite that could be made by melt mixing of PCM/High Density Polyethylene (HDPE)/ Ethylene-vinyl acetate (EVA) and ABS silica in defined proportions. PCM/hydrophobic silica dry powder can be incorporated into the wet mix of cement/solite to provide an effective thermal storage. However a higher ratio of cement needs to be used to mitigate the reduction of compressive strength of the composite with the progressive increase of the PCM.

## 4.1 Cementitious materials with Microencapsulated PCM

In most of aforementioned researches main consideration has given to method of containment of PCM in developing thermal storage composite materials. Studies suggest that main problems with PCM incorporation are leakage and evaporation of PCM and contact with the outer environment which can deteriorate the matrix material properties. Microencapsulation is a latest and advanced technology for incorporation of PCMs into building materials. Prospective PCMs that can be applied in the buildings should have their phase transition temperature in the range of human comfort temperature. This method of application creates finely dispersed PCMs with high surface area for greater amount of heat transfer and prevents any interaction between PCM and the concrete constituents.

The results from a study of two actual size concrete tests building using microencapsulated PCM were presented by Cabeza *et al*.(2007) . A commercial product, Micronal® PCM from BASF has been used for the experiment. 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.

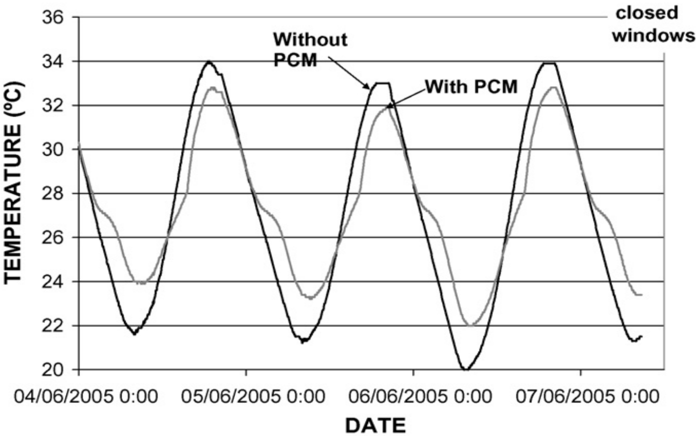

***Figure 5: South wall temperatures with and without PCM (Cabeza et al. 2007)***

The opportunities presented by the microencapsulation of PCM in gypsum plaster was investigated by Schossig *et al*. (2005) As the capsules are very small, destruction of capsules are 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 showed that microencapsulation of PCM results in easy application, improved heat transfer and good compatibility with conventional construction material. The PCM walls facilitate low fluctuations in the indoor air temperature.

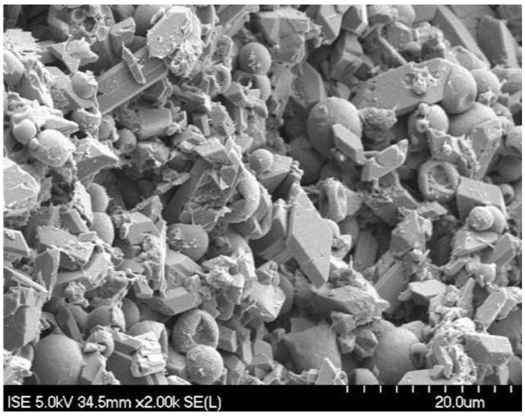

***Figure 6: SEM image of PCM micro-capsules in gypsum plaster. The PCM micro-capsules with an average diameter of 8 mm are homogeneously dispersed between the gypsum crystals (Schossig et al. 2005)***

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.

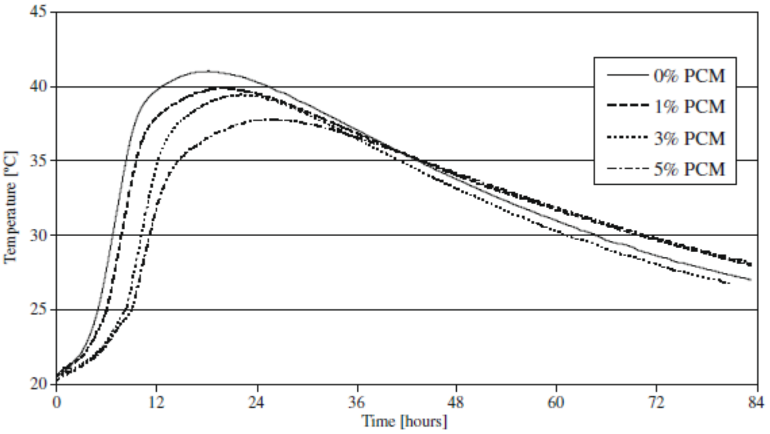

***Figure 7: Temperature development of four self-compacting mixes in the kernel of the molds in a semi-adiabatic environment during the first 3.5 days after casting (Hunger et al. 2009).***

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 acts 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 lead to lower compressive strengths in the composites, 3% PCM content in the concrete accompany compressive strength of $35N/mm^2$ which is adequate for most constructional purposes (Hunger et al. 2009).

