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Thermal Properties of Lightweight Concrete Incorporating High Contents of Phase Change Materials

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Abstract

This research investigated the latent heat and energy storage of lightweight concrete containing high contents of phase change material (PCM) (up to about 7.8% by weight of concrete). PCM - Polyethylene Glycol (PEG) with a fusion temperature of approximately 42-46˚C was impregnated into porous lightweight aggregates up to 24% by weight. The PCM aggregates were then used to replace normal lightweight aggregate at a rate of 0, 25, 50, 75 and 100% by volume. The samples were subjected to series of experiments such as compressive strength (EN12390-3 2002), flexural strength (ASTM C78), thermal conductivity

(ASTM C518) and the thermal storage of phase change materials examined using a heat flow meter apparatus (ASTM C1784) at the age of 28 days. Results show that the existence of PCM aggregates affects both mechanical and thermal properties of concrete to different degrees. The mechanical properties appear to improve with increasing PCM aggregate content. For thermal properties such as thermal conductivity and specific heat, the state of the PCM (liquid or solid state) as well as the testing temperature during the test, show significant influence on the obtained results. The latent heat was found to increase proportionally with the increasing PCM aggregate replacement rate.

Keywords: Latent Heat, Heat Storage, Specific Heat, Thermal Conductivity, Lightweight Aggregate, Lightweight Concrete, Phase Change Material, PCM carrier.

1. Introduction

Global energy demand is increasing and is expected to continue to increase every year. From 1980 to 2012, the energy consumption of three of the world's largest economies (USA, China and the EU) increased by 85%. Interestingly, the energy demand from the building sector has been reportedly increasing at a greater rate than the commercial sector [1]. In 2010, global energy demand in the building sector was approximately 115 EJ, 32% of total global energy demand [2]. In Thailand, energy usage in the household sector accounts for about 24% of total energy production [3]. Most of it is spent on conditioning the temperature in houses and buildings because Thailand is located in a hot and humid climate region. In order to reduce the energy consumption, construction materials with good thermal insulation are necessary. Conventionally, thermal properties of concrete can be enhanced by simply incorporating air voids into concrete mixture by means of utilizing porous aggregates or by using aerated cement paste. Although the existence of air voids in concrete enhances the thermal

insulation, it also interferes with the mechanical properties. It is expected that 5% of compressive strength drops for every 1% of air volume inserted into concrete.

To enhance thermal performance with the least effect on existing properties, thermal enhancing agents such as phase change materials (PCM) can be used. PCMs are high latent heat materials capable of changing phase at a specific temperatures. This allows materials to improve thermal storage capabilities through latent heat captivity. The PCM begins to melt as the temperature approaches the melting point, and a large amount of latent heat is absorbed at near constant temperature until it is fully melted. On the contrary, as the temperature cools down to reach the solidification point, liquid PCM begins to solidify and the stored latent heat is released back to the environment. This ability can be used to enhance heat storage, slow down rate of heat transmission, and shift the period of peak temperature [4-8].

The application of PCM in house components began in 1947when Glauber's salts in steel drums were used as heat storage components in Dover, Massachusetts [9]. Trombe walls are another example of an early PCM applications. Invented by Felix Trombe, a French engineer, they are passive solar walls constructed from masonry bricks with a void containing water in the middle. The water provided heat storage capacity during the day time and released out during the night time.

The use of PCMs in construction materials has developed over time. Oliver [10] studied thermal behavior of gypsum boards containing 45% by weight of PCM. The results showed that gypsum boards (15 mm thick) with PCM can store energy up to 5 times of conventional laminated gypsum boards within temperature ranges of 20-30°C. Silva, et al. [11] worked with incorporation of PCM macro encapsulated into typical Portuguese clay brick masonry enclosure walls and subjected them to series of temperature ranges in a climate chamber.

The results showed that the walls with PCM can reduce the indoor temperature swing from 10°C to 5°C and delay the duration to reach peak temperature up to about 3 hours.

In the case of cementitious materials, there are number of ways to incorporate PCM into concrete. The simplest one is to treat PCM as a constituent material to be mixed with concrete. Cunha et al [12] reported the increase in workability and the reduction in absorption when PCM is added into concrete mixture. Sukontasukkul et al [13] tested thermal performance of exterior wall panels plastered with mortars mixed with PCM (polyethylene glycol type, PEG). The PEG mortar exhibited better workability and water retention. The pull-out and compressive strength also increased with the increasing PCM content. The exterior walls plastered with PCM mortar exhibited better thermal storage and extending the time to reach peak temperature. However, after a number of temperature cycles, leaking of melted PCM was regularly observed.

