

A review on thermal and mechanical properties of concrete containing phase change material

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Abstract – Phase change materials (PCMs) are high thermal energy storing materials. Incorporation of these materials into building elements such as concrete are found to be advantageous for thermal comfort. Adding PCMs into concrete is reported to give high thermal mass which gives higher energy efficiency. Researches show that effective thermal conductivity of concrete reduces with increasing PCM content in concrete. Energy efficiency and heat capacity of PCM-concrete are reported to be higher than plain concrete. However mechanical properties such as compressive strength and bending strength reduce with increasing PCM content. In this paper thermal properties of PCM-concrete product are reviewed along with some mechanical properties. Thermal characteristics like effective thermal conductivity and coefficient of thermal expansion are important criteria to understand the thermal behavior of concrete. These properties for different building materials employing PCMs as latent heat storage system are reviewed using previous researches. Incorporating PCM into concrete is found to lower the peak temperature in summer days. PCM inclusion also retards the time of occurrence of this peak temperature. PCM in concrete is reported to slow down the cooling period which in turn reduces the risk of thermal cracking. PCM absorbs high heat which reduces cooling as well as heating load in building. This review paper assembles thermal properties of PCM-concrete with mechanical properties to understand the complete behavior of concrete when PCMs are employed.

Key Words: Phase change materials (PCM), Concrete, Thermal energy storage, Thermal properties, Mechanical properties, Thermal cracking

1.INTRODUCTION

Phase change materials (PCMs) are thermal energy storing materials. These materials store energy in the form of both sensible and latent heat. When the temperature increases they firstly act as a sensible heat storage system. With further increase in temperature they start changing their phase and now they work as a latent heat storage system. Many researches show that adding phase change materials in building elements like concrete, increases thermal mass of building. In this way energy efficiency of the building is increased and energy demands for cooling and heating is decreased [5,7,8,9,39,40]. Thermal energy storage in PCM can be classified in two ways: first as sensible heat storage

and second as latent heat storage. In sensible heat storage system heat is stored/released with temperature change and the phase remains same hence a large volume needs to be handled whereas for latent heat storage system heat is stored/released as heat of fusion or heat of solidification, hence a large energy can be stored. Utilization of these heat storing capacities of PCMs are found advantageous in building and constructions. Some thermal characteristics of concrete such as effective thermal conductivity and heat capacity are essential criteria to understand thermal behavior of buildings and designs. Incorporating PCMs into concrete decreases the effective thermal conductivity [5,9] and increases thermal heat capacity [7,8,39]. Researches also show that embedding phase change materials in concrete reduces the risk of thermal cracking [3,6]. Adding PCMs in concrete is found to give more thermal comfort while saving energy for heating and cooling.

This review paper is concerned with the thermal characteristics of PCM embedded concrete. Thermal behavior is important concern to know the energy efficiency and life span of cementitious material and concrete. The paper present here describes the thermal behavior of PCM based concrete with the help of various researches.

1.1 Phase change theory

The phase change of any thermodynamic system can be defined as transformation of its one phase to another. That means the physical property like density, volume etc. are changed. The material can be classified as a pure material and a mixture. A mixture can again be classified as a eutectic and a non-eutectic. The phase change behavior of these materials is important concern to describe the phase change materials. Let us understand phase change in different materials:

(1) The phase change of a pure material:-

A pure material is defined as the substance which has a fixed chemical composition in every phase e.g. water, carbon dioxide etc. There are three principle phases- Solid, Liquid and Gas. Matters can be found in any of these states at atmospheric condition. The phase transformation from Liquid to Solid is called solidification and from Solid to Liquid is called fusion. The existence of phase of a matter is normally shown by phase diagram. The phase diagram is a diagram between pressure p and temperature T . Let us consider that at atmospheric pressure p_0 and temperature T_0 any matter is in its phase 2. This can be shown in phase diagram as below:

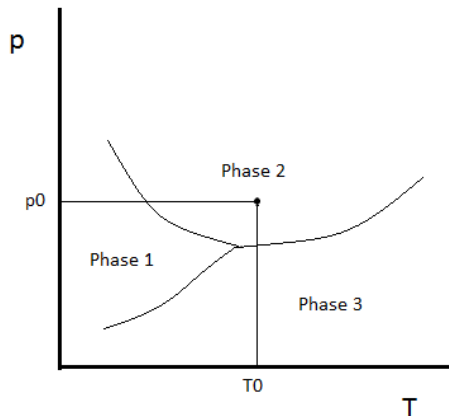


Fig -1: Phase diagram representation

(2) The phase change of a mixture:-

The binary diagram is used to show the locations of different phases of a mixture. If complete solid solubility of two components both in liquid and solid phases takes place then the system is called as an Isomorphous system. Three phases in the phase diagram can be identified as liquid (L), solid + liquid ($\alpha+L$), solid (α). In the figure below the liquidus line separates liquid from liquid + solid and the solidus line separates solid from liquid + solid.

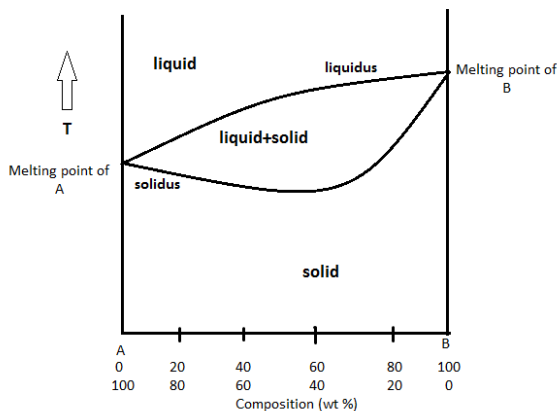


Fig -2: Phase diagram of Isomorphous system

If the matters are partially soluble in solid state, the phase diagram can be shown as below. In this condition the melting point is as low as all the components crystallize simultaneously.

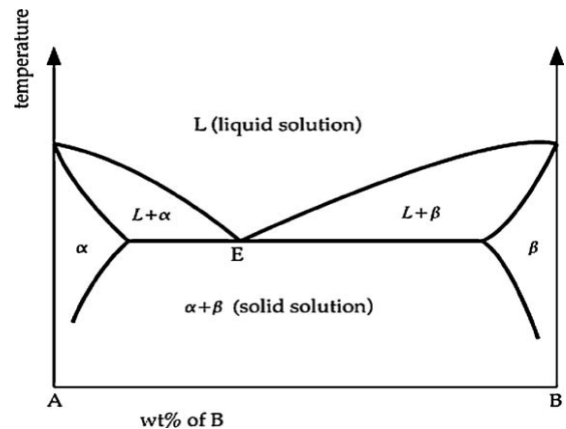


Fig -3: Binary phase diagram with eutectic point

1.2 Phase change materials (PCM)

A phase change material (PCM) is a substance which, melts and solidifies at a certain temperature and it has a high heat of fusion. It is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid state and vice versa; Thus, PCMs can be called as latent heat storage (LHS) units.