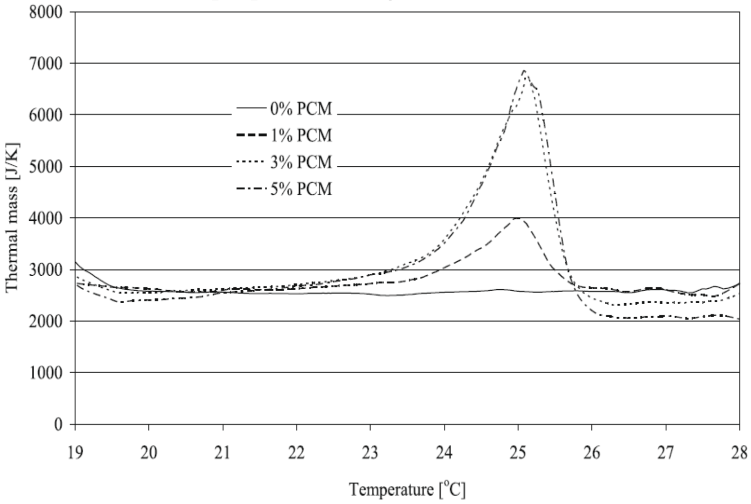

***Figure 8: Thermal mass of the PCM mixes versus temperature (Hunger et al. 2009)***

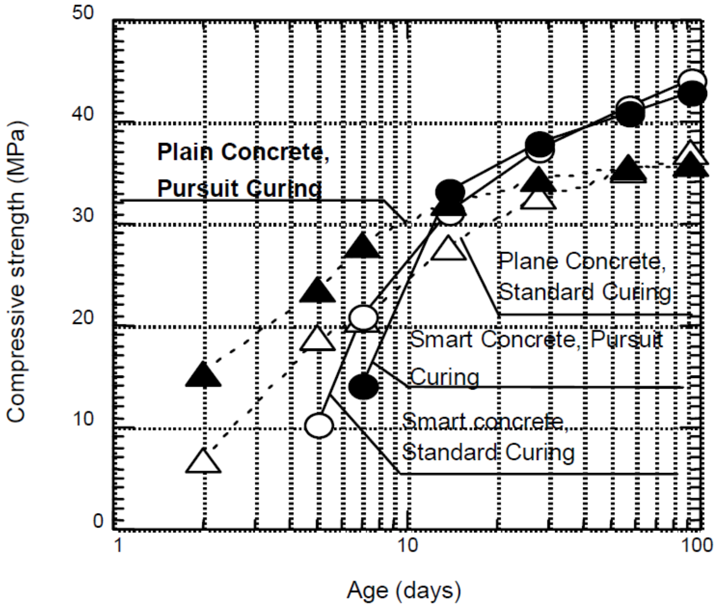

***Figure 9: Development of the compressive strength of smart concrete with PCM and plain concrete. (Mihashi et al. 2002)***

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.

# 5. Analytical Investigations of PCM

The characterization of material properties of building materials with PCMs and the analysis of the thermal performance of these materials in a building is 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, Lehtiniemi & Henell 2004). Analytical solutions which have developed to solve phase change problems deals with simple geometry and boundary conditions. Stefan Problem is a 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) has analyzed 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 investigated with finite element modelling. Simulations indicated that fluctuations of indoor room temperature can be reduced with using PCM in cement compound. 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 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 effect 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 behaviour of building 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 behaviour 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.

# 6. 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. The thermal mass of the building structures can be increased with the incorporation of PCMs into building materials. It will enhance the occupants comfort and reduce the consumption of energy for space conditioning.

However most of the existing TES systems have been explored with wallboards and plaster materials and comparatively a few researches have been done on TES systems using cementitious materials. 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. Thus, there is a necessity for comprehensive experimental investigations on microencapsulated PCM applications with cementitious materials as the most widely used construction materials in buildings. Moreover it should be noted that these experiments must address some concerns with PCM integration with concrete which includes reduction in early stage compressive strength and compatibility of PCMs due to alkalinity. With relates to numerical modelling of PCM integrated concrete, current finite element models has based on number of assumptions and there is no currently available model on microencapsulated PCM in concrete. Thus comprehensive experimental studies and numerical modelling is recommended for understanding the behavior of microencapsulated PCM in concrete.

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