An effective way in preventing PCM leakage is using encapsulation techniques [14-16]. By adopting encapsulation, the PCM is stored inside small polymeric spherical capsules. The method not only prevents leakage, but also provides a large surface area of heat transfer. However, due to the increase in porosity and weak bond strength, an evident drop in strength is regularly observed. With this disadvantage, the use of PCM encapsulation is limited to a very small fractions (less than 10%). Cao et al [17] determined the thermal properties of concrete mixed with microencapsulated PCM (MPCM) from 0 to 2.7% by weight of concrete. They reported no change in the value of specific heat due to the low MPCM concentrations. The latent heat was found to increase linearly from 0 to 2.25 J/g as the MPCM content increased from 0 to 2.7% by weight. The compressive strength, on the other hand, was found to decrease significantly (up to 51%) due to high porosity and poor bond. Sakulich et al [18] used fine aggregate impregnated with PCM to reduce freeze/thaw damage of bridge deck

concrete. They recommended a PCM dosage of 50 kg/m^3 of PCM to increase bridge deck service life by at least one year.

In this study, in order to increase the PCM concentrations, the use of porous aggregates as a PCM carrier was proposed. The PCM aggregates were prepared by impregnating PCM (polyethylene glycol type, PEG) into aggregates at elevated temperatures. During the specimen preparation, the PCM aggregates were then used to replace the regular porous aggregates at the rate of 25 %, 50 %, 75 % and 100% by volume which equals to about 2.1 %, 4.0 %, 6.0 % and 7.8% by weight of concrete, respectively. The specimens were subjected to a series of tests including density, absorption, compressive and flexural strength, thermal conductivity and thermal storage properties (specific heat, sensible and latent heat). The effect of PCM content on thermal conductivity and thermal storage properties such as specific heat, total, sensible and latent heat were also investigated. In addition, the effect of PCM state on the thermal conductivity tests was also examined.

2. Experimental Procedure

2.1 Materials

- Portland Cement Type I (ASTM C150) with specific gravity of 3.15.
- River sand passing sieve no. 4 with FM = 2.45. and specific gravity of 2.47.
- Lightweight aggregates with properties given in Table 1.
- Phase change material: Polyethylene glycol type 1450 with properties as shown in Table 2.

Table 1 Properties of lightweight aggregates

Specification	Value	
Maximum particle size	10 mm	

Unit weight	732 kg/m^3	
Percent of voids	72	
Bulk specific gravity (Dry Basis)	1.08	
Bulk specific gravity (SSD Basis)	1.25	
Apparent specific gravity	1.3	
Apparent porosity	18.1%	
Percent absorption	17.5%	

Table 2 Properties of Polyethylene Glycol type 1450

Specification	Unit	Test Result
Melting point	°C	42-46
Specific gravity	at 25 °C	1.09
Latent heat	kJ/kg	155
Thermal conductivity*	W/m K.	0.23
Liquid specific heat*	J/kg.K	2100
Flash point	°C	285
Range of Avg. Molecular Weight		1305-1595
Physical Form		Flake

2.2 Preparation of PCM aggregates

The polyethylene glycol (PEG) was impregnated into lightweight aggregates at two different temperatures of 100 °C and 120°C. The process began with drying lightweight aggregates using an oven at 100°C for 24 hours. After that the aggregates were placed in containers and submerging with melted PCM. The containers were placed in the oven at two different

degrees: 100 °C and 120 °C for up to 8 hours. Every hour, samples were extracted and weighed to measure weight change and calculate the degree of impregnation using equation 1.

$$\%Impregnation = \frac{W_t - W_i}{W_i} \times 100 \quad (1)$$

where W_i is the initial dry weight before submersion.

W_t is the weight after submerging in PCM at any time.

The process continued until the highest impregnation percentage is reached and weight change becomes constant over time. The time to reach the highest percentage was used in preparing the PCM lightweight aggregates (PCM-LWA).

2.3 Preparing concrete samples

The PCM lightweight aggregates (PCM-LWA) were prepared using the results obtained from Section 2.2 for the highest impregnation level at the shortest time. The mix proportions by weight for the control mix were set at 1 : 0.42 : 1.02 : 1.15 (Cement : Water : LW aggregate : Sand). Conventional lightweight aggregate (LWA) was replaced by PCM-LWA at a rate of 25 % to 100% by volume with the PCM weight being equivalent to 2.1 to 7.8%. Detailed mix proportions are given in Table 3.