Latent heat storage in PCMs can be achieved through liquid to solid, solid to liquid, solid to gas and liquid to gas phase changes. But it has been observed that only solid to liquid and liquid to solid phase changes are practical for PCMs. Although liquid to gas transitions have a higher heat of transformation than solid to liquid transitions, liquid to gas phase changes are Impractical for thermal storage because for this type of transition large volumes or high pressures are required to store the materials in their gaseous phase. Except this solid to gas phase changes are typically very slow and have a relatively low heat of transformation.

At the beginning when the solid transforms to liquid, PCMs behave like sensible heat storage (SHS) materials; They absorb heat and hence their temperature rises. When PCMs reach the temperature at which they change their phase (i.e. melting point temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. At this stage heat is absorbed as latent heat storage (LHS) system. When the ambient temperature around a liquid material falls, the PCM solidifies and releases its stored latent heat. A large number of PCMs are available in the temperature range of -5°C to 190°C . Also for the human comfort range between $20-30^{\circ}\text{C}$, some PCMs are available with a good effectiveness. These PCMs store about 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry or rock. The use of PCMs in building envelopes and in concrete is coming into existence from last two to three decades.

1.3 Classification of phase change materials

A large number of phase change materials (organic, Inorganic and eutectic) are available for any required temperature range. There are a large number of organic and inorganic chemical materials available, which are identified as PCMs. These are categorized and identified according to the melting temperature and latent heat of fusion. The classification of PCM is shown below:

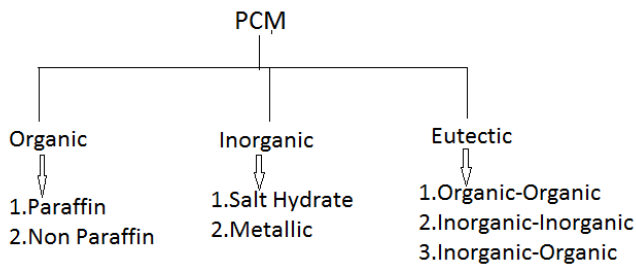


Fig -4: Classification of PCM

(1) Organic phase change materials:-

Organic phase change materials are further classified as paraffin and non-paraffin. Some advantages of organic phase change materials are as follows:

1. Organic PCMs have high heat of fusion
2. These are chemically stable and hence very useful
3. These PCMs have ability to melt congruently without phase segregation
4. These have self-nucleating property and freeze without much subcooling hence do not need to use nucleating agent to prevent subcooling
5. These are safe and non-reactive and also these can be recycled
6. These PCMs are compatible with conventional materials of construction so these can be used with building envelopes and concrete
7. These PCMs are non-corrosive

Several disadvantages of organic PCMs are listed below:

1. The volumetric latent heat storage capacity of these PCMs is low
2. The cost of these PCMs is high as compared to other types of PCMs
3. In solid state the thermal conductivity of these PCMs is low
4. These PCMs can be flammable

Organic phase change materials are further classified as follows:

(i) Paraffin

Paraffin wax is mostly a mixture of straight chain n-alkanes. The general formula of paraffin can be given as (C_nH_{2n+2}) . The crystallization of this chain releases a large amount of latent heat. In this chain as the carbon content or chain length increases, melting point and latent heat of fusion also increase.

Paraffin can be used as energy storage materials because of its availability in a large temperature range. Paraffin is safe, reliable, less expensive and non-corrosive than non-paraffin. This is also chemically inert and stable up to sufficiently high temperature range. Paraffin shows little volume changes on melting and have low vapor pressure in the melt form. Because of these properties paraffin can be used for longer melt-freeze cycle. Paraffin shows few undesirable properties like: (i) low thermal conductivity, (ii) non-compatibility with the plastic container and (iii) moderately flammability. But all these undesirable effects can be eliminated up to some extent by modifying the wax quality and the storage unit.

(ii) Non-paraffin

The non-paraffin organic PCMs are normally fatty acids and some other are esters, alcohols, glycols etc. The general formula of fatty acid is given as $CH_3(CH_2)_{2n}.COOH$. A large number of non-paraffin organic PCMs are available with high variation in their properties. Some useful features of these organic materials are as follows: (i) high heat of fusion, (ii) inflammability, (iii) low thermal conductivity, (iv) low flash points, (v) less toxicity, and (vi) reproducible melting and freezing behavior with no supercooling. The major drawback of these PCMs is their cost, which are 2–2.5 times higher than that of technical grade paraffin. Some other disadvantages of these PCMs are that these are a little corrosive. The melting points of these PCMs are almost similar to that paraffin wax. The melting and freezing properties of these non-paraffin organic PCMs are good. Also these are thermally stable for long number of cycles. Different kinds of non-paraffin PCMs have been studied to assess their suitability for use in concrete. Butyl stearate (BS) is found to be the most appropriate non-paraffin organic PCM because of its relatively low cost, suitable melting point at human comfort temperature, high latent heat storage and low volume change during phase change transition, inflammability and stable nature.

(2) Inorganic phase change materials:-

Inorganic phase change materials are further classified as salt hydrates and metallics.

(i) Salt hydrates

These are formed by salt and water molecules. The general formula of salt hydrates can be given as $A.nH_2O$. Here A stands for any salt. In salt hydrate water and salt molecules are combined, at higher temperature when it melts it breaks into salt and few moles of water molecules.

Salt hydrates are very important among other PCMs and these are extensively used because of some good properties like:

1. These have high latent heat of fusion, which is essential to use any PCM as energy storage unit.
2. These have higher thermal conductivity than those of paraffin and non-paraffin.
3. Volume change is sufficiently small on melting. This property makes these materials easy for handling.
4. These materials are non-corrosive.
5. These are compatible with plastic containers.
6. These materials are less toxic.
7. These materials are not expensive, hence useful as a heat storing system.

Apart from these good properties salt hydrates have few drawbacks. These drawbacks are:

1. The salt hydrates melt incongruently. The n mole of water present in the hydrates is not sufficient to dissolve the one mole of salt.
2. Another common problem is of supercooling. For salt hydrates the rate of nucleation is very low at the fusion temperature.
3. Other problem may include degradation and inoperative characteristic after more number of cycles.

The problem of incongruent melting can be overcome by few means such as:

- i. By adding thickening agents
- ii. By encapsulating the PCM
- iii. By modifying the chemical composition
- iv. By using excess of water
- v. By incorporating mechanical stirrer

The rate of nucleation can be increased by using nucleating agents. This helps to overcome the problem of supercooling.

(ii) Metallics

In this group melting metals are taken. Metallics are usually not considered for PCM usage and not much research have been carried out for this, because use of metallics is concerned with various engineering problems. Although metallics have some good properties like:

- i. High heat of fusion per unit volume
- ii. High thermal conductivity
- iii. Low vapor pressure as compared to others.

(3) Eutectics:-

A eutectic is a mixture of two or more components which has a minimum melting temperature composition. The most important advantage of this mixture is that its components melt and freeze congruently. On melting both of its components liquefy simultaneously without segregation. Since this melts congruently without segregation hence can be utilized for the purpose of energy storage. A eutectic can

be a mixture of Organic-organic, Inorganic-inorganic or Organic-inorganic.

1.4 Incorporation techniques of PCM in concrete

PCM may be incorporated in concrete by various methods. This can be categorized in two ways:

(1) Traditional methods:

Three techniques are mostly employed. These three techniques are direct mixing, immersion and impregnation.