Table 3 Mix proportions for 1 m^3

Type of Concrete*	Unit weight kg/m^3					Equivalent PCM Content
	LWA	PCM-LWA	Sand	Cement	Water	(% by weight of concrete)
100L0P	488	0	550	477	200	0.0

75L25P	366	149	550	477	200	2.1
50L50P	244	298	550	477	200	4.0
25L75P	122	447	550	477	200	6.0
0L100P	0	595	550	477	200	7.8

*Note: aLbP a = volume fraction of LWA and b = volume fraction of PMC-LWA

2.4 Experimental series

After the specimens were prepared and cured for 28 days, they were subjected to a series of experiments as follows:

- Density test (ASTM C138)
- Water absorption test (ASTM C642)
- Compressive strength (EN12390-3 2002)
- Flexural strength (ASTM C78)
- Steady-state thermal transmission properties by means of heat flow meter apparatus (ASTM C518-17)
- Thermal storage properties of phase change materials and products (ASTM C1784 – 14)

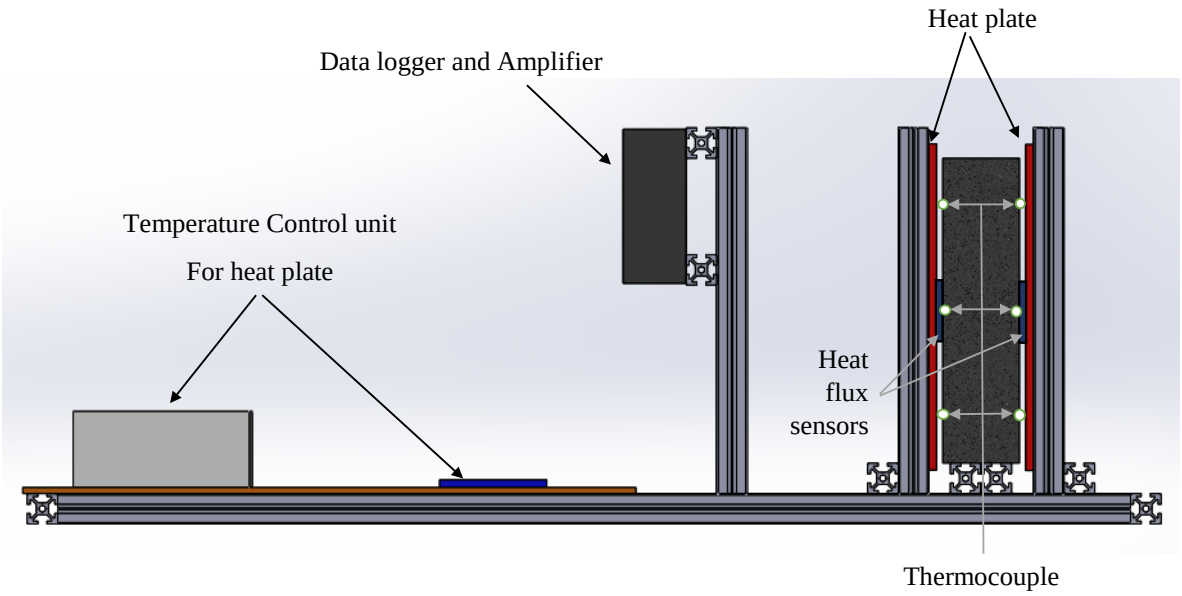


Fig. 1 Heat flow meter apparatus

Table 4 Specification of the measurement

Heat Plate	Temperature of 30 ˚C – 100 ˚C
Thermocouple wire	Type K, -50 ˚C to 250 ˚C
Heat flux sensor (Hioki)	
Temperature range	Sensor: -40 ˚C to 150 ˚C, Cords: -40 ˚C to 120 ˚C
Heat flow	769 w/m^2 - 384,615 w/m^2
Data logger (Hioki LR8431-20)	
Parameters	Voltage, heat flow, thermocouple, pulse, RPM
Heat flow and Voltage	±10 mV to ±60 V, 1-5V, Max. resolution 500 nV
Temperature range	−200 ˚C to 1800 ˚C (Depend on type of thermocouple)
Type of thermocouples	K, J, E, T, N, R, S, B
Recording period	10 ms – 1 hour
Display	Graph and Raw data

2.5 Thermal Test and Data Analysis

The thermal tests were carried out using a heat flow meter apparatus (Fig.1). The apparatus was capable of measuring energy storage in the test specimen, which in turn was used in determining thermal conductivity, specific heat, and latent heat of PCM products. The apparatus consisted of two hot plate exchangers connected to a control unit. A specimen with dimension of 200 x 200 x 50 mm was placed between the two hot plates. Two heat flux sensors and eight K-type thermocouples were installed on both surfaces and in the middle of the sample to measure temperature variations and heat fluxes throughout the sample. To minimize the heat transferred to the surrounding environment, a 50 mm thick of insulating wool was used to cover around lateral sides of the sample. The heat transfer through the concrete sample is assumed to be one dimensional condition. All sensors and thermocouples were connected to an automatic data acquisition box. The apparatus specification is given in Table 4.

2.5.1 Thermal conductivity

In this study, the thermal conductivities of concrete mixed with PCM-LWA were measured at two temperatures above and below the melting point of PCM (25 and 55°C) to investigate the effect of PCM state (solid and liquid) on the thermal conductivity.

To begin the test, both heat plates were kept at a constant temperature until the heat flux is constant and the temperature of the sample is the same as the heat plates. Then the temperature of one of the heat plates was set to a new target temperature. The temperature difference causes the heat to transfer through the concrete sample. The heat flux sensor measured the total heat required for the sample to reach equilibrium (steady-state). At the

steady-state, the test was terminated. The recorded data was used to calculate the thermal conductivity by:

$$\lambda_T = S.E.\left(\frac{L}{\Delta T}\right) \quad (1)$$

where λ_T is thermal conductivity at any temperature (W/m · K), S is the calibration factor of the heat flux transducer (W/m^2)/V, E is heat flux transducer output (V), L is the distance between the heat plates (m) and ΔT is temperature difference across the specimen (K).

2.5.2 Latent heat

To test for latent heat, the energy storage in a specimen over a temperature range was determined. At the beginning of the test, the temperatures of both heat plates were increased from room temperature to the beginning temperature (35°C). The heat flow was measured simultaneously until the heat plates and specimen reached the same temperature level and entered steady-state. The steady-state was defined as the reduction in the amount of energy entering the specimen from both plates to a very small and near constant value (ASTM C1784). The total energy was measured and recorded. Next, the two heat plates were set to the new identical temperature and held until the steady state was achieved again. The energy absorbed by the specimen was also recorded. Repeating the similar procedure until the steady state of the final temperature was achieved, the test was then terminated. Using the series of temperature step change, the enthalpy and accumulated enthalpy storage were determined and used in calculating the specific, sensible and latent heats.

In this study, since the melting temperature the PCM was around 42-46°C, the range of test temperature was set at 35 °C to 55°C with 2°C incrementing steps to cover PCM at both solid and liquid states. First, the graph between the cumulative enthalpy storage versus time was

plotted and used to determine two specific heats: the specific heat of a solid PCM product, C_{pS} (below melting point) and the specific heat of a melted PCM product, C_{pM} (above melting point). Both specific heats are calculated using the baseline of the correlation graph between the accumulate enthalpy and temperature at each step. The baseline is obtained by performing a linear regression using the first data and subsequent data points until the regression coefficient (R^2) is smaller than 0.995. The slope of the line connecting the first to the last data point with R^2 greater than 0.995 is defined as the specific heat values (Fig.2). This procedure was performed under both solid and liquid conditions to obtained C_{pS} and C_{pM}, respectively.

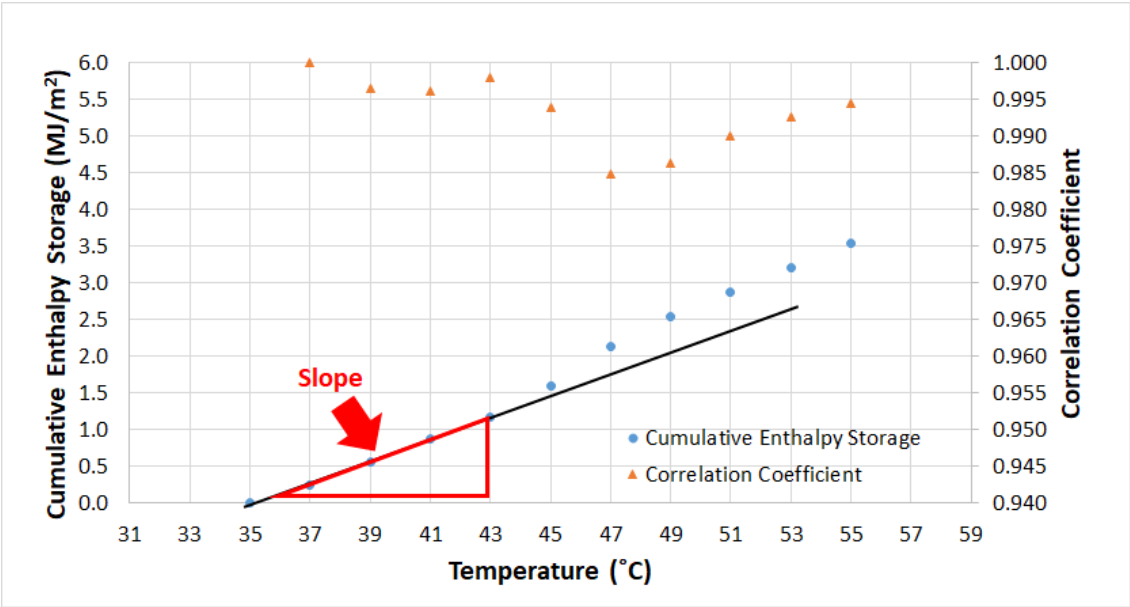


Fig. 2 Determination of Specific Heat using Baseline Correlation

To calculate the latent heat, it was assumed that the total enthalpy stored in the specimen at the PCM active range consists of 2 parts: sensible and latent heats. The total heat (h_t) is the summation of enthalpy over the PCM active temperature range using Eq.1.