(i) Direct mixing technique:-

This is one of the simplest methods. In this liquid or powdered PCMs are directly mixed in concrete material. PCMs are added in a definite amount to the concrete as other ingredients of concrete are added. This is very simple method but leakage of PCM may occur, which is a problem.

(ii) Immersion technique:-

In this technique the porous concrete products are immersed into melted PCM. The concrete products then absorb PCM into the pores. The concrete products are left for some time to soak PCM. The soaking capacity will increase according to the absorption capacity of concrete, temperature at which soaking is to be done and type of the PCM used for the purpose. The main problem with this method is of PCM leakage.

(iii) Impregnation technique:-

In this technique firstly the porous or light weight aggregate is evacuated and then this evacuated aggregate is dipped into liquid PCM. This is left for soaking in a controlled environment for some time. After that this PCM soaked aggregate is added to concrete mix.

(2) Newly developed techniques:

Newly developed techniques are some special techniques which are developed to prevent leakage of PCM. These techniques also help to retain properties of PCMs after long term of use. Some of the special techniques are described here.

(i) Microencapsulation:-

Microencapsulation is a modification in direct mixing technique. In microencapsulation, PCM particles are firstly enclosed in a capsule of thin and high molecular weight polymers. This process of sealing of PCM particles prevents chemical reaction of PCM with building materials. This also helps to prevent leakage of PCM during phase change. Some common processes to encapsulate organic PCMs are: Interfacial polymerization, in-situ polymerization, emulsion polymerization, spray drying etc. Microencapsulated PCM developed by BASF as Micronal® PCM is shown in figure below:

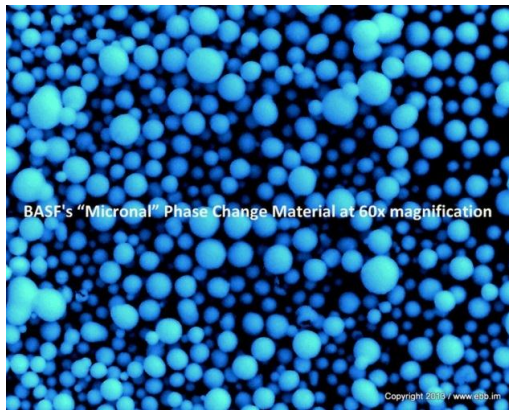


Fig -5: BASF's Micronal® PCM at 60×magnification

(ii) Shape-stabilized PCM:-

Shape-stabilized PCM is prepared by mixing liquid PCM with a supporting material and cooled down until this becomes solid. The most common supporting material used is high density polyethylene (HDPE) and styrene butadiene styrene (SBS). The selection of supporting material is important because it supports PCM for long term of use.

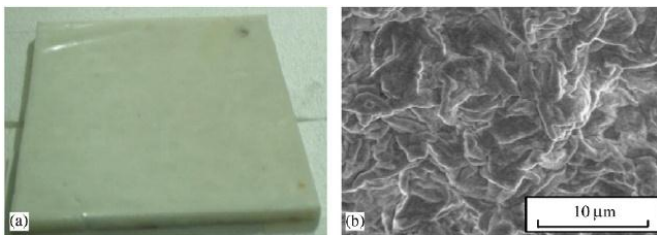


Fig -6: (a) shape-stabilized PCM plate (b) SEM (Scanning Electron Microscope) view of this PCM

1.5 Stability of PCM in concrete

For incorporation of PCM in any application, it is important that they must be stable after long term of use. When we use PCM in concrete it is important to check alkalinity level of concrete. This is important because every PCM is not suitable for use in concrete. Some PCMs increase the alkalinity level of concrete which degrade its quality after long term of use. Many investigations have been done to check for alkalinity of various types of concrete. Hawes [14] investigated for the alkalinity of various types of concrete. He determined the pH value of water in which the specimens of concrete were immersed for 28 days. He found that concrete block with increasing alkali content were as follows: autoclaved concrete block, regular concrete block, pumice concrete and lightweight concrete with expanded shale aggregate. He also found that butyl stearate, 1-dodecanol, 1-tetradecanol imposed less alkalinity than paraffin wax. As a conclusion Hawes [14] proposed for the use of pozzolans to reduce the alkalinity level of concrete. PCM is used as latent heat storage media in concrete. But most of the PCMs are flammable; hence for the stable use of PCM its low flammability check should be done. Hawes [14]

investigated for the fire resistance of concrete containing PCM. He conducted fire test for different PCM-concrete specimens. As a conclusion he found that concrete product may be flammable if PCMs are directly mixed in high concentration. Macro-encapsulation or microencapsulation may be a good solution to increase the fire resistance of concrete product.

For long term use of the PCM-concrete product it is important that the thermal properties of PCM should not be changed after a great number of cycles. A good PCM is one which shows same or almost same thermal, chemical and physical properties after a repeated number of freezing and melting cycles. Thermal stability tests for various phase change materials have been conducted by many researchers. Thermal stability tests for different PCMs are discussed ahead.

(1) Thermal stability test for organic PCMs

The most widely used instrument for performing thermal stability test is differential scanning calorimeter (DSC). This technique is used to obtain melting temperature and heat of fusion of PCM samples. It also includes product stability and phase change crystallization.

As organic PCMs are classified into paraffin and non-paraffin, the thermal stability tests have been performed for both groups by many researchers. The researches carried out for both groups are described as follows:

(i) Test in paraffin wax:-

Hadjieva et al. [15] performed DSC test for paraffin wax of technical grade with formula $C_{22}H_{44.1}$. They found initial and final melting point as 47.1 and 46.6°C with initial and final latent heat as 166 and 163kJ/kg for 300 numbers of thermal cycles. They also studied paraffin wax of technical grade with formula $C_{22}H_{48.4}$. For this they found initial and final melting point 57.1 and 57.8°C respectively with initial and final latent heat as 220 and 224kJ/kg for the same numbers of cycles.

Sharma et al. [16] checked for stability of commercial grade paraffin wax. They found initial and final melting point as 53 and 53°C with initial and final latent heat as 184 and 165kJ/kg for 300 numbers of cycles.

Shukla et al. [17] performed test for paraffin wax 58-60. It was found that initial and final melting points were 58.27 and 55°C with initial and final latent heat as 129.8 and 102kJ/kg for 600 numbers of cycles. Test for paraffin wax 60-62 was also performed for the same numbers of cycles. The initial and final melting points were 57.78 and 59°C with initial and final latent heat of fusion as 129.7 and 109kJ/kg.

Silakhori et al. [18] conducted DSC test for microencapsulated paraffin wax 53 (0.1 g)/ polyaniline (0.9 g). It was found that initial and final melting points were 53.2 and 53.4°C with initial and final latent heat as 31 and 30.5kJ/kg for 1000 numbers of cycles. Similar test for microencapsulated paraffin wax 53 (0.2 g)/ polyaniline (0.8 g) was also performed. For this initial and final melting temperature obtained were 53.8 and 54.4°C with initial and

final latent heat of fusion as 65.1 and 60.5kJ/kg for same numbers of cycles.

(ii) Test in non-paraffin materials:-

Sharma et al. [16] carried out test for Acetamide. It was found that initial and final melting points were 82 and 81°C with initial and final latent heat of fusion as 263 and 241kJ/kg for 300 numbers of cycles.

El-Sebaili et al. [19] conducted test for Acetanilide. Initial and final melting points were found to be 113 and 106°C with initial and final latent heat of fusion as 169.4 and 154kJ/kg for 500 numbers of cycles.

Shukla et al. [17] conducted test for Erythritol. The initial and final melting points were found to be 117 and 119°C with initial and final latent heat of fusion as 339 and 305kJ/kg for 1000 numbers of cycles.

Hasan and Sayigh [20] performed test for Myristic acid. The initial and final melting points were found to be 50.4 and 49.8°C with initial and final latent heat of fusion as 189.4 and 163.5kJ/kg for 450 numbers of cycles. They also conducted test for Palmitic acid for which initial and final melting points were 57.8 and 57.7°C. The initial and final latent heat of fusion were 201.2 and 184.4kJ/kg for 450 numbers of cycles. For stearic acid the initial and final melting points were 65.2 and 65.9°C with initial and final latent heat of fusion as 209.9 and 185.3kJ/kg for 450 numbers of cycles.

Sari [21] performed DSC test for Lauric acid. The initial and final melting points obtained were 42.6 and 41.3°C with initial and final latent heat of fusion as 176.6 and 156.6kJ/kg for 1200 numbers of cycles.

(2) Thermal stability test for inorganic PCMs

Inorganic PCMs are classified as salt hydrates and metallics.

(i) Test in salt hydrates:-

Kimura and Kai [22] performed test for calcium chloride hexahydrate. For this melting point obtained was 29.8°C with latent heat of fusion as 190.8kJ/kg for 1000 numbers of cycles. For test conducted in Sodium acetate trihydrate the melting point obtained was 58°C with latent heat of fusion as 252kJ/kg for 100 numbers of cycles. They also conducted test for Trichlorofluoromethane heptadecahydrate. The melting point obtained was 8.5°C with latent heat of fusion as 219kJ/kg for 100 numbers of cycles.

Marks [23] performed test on Glauber’s salt. Melting point obtained was 32.4°C with latent heat of fusion as 238 for 320 numbers of cycles.

Porisini [24] performed test on Glauber’s salt and obtained melting point 32°C for 5650 cycles. For NaOH.3.5H₂O the melting point obtained was 15°C and for Na₂SO₄.0.5NaCl.10H₂O melting point was 20°C with same number of cycles.

El-Sebaili et al. [19] performed test for Magnesium chloride hexahydrate. The melting point obtained was

111.5°C with latent heat of fusion as 155.11kJ/kg for 500 cycles.

(ii) Test in metallic:-

Sun et al. [25] performed test for Al-34%Mg-6%Zn alloy. Melting point obtained was 454°C with latent heat as 314.4kJ/kg for 1000 cycles.

(3) Thermal stability test for eutectics

Eutectics are classified as organic-organic eutectics, inorganic-inorganic eutectics and organic-inorganic eutectics. The stability test performed in organic and inorganic eutectics are shown individually in tables below:

Table -1: Thermal stability for organic eutectics

Thermal stability cycle for organic eutectics				
PCM	Melting point (°C)	Latent heat (kJ/kg)	No. of thermal cycles	Reference
Ammonium alum (15%) + ammonium nitrate (85%)	53	170	1100	Jotshi et al. [26]
Butylstearate (49wt%) +Butyl palmitate (48wt%) + other (3wt%)	17	138	100	Feldman et al. [27]
Capric acid (65mol%) + lauric acid (35mol%)	13	116.76	120	Dimaano & Escoto [28]
Capric acid (73.5wt%) + myristic acid (26.5wt%)	21.4	152	5000	Shilei et al. [29]
Capric acid (83wt%) + stearic acid (17wt%)	24.68	178.64	5000	Karaipeli et al. [30]
Caprylic acid (70wt%)+1-dodecanol(30wt%)	6.52	171.06	120	Zuo et al. [31]
Methyl stearate+methyl palmitate	23.9	220	50	Nikolic et al. [32]
Stearic acid+glyserol	63.45	149.4	1000	Sari et al [33]
Palmitic acid+glyserol	58.50	185.9	1000	Sari et al. [33]
Myristic acid+glyserol	31.96	154.3	1000	Sari et al. [33]
Lauric acid(66wt%)+myristic acid(34wt%)	34.2	166.8	1460	Sari [34]
Lauric	35.2	166.3	1460	Sari

acid(69wt%)+palmitic acid(31wt%)				[34]
Myristic acid(64wt%)+stearic acid(36wt%)	44.1	182.4	1460	Sari [34]

Table -2: Thermal stability for organic eutectics

Thermal stability cycle for Inorganic eutectics				
PCM	Melting point (°C)	Latent heat (kJ/kg)	No. of thermal cycles	Reference
CaCl ₂ .6H ₂ O (80mol%)+ CaBr ₂ .6H ₂ O (20mol%)	20	117	1000	Kimura and Kai [22]
CaCl ₂ .6H ₂ O (93wt%) + Ca(NO ₃) ₂ .4H ₂ O (5wt%) +Mg(NO ₃) ₂ .6H ₂ O(2wt%)	24	125	1000	Kimura and Kai [22]
CaCl ₂ .6H ₂ O (96wt%)+ KNO ₃ (2wt%)+ KBr (2wt%)	23	138	1000	Kimura and Kai [22]
CaCl ₂ .6H ₂ O (96wt%)+ NH ₄ NO ₃ (2wt%)+ NH ₄ Br (2wt%)	20	141	1000	Kimura and Kai [22]
NaCH ₃ COO.3H ₂ O (90wt%)+NaBr.2H ₂ O (10wt%)	51	175	1000	Kimura and Kai [22]
NaCH ₃ COO.3H ₂ O (85wt%)+NaHCOO.3H ₂ O (15wt%)	49	170	1000	Kimura and Kai [22]
Mg(NO ₃) ₂ .6H ₂ O (93wt%)+MgCl ₂ .6H ₂ O (7wt%)	78	152.4	1000	Nagano et al. [35]

2. THERMAL PROPERTIES OF PCM-CONCRETE

Thermal properties of concrete containing PCMs are analyzed by various researchers. They analyzed thermal characteristics by mixing different PCMs in concrete. L.F. Cabeza et al. [2] investigated the use of microencapsulated PCM in concrete walls for energy savings. They constructed and installed two real size concrete cubicles to study the effect of the inclusion of PCM with melting point of 26°C and phase change enthalpy of 110kJ/kg. These cubicles were constructed in the locality of Puigverd of Lleida (Spain). Their results showed that wall with microencapsulated PCM had improved thermal inertia than wall without PCM. Also they measured a lower inside temperature with PCM wall as compared to without PCM wall.

D.P. Bentz and R. Turpin [3] demonstrated potential applications of phase change materials in concrete technology. They found that PCM was good in enhancing the performance of concrete technology in several applications. They experienced that PCMs may added directly or in a microencapsulated form in the concrete. Also the porous light

weight aggregate can be utilized as a PCM carrier. They demonstrated that PCM mortar under semi-adiabatic curing condition could be used to limit the temperature rise.