$$h_t = \sum_{T_L}^{T_U} \Delta h \qquad (1)$$

The sensible heat (h_s) was determined using the specific heats below and above the active range of the PCM (i.e., C_{pS} and C_{pM}) equals to:

$$h_s = \frac{(C_{pS}+C_{pM})(T_U-T_L)}{2} \quad (2)$$

The latent heat of specimen with PCM product equals to the difference between the total heat and the sensible heat.

$$h_l = h_t - h_s = \sum_{T_L}^{T_U}(\Delta h) - \frac{(C_{pS}+C_{pM})(T_U-T_L)}{2} \quad (3)$$

where h_l is the latent heat of PCM product, h is the enthalpy (J/m^2), ^{TU} is an upper temperature limit of the PCM active Range (°C), T_L is a lower temperature limit of the PCM active Range (°C), C_{pS} is the specific heat of a solid PCM product and C_{pM} is the specific heat of a melted PCM product.

3. Results and discussion

3.1 PCM Impregnation

The PCM was impregnated into the lightweight aggregates using the method described in Section 2.2. The relationship between weight change and time is shown in Fig. 3. As soon as the lightweight aggregates are submersed into the melted PCM, the weight increases immediately by approximately 7% due to self-sorptivity of the aggregates. After that the weight increases gradually with time until reaching the steady state. At the steady state, the maximum impregnation level of 24% by weight is achieved. The temperature level plays an important role on the time taken to reach the steady state. The time to steady state decreases with the increasing temperature, with steady state of aggregates impregnated under 120°C achieved within 7 hours compared to 9 hours for those at 100°C. The shorter duration is partly due to a decrease in viscosity of the PEG with increasing temperature. Fig. 4 shows the

decrease in viscosity from 29.1 cP to 21.8 cP as the temperature increases from 100 °C to 120 °C, respectively.

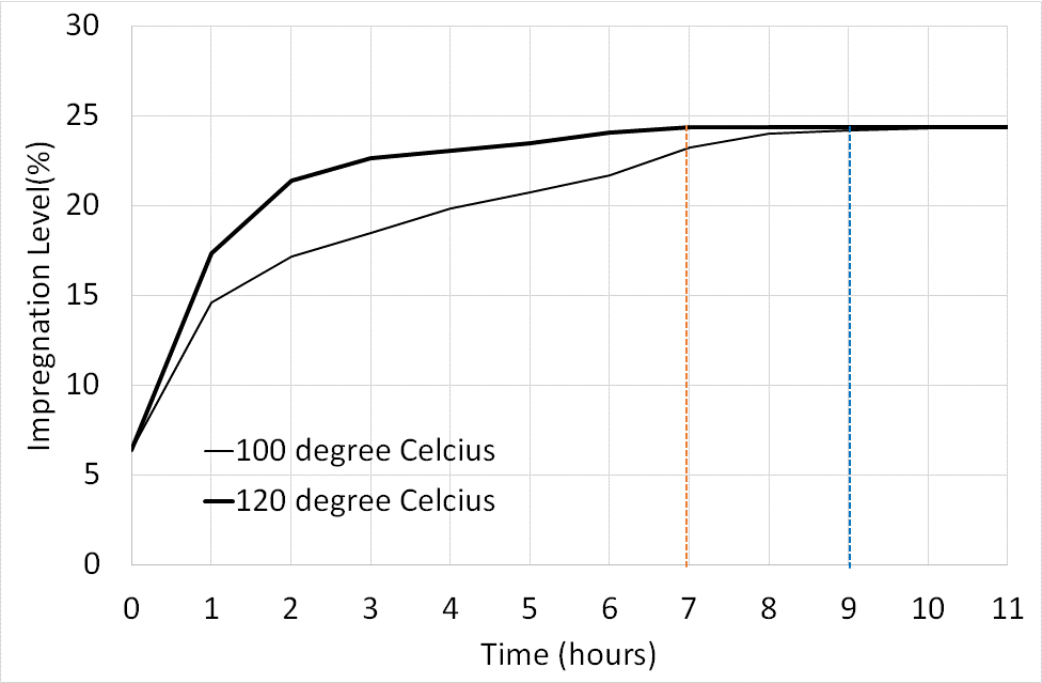


Fig. 3 Change in impregnation level with time

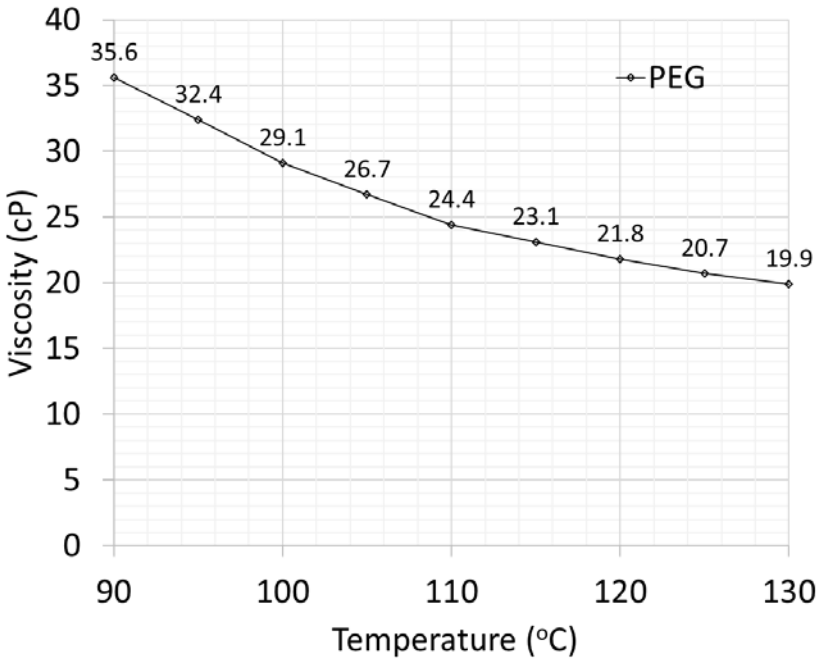


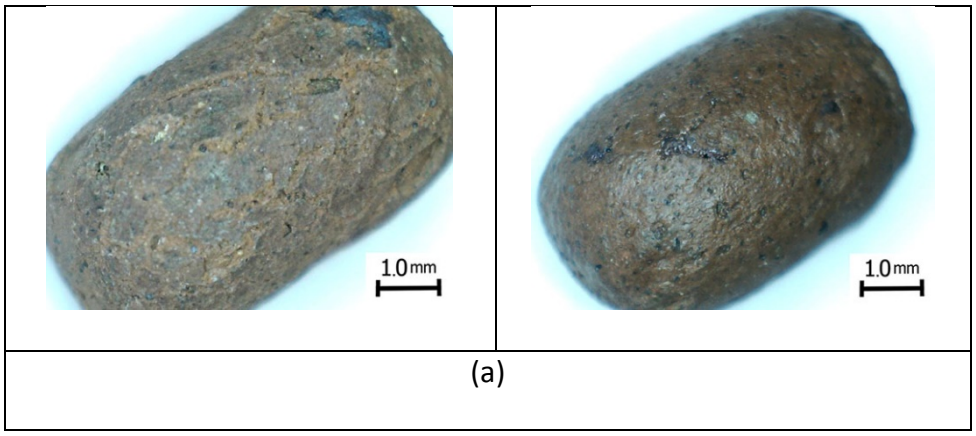
Fig. 4 Change in viscosity of PEG with Temperature

3.2 Properties of PCM-LWA

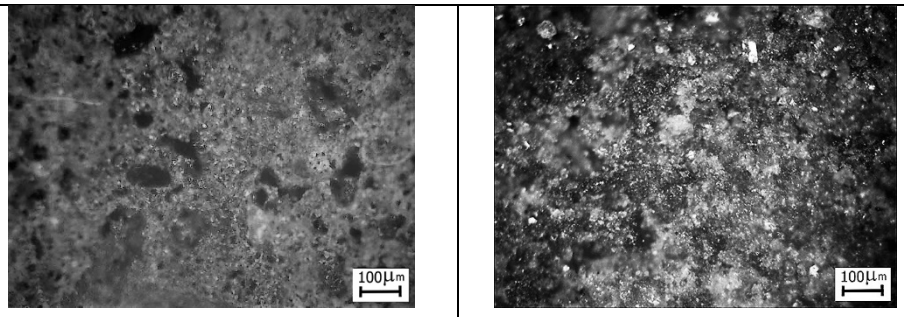
PCM-LWA samples exhibit lower absorption and higher specific gravity than LWA without PCM (Table 5). This is due to the effect of PCM filling pores inside the aggregates. Figure 5 shows a comparison between PCM-LWA and LWA on the external surfaces and cut sections. The surface of PCM-LWA appears to be less porous than LWA with evidence of PCM coating the outer surface. The 100x images of the cut sections also show the effect of PCM filling up pore spaces in the PCM-LWA.

Table 5 Properties of LWA and PCM-LWA

	Unit	LWA	PCM-LWA	Difference (%)
Percent absorption	%	16.0	0.17	- 98.9
Specific gravity		1.0	1.30	+ 22.0



(a)



(b)

LWA	PCM-LWA

Fig. 5 Comparison between (a) Surface and (b) Cut section of PCM-LWA and LWA.

3.3 Properties of Concrete mixed with PCM-LWA

3.3.1 Density and Absorption

The replacement of LWA with PCM-LWA in concrete increases the density and lowers the absorption of concrete. This is because the PCM-LWA is denser than LWA and by gradually increasing the ratio of PCM-LWA, the concrete density increases and the absorption decreases. Figure 6 shows the increase in density from 1747 kg/m^3 to 1903 kg/m^3 as the LWA is replaced by the PCM-LWA up to 100% by volume. The absorption also decreases 2.20 % to 1.75 % when the LWA is entirely replaced by the PCM-LWA. The replacement of porous aggregates with denser aggregates (PCM-LWA) is a key role in the increasing density and decreasing absorption.