C. Voelker et al. [4] investigated for temperature reduction due to the application of phase change materials. They found in their study that utilization of phase change materials in buildings increases the thermal mass and contributes to an improvement of the thermal protection in summer. They performed their measurements using paraffin as well as a salt mixture. A reduction in the peak temperature of up to 4 K could be ascertained.

M. Hunger et al. [5] analyzed the behavior of self-compacting concrete containing micro-encapsulated phase change materials. In order to evaluate the effect of PCM on the thermal conductivity of concrete they prepared three mixes containing 1% PCM, 3% PCM and 5%. Two samples of 100 mm×100 mm× 50 mm of every mixture were prepared for the measurements. Their results for thermal conductivity measurements are presented in figure below. From the graph it is clear that the addition of PCM particles into the mass of the concrete results in a reduction of thermal conductivity. The reduction in thermal conductivity is due to increased air content and because of the use of low thermal conductivity material like paraffin.

For the measurement of specific heat capacity, they prepared four samples of four different mixes in the dimensions, 200 mm×200 mm×30 mm. The samples were introduced in the sample holder of the thermal analysis device at a temperature of 19°C and were heated up to 28°C. The temperature of the device during the heating process was maintained constant at 32°C. The temperature of the samples and the heat flux from the device to the samples were recorded by them and the heat capacity and thermal mass of the samples were calculated as shown in chart 2 and 3.

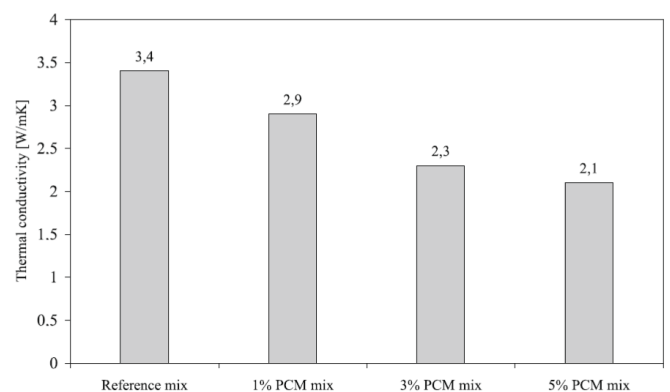


Chart -1: Thermal conductivity of PCM mixes measured by M. Hunger et al.

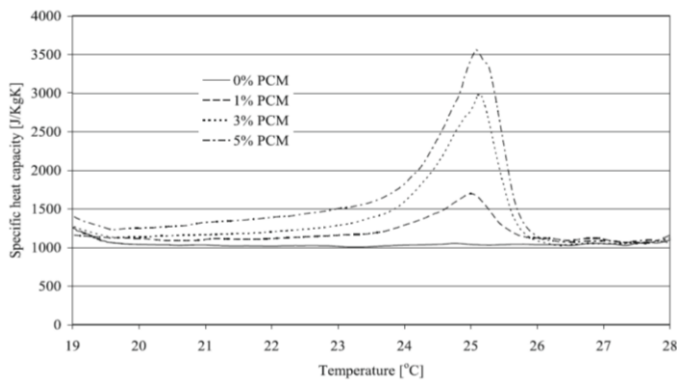


Chart -2: Specific heat capacity of PCM mixes with temperature measured by M. Hunger et al.

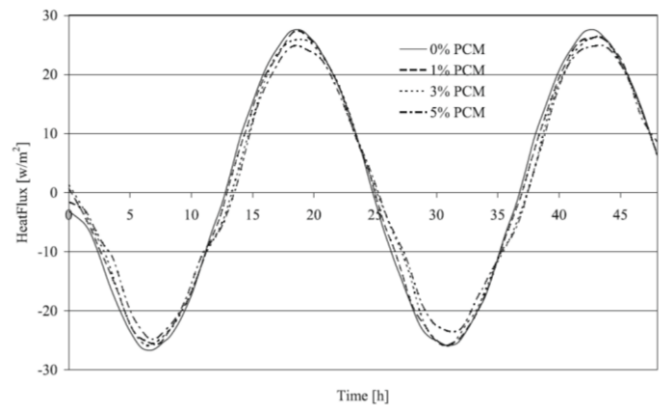


Chart -4: Heat flux on the side of the sample corresponding to the indoor wall surface.

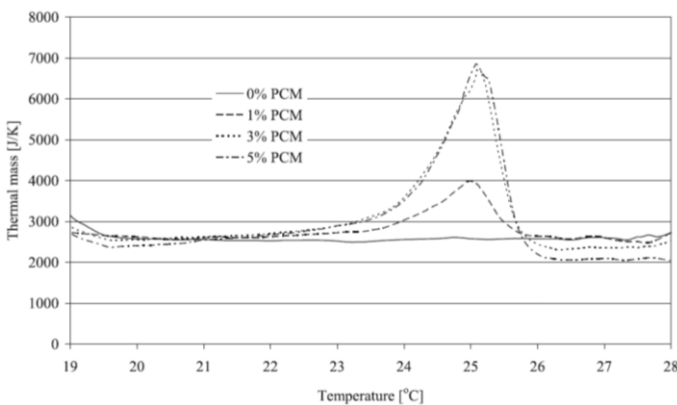


Chart -3: Thermal mass of PCM mixes with temperature measured by M. Hunger et al.

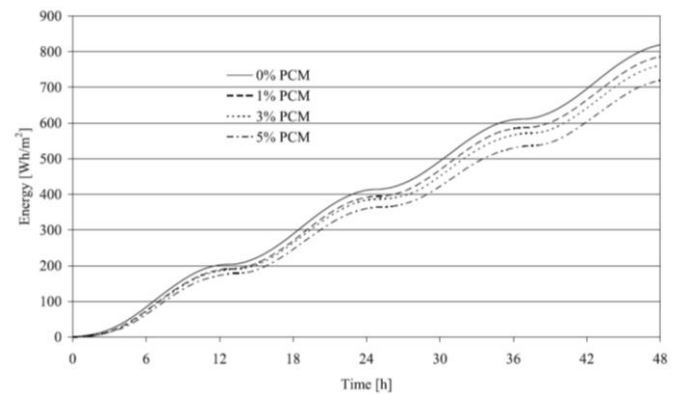


Chart -5: Energy required for maintaining indoor temperature stable at 23.5°C

Heat flux on the side of the sample corresponding to the indoor wall surface is also measured. For this the outdoor temperature is assumed to have a sinusoidal variation from 18.5°C to 28.5°C for 48 h, while the indoor temperature is set stable at a level of 23.5°C. Temperatures and heat fluxes on both surfaces of the same samples as the ones used for the specific heat capacity measurements were recorded by them. The heat flux measurement with respect to time is represented in chart 4. The heat flux measurements of below chart demonstrate an up to 11% variation in the measured maximum and minimum peak values for the sample with 5% PCM content. The calculated energy corresponds to the energy required by an air-conditioning system to maintain the indoor temperature constant at 23.5°C.