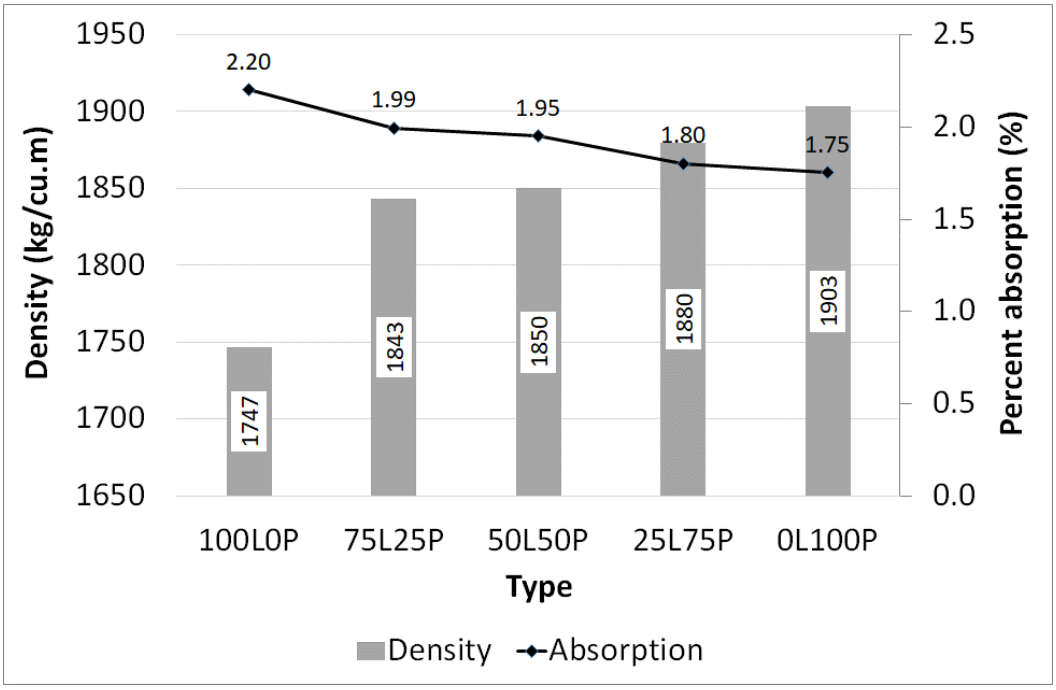


Fig. 6 Density and Absorption of Concrete mixed with PCM-LWA

3.3.2 Compressive and Flexural strength of concrete

Results of the compressive and flexural strengths are presented in Fig. 7. The results show that increasing the ratio of PCM-LWA causes an increase in compressive strength of concrete. The maximum compressive strength of 25.42 MPa is obtained at 100% replacement rate. The increase in compressive strength is partly due to improvement of PCM-LWA properties which is higher in density and less porous.

In the case of flexural load, the load capacity increases with the increasing PCM-LWA replacement ratio up to 75% then decreased. This rate is defined as the optimum replacement ratio for bending load where the maximum load of 11.15 kN is obtained. The small reduction in flexural load capacity is due to effect of PCM coating around the surface of lightweight aggregate which could negatively affect the bond between aggregates and cement paste. The effect of PCM coating is more pronounced under flexural load due to the nature of flexural load which creates tensile stresses at the lower half of the specimen and these tensile stresses are sensitive to the aggregate-paste bond strength.