F. Fernandes et al. [6] investigated for using phase change materials to mitigate thermal cracking in cementitious materials. They found that inducing PCMs into cementitious composites give a reduction in peak temperature. This reduction was up to 3-5°C. They observed a significant result during cooling period that PCM inclusion reduces cool down period which consequently reduces the risk of thermal cracking. They also observed that both plain and PCM containing pastes experience similar thermal deformation levels across the imposed temperature cycles. Since the thermal strain developed was essentially equal at equal temperatures, this implied that plain and PCM containing systems both demonstrate similar coefficients of thermal expansion.

A.M. Thiele et al. [7] performed diurnal thermal analysis of microencapsulated PCM-concrete composite walls. In this analysis they found that increasing the PCM volume fraction significantly reduced the heat transfer through the wall. A PCM volume fraction of 0.5 reduced the range of variation in inner wall heat flux by more than 90% compared with the plain concrete. They also found that adding microencapsulated PCM to concrete delayed the peak inner wall heat flux corresponding to the maximum cooling load. By increasing the latent heat of fusion they got delayed heat transfer through the wall. The energy flux reduction was

increased from 25% to 64% and the time delay increased from 0.8 to 5.7 h as the latent heat of fusion increased from 100 to 400kJ/kg.

A.M. Thiele et al. [8] performed annual energy analysis of concrete containing phase change materials for building envelopes. They observed that adding microencapsulated PCM to the concrete wall decreased the amplitude of the inner surface heat flux throughout the year. The amplitude of the positive heat flux into the building requiring cooling was reduced substantially more than that of the flux out of the building requiring heating. They also noted that the total thermal load reduced much more in summer months when the temperature oscillations were centered closer to the desired indoor temperature.

A. Ricklefs et al. [9] performed test to find out thermal conductivity of cementitious composites which contained microencapsulated phase change material. They used a guarded hot plate apparatus to find out effective thermal conductivity of simple OPC paste and cement mortar both containing microencapsulated phase change material up to 30% volume fraction. Cement paste and cement mortar were prepared with 0.45 water to cement ratio and temperature range of 10-40°C. All these specimens were aged more than 28 days. They found that thermal conductivity remained nearly constant between temperature range of 10-50°C and decreased as the microencapsulated PCM volume fraction increased. The thermal conductivity was larger for composites made up of cement mortar (1.2-1.8 W/mK) than of simple cement paste (0.8- 1.2 W/mK).

2. MECHANICAL PROPERTIES OF PCM-CONCRETE

Mechanical properties such as compressive strength, density, bending strength, porosity etc. are essential to be considered for PCM-concrete product. Since inclusion of PCM into concrete or cementitious composite may decrease mechanical strength, so it is important to investigate for mechanical properties along with the thermal properties. Some of the mechanical properties are discussed here as how they are affected with the inclusion of PCM in concrete.

T. Lecompte P. Le Bideau P. Glouannec D. Nortershauser S. Le Masson [10] investigated for mechanical and thermo-physical behaviour of concretes and mortars containing phase change material. Two types of mix were prepared by them. The first was a very basic mix used for mortars and concretes which are described below:

- Mortar M1 : 1 bucket of cement, 3 buckets of sand
- Mortar M2 : 1 bucket of cement, 2 buckets of sand, 2 buckets of PCM
- Concrete C1: 1 bucket of cement, 2 buckets of sand, 2 buckets of gravels
- Concrete C2: 1.2 bucket of cement, 1.5 bucket of sand, 1.5 bucket of gravels, 2 buckets of PCM

And the second was more sophisticated to properly evaluate the action of PCM in concretes. The phase change material used was a microencapsulated paraffin n-octadecane (C₁₈H₃₈) provided by Microtek laboratories MPCM 28. The

compressive strength obtained by them is shown in the chart 6. It was observed by them that the presence of phase change materials lowered the compressive strength of concrete and mortar. They assumed that PCM capsules probably behave more like voids than the common aggregates in mortars and concrete. The below chart shows that compressive strength is decreased as PCM introduced to concrete and mortar mix.

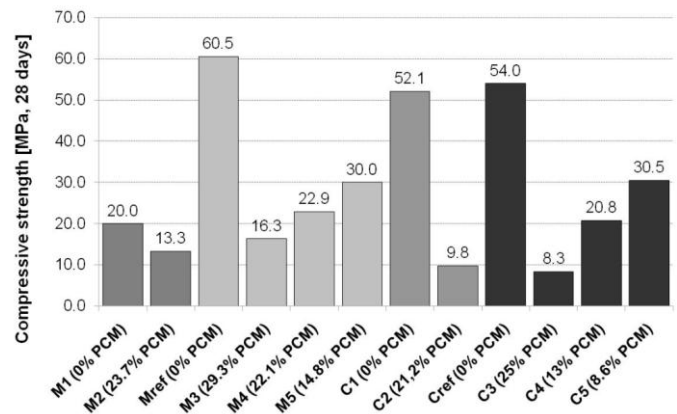


Chart -6: Compressive strength obtained with PCM

A. Figueiredo et al. [11] incorporated PCM in concrete to find out some thermal and mechanical properties. They prepared different mixes. They found in their study that concrete compressive strength loss by incorporating PCM was about 68% in average. The effect of the incorporation method of the PCM and the addition of water in the mixture process led to a lower loss of compression strength in the concrete specimens with PCM incorporation.

M. Aguayo et al. [12] used two types of microencapsulated PCM named as PCM-M and PCM-E. These PCMs were used as replacement of fine aggregate in different volume fraction. The graphs obtained for compressive strength and flexural strength are shown in chart 7. In the graph there is a consistent reduction in strength when PCM-M replaces sand in the mortars but the strengths of mortars containing up to 15% of PCM-E by volume are higher than that of the plain mortar at all ages. The compressive strength of mortar is highest for PCM-E when 10% of sand is replaced by PCM. For PCM-E concrete, compressive strength remains higher in each case. Trend obtained for flexural strength of PCM-E and PCM-M is also shown in the chart. Flexural strength is also higher for PCM-E.

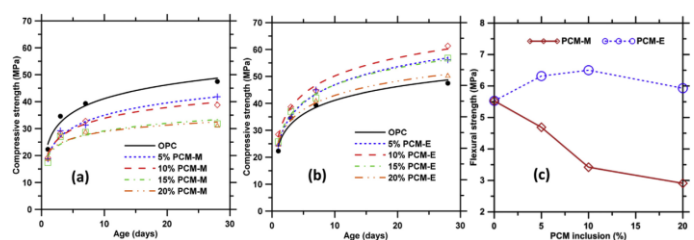


Chart -7: (a) compressive strength for PCM-M (b) compressive strength for PCM-E (C) flexural strength for PCM-M and PCM-E

T. Xu et al. [13] investigated the properties of concrete block in which they incorporated polyethylene glycol/SiO₂ as phase change material. They found a negative effect of the quantity of the PEG/SiO₂ PCM on the compression strength of the concrete. They observed that for the concrete without PCM, the compression strength was 23.61 MPa. This value dropped rapidly to 7.5 MPa when the mass ratio of the composite PCM was changed from 0 to 4.5%. The rate of the decline was about 68.2%. When the mass ratios of the composite PCM were 7.5% and 9%, the global compression strength of the concrete were 4.392 MPa and 3.828 MPa.

M. Hunger et al. [5] analyzed mechanical properties of self compacting concrete containing microencapsulated PCM. They prepared five standard cubes for each mixture with an edge length of 150 mm. Compressive strength test was performed after 28 days of production. The test result is shown in the chart below. From the data obtained it was clearly observed that increasing PCM dosage in concrete reduced the compressive strength. It was concluded that the compressive strength of the specific mixture prepared by them decreased by 13% for each additional percentage of PCM

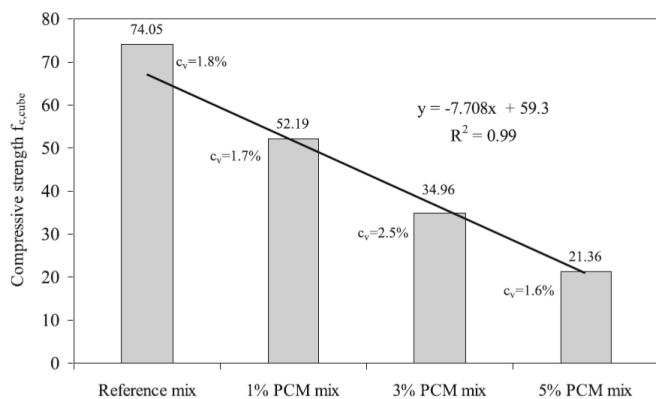


Chart -8: Compressive strength of PCM mix after 28 days

T. Lecompte P. Le Bideau P. Glouannec D. Nortershauser S. Le Masson [10] found in their studies that the value of bending strength was similar to one that observed for compressive strength. The bending strength value was between 1.7 MPa for high PCM content mixes to 6.1 MPa for the lowest PCM content mix.

A. Figueiredo et al. [11] created 12 test specimens with rectangular dimensions for testing bending strength. They found a reduction of 25% in bending strength for the specimens incorporating PCM in comparison to the reference concrete test specimens, and a reduction of 43% for the concrete incorporating PCM in the specimens with temperature influence. They observed Loss of 51.75% of the maximum bending strength for the specimens incorporating PCM in comparison to the reference concrete test specimens,

and 63% loss when the specimens were subjected to the temperature effect.

T. Xu et al. [13] tested for the apparent density of the concrete containing PEG/SiO₂ PCM with fixed sizes but different PEG mass fraction. It was observed that the apparent density of the concrete had a three-stage decreasing behavior as the PEG content increased. At the first stage, a sharp decline occurs from 0 to 1.5% total PEG mass fraction. Secondly when it came to the range 1.5-7.5%, the apparent density varied smoothly. At the third stage rapid decrease in apparent density was observed.

M. Hunger et al. [5] found that density of concrete decreased by increasing PCM content. In the similar way the porosity was increased as the amount of PCM was increased. The result obtained by their test is represented in chart below:

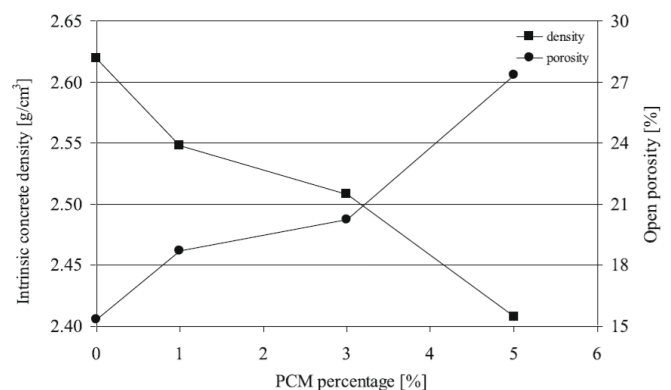


Chart -9: Plot for density and porosity with PCM percentage

3. CONCLUSIONS

This review paper is prepared for analyzing thermal and some mechanical characteristics of concrete containing phase change materials. Based on the reviewed research papers following conclusions can be drawn:

1. Incorporating phase change materials in concrete has a potential to increase thermal mass. PCM incorporated in concrete gives reduction in peak temperature in summer days. It also delays the time of occurrence of peak temperature.
2. Thermal conductivity of concrete decreases by increasing the PCM percentage in concrete mix.
3. Specific heat capacity of concrete increases as the dosage of PCM is increased in the concrete mix.
4. Heat flux inside the concrete block reduces by incorporating phase change materials.
5. For maintaining a desired inside temperature in a building, energy required by PCM-concrete mix is less as compared to normal concrete mix.
6. Increase in specific heat capacity of concrete by incorporating PCM consequently increases the cool down period which in turn reduces the risk of thermal cracking.
7. PCM incorporation in concrete produces almost similar thermal strain. This implies that coefficient

- of thermal expansion for plain concrete and PCM mixed concrete are almost same.
8. Energy requirement throughout the year reduces by incorporating PCM in concrete. This is because the peak temperature of a building reduces.
 9. PCM incorporation in concrete reduces the compressive strength. Although this loss in compressive strength can be reduced by using appropriate type of PCM and modifying incorporation means.
 10. PCM inclusion in concrete reduces bending strength. To overcome this appropriate mix needs to be designed.
 11. The apparent density of concrete decreases as the amount of PCM inclusion increases. Porosity of concrete block increases with the increase in PCM dosage.

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REFERENCES

- [1] T.D. Brown, M.Y. Javaid, The thermal conductivity of fresh concrete, *Matériaux et Construction* 3 (6) (1970) 411-416.
- [2] L.F. Cabeza, C. Castellon, M. Nogues, M. Medrano, R. Leppers, O. Zubillaga, Use of microencapsulated PCM in concrete walls for energy savings, *Energy Build.* 39 (2) (2007) 113-119.
- [3] D.P. Bentz, R. Turpin, Potential applications of phase change materials in concrete technology, *Cem. Concr. Compos.* 29 (7) (2007) 527-532.
- [4] C. Voelker a, O. Kornadt , M. Ostry, Temperature reduction due to the application of phase change materials, *Energy and Buildings* 40 (2008) 937-944.
- [5] M. Hunger , A.G. Entrop, I. Mandilaras, H.J.H. Brouwers, M. Founti, The behavior of self-compacting concrete containing micro-encapsulated Phase Change Materials, *Cement & Concrete Composites* 31 (2009) 731-743.
- [6] F. Fernandes, S. Manari, M. Aguayo, K. Santos, T. Oey, Z. Wei, G. Falzone, N. Neithalath, G. Sant, On the feasibility of using phase change materials (PCMs) to mitigate thermal cracking in cementitious materials, *Cem. Concr. Compos.* 51 (2014) 14-26.
- [7] A.M. Thiele, G. Sant, L. Pilon, Diurnal thermal analysis of microencapsulated PCM-concrete composite walls, *Energy Convers. Manage.* 93 (2015) 215-227.
- [8] A.M. Thiele, A. Jamet, G. Sant, L. Pilon, Annual energy analysis of concrete containing phase change materials for building envelopes, *Energy Convers. Manage.* 103 (2015) 374-386.
- [9] A. Ricklefs, A. M. Thiele, G. Falzone, G. Sant, L. Pilon, Thermal conductivity of cementitious composites containing microencapsulated phase change materials, *International Journal of Heat and Mass Transfer* 104 (2017) 71-82.
- [10] T. Lecompte P. Le Bideau P. Glouannec D. Nortershauser S. Le Masson, Mechanical and thermo-physical behaviour of concretes and mortars containing Phase Change Material, *Energy and Buildings* (2015), <http://dx.doi.org/10.1016/j.enbuild.2015.02.044>.
- [11] A. Figueiredo, J. L., Romeu Vicente, C. Cardoso, Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM for applications in thermally activated slabs, *Construction and Building Materials* 112 (2016) 639-647.
- [12] M. Aguayo, S. Das, A. Maroli, N. Kabay , J. C.E. Mertens, S. D. Rajan, G. Sant, N. Chawla, N. Neithalath, The influence of microencapsulated phase change material (PCM) characteristics on the microstructure and strength of cementitious composites: Experiments and finite element simulations, *Cement and Concrete Composites* 73 (2016) 29-41.
- [13] T. Xu, Q. Chen, Z. Zhang , X. Gao, G. Huang, Investigation on the properties of a new type of concrete blocks incorporated with PEG/SiO₂ composite phase change material, *Building and Environment* 104 (2016) 172-177.
- [14] Hawes DW. Latent heat storage in concrete. PhD Thesis. Concordia University, Montreal, Quebec, Canada; 1991.
- [15] Hadjieva M, St. Kanev, Argirov J., Thermo-physical properties of some paraffins applicable to thermal energy storage. *Solar Energy Materials and Solar Cells* 1992;27:181-7.
- [16] Sharma SD, buddhi D, Sawhney RL, Accelerated thermal cycle test of latent heat storage materials, *Solar Energy* 1999;66(6):483-90.
- [17] Shukla A, Buddhi D, Sawhney RL, Thermal cycling test of few selected inorganic and organic phase change materials, *Renewable Energy* 2008;33:2606-14.
- [18] Silakhori M, Naghavi MS, Metselaar HSC, Mahlia TMI, Fauzi H, Mehrali M. Accelerated thermal cycling test of microencapsulated paraffin wax/poly aniline made by simple preparation method for solar thermal energy storage. *Materials* 2013;6:1608-20.
- [19] El-Sebaai AA, Al-Amir S, Al-Marzouki FM, Faidah AS, Al-Ghamdi AA, Al-Heniti S, Fast thermal cycling of acetanilide and magnesium chloride hexa hydrate for indoor solar cooking, *Energy Conversion Management* 2009;50:3104-11.
- [20] Hasan A, Sayigh AA, Some fatty acids as phase-change thermal energy storage materials, *Renew Energy* 1994;4(1):69-76.
- [21] Sari A., Thermal reliability test of some fatty acids as PCMs used for solar thermal latent heat storage applications, *Energy Convers Manag* 2003;44:2277-87.
- [22] Kimura H, Kai J, Phase change stability of CaCl₂.6H₂O. *Solar Energy* 1984;33(1):49-55.
- [23] Marks S, An investigation of the thermal energy storage capacity of glauber's salt with respect to thermal cycling, *Solar Energy* 1980;25:225-58.
- [24] Porosini FC, Salt hydrates used for latent heat storage: corrosion of metals and reliability of thermal performance, *Solar Energy* 1988;41:193-7.
- [25] Sun JQ, Zhang RY, Liu ZP, Lu GH, Thermal reliability test of Al-34%Mg-6%Zn alloy as latent heat storage material and corrosion of metal with respect to thermal cycling, *Energy Conversion and Management* 2007;48(2):619-24.

- [26] Jotshi CK, Thermal storage in ammonium alum/ammonium nitrate eutectic for solar space heating applications, *Solar Energy Engineering* 1998;120: 20–4.
- [27] Feldman D, Banu D, Hawes D, Ghanbari E, Obtaining an energy storing building material by direct incorporation of an organic phase change material in gypsum board, *Solar Energy Materials* 1991;22:231–42.
- [28] Dimaano M, Escoto A, Preliminary assessment of a mixture of capric acid and lauric acids for low-temperature thermal energy storage, *Energy* 1998;23:421–7.
- [29] Shilei L, Neng Z, Guohui F, Eutectic mixture of capric acid and lauric acid applied in building wallboards for heat energy storage, *Energy and Buildings* 2006;38:708–11.
- [30] Karaipekli A, Sari A, Kaygusuz K. Thermal properties and thermal reliability of capric acid/stearic acid mixture for latent heat thermal energy storage. *Energy Sources* 2009;31:199–207.
- [31] Zuo J, Li W, Weng L. Thermal performance of caprylic acid/1-dedocanol eutectic mixture as phase change material (PCM). *Energy and Buildings* 2011;43:207–10.
- [32] Nikolic R, Marinovic-Cincovic M, Gadzuric S, Zsigrai IJ. New materials for solar thermal storage solid/liquid transitions in fatty acid esters. *Solar Energy Materials & Solar Cells* 2003;79:285–92.
- [33] Sari A, Bicer A, Karaipekli A, Alkan C, Karadag A. Synthesis, thermal energy storage properties and thermal reliability of some fatty acid esters with glycerol as novel solid–liquid phase change materials. *Solar Energy Materials and Solar Cells* 2010;94:1711–5.
- [34] Sari A. Eutectic mixtures of some fatty acids for low temperature solar heating applications: thermal properties and thermal reliability. *Applied Thermal Engineering* 2005;25:2100–7.
- [35] Nagano K, Ogawa K, Mochida T, Hayashi K, Ogoshi H. Thermal characteristics of magnesium nitrate hexahydrate and magnesium chloride hexahydrate mixture as a phase change material for effective utilization of urban waste heat. *Appl Therm Eng* 2004;24(2–3):221–32.
- [36] Hawes DW, Feldman D. Absorption of phase change materials in concrete. *Sol Energy Mater Sol Cell* 1992;27(2):91–101.
- [37] Hawlader M, Uddin M, Khin MM. Microencapsulated PCM thermal energy storage system. *Applied Energy* 2003;74:195–202.
- [38] Zhang Y, Lin K, Yang R, Di H, Jiang Y. Preparation, thermal performance and application of shape-stabilized PCM in energy efficient buildings. *Energy and Buildings* 2006;38(10):1262–9.
- [39] F. Kuznik, D. David, K. Johannes, J.J. Roux, A review on phase change materials integrated in building walls, *Renewable and Sustainable Energy Reviews* 15 (2011) 379–391.
- [40] T. Ling, C. Poon, Use of phase change materials for thermal energy storage in concrete: An overview, *Construction and Building Materials* 46 (2013) 55–62.
- [41] D. Zhou, C.Y. Zhao, Y. Tian, Review on thermal energy storage with phase change materials (PCMs) in building applications, *Applied Energy* 92 (2012) 593–605.
- [42] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renewable and Sustainable Energy Reviews* 13 (2009) 318–345,
- [43] M. K. Rathod, J. Banerjee, Thermal stability of phase change materials used in latent heat energy storage systems: A review, *Renewable and Sustainable Energy Reviews* 18(2013)246–258.
- [44] G. Ferrer, Aran Solé, C. Barreneche, I. Martorell, L. F. Cabeza, Review on the methodology used in thermal stability characterization of phase change materials, *Renewable and Sustainable Energy Reviews* 50(2015)665–685.