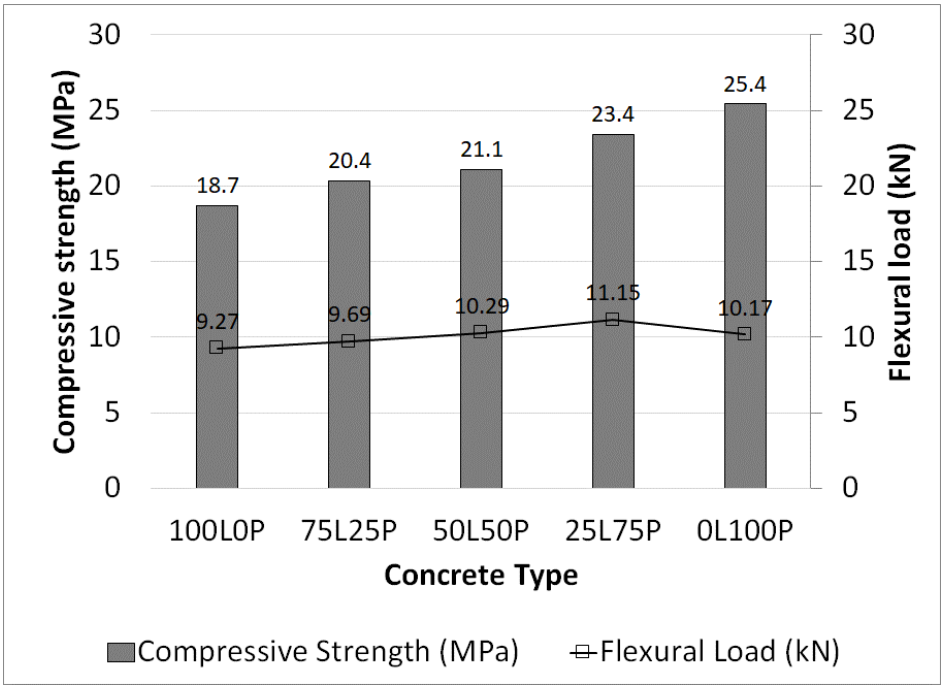


Fig. 7 28 Day-Compressive strength and flexural load of concrete mixed with PCM-LWA

3.3.3 Thermal conductivity

In this study, the thermal conductivity (TC) was measured at temperature levels below and above the PCM melting temperature (42 ^{o}C - 46°C) to investigate the effect of PCM state on TC. Two temperatures were selected: 25 ^{o}C and 55 ^{o}C. The testing procedure as described in Section 2.5.1 was carried out and the results are plotted in Fig. 8.

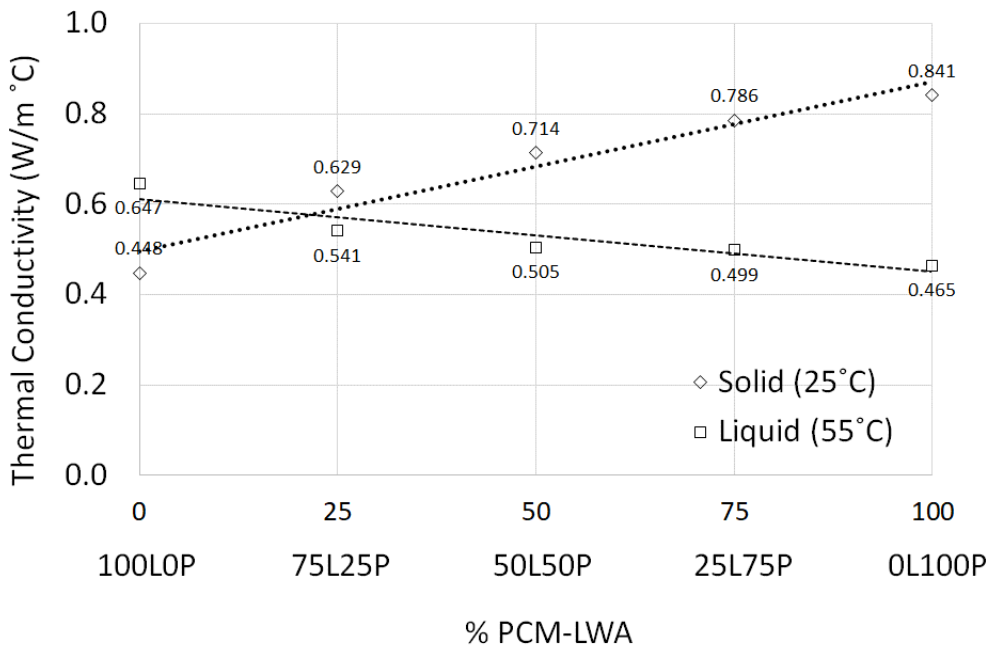


Fig. 8 Thermal Conductivity of PCM-LWA Concrete under Solid and Liquid State

When tested with PCM under solid condition or at 25°C, the thermal conductivity of concrete with conventional LWA (without PCM) was 0.448 W/m°C. With PCM-LWA, the TC with PCM under solid state (TC_s or TC_{25}) increased with the increasing PCM-LWA content. The highest TC_s of 0.841 W/m°C was observed in concrete with 100% PCM-LWA (0L100P). The increase in thermal conductivity is mainly due to the increasing solid content of concrete. Since the solid PCM is replacing pores inside the aggregates, it reduces the air content and causes the TC to increase.

Contrarily, when tested with PCM under liquid state or temperatures higher than the melting point of PCM (55°C), the thermal conductivity at 55°C (TC_{55}) of the concrete with conventional LWA is observed at 0.647 W/m°C which is about 30% higher than specimens tested at 25°C. This shows that the TC is directly influenced by the level of testing temperature. The TC was found to decrease with the increasing PCM-LWA content. This is mainly due to the effect of PCM phase changing process and energy storage phenomenon. When the temperature rises

to around the melting temperature, the PCM begins to melt and store energy. The PCM cannot be considered as regular liquid because it has an ability to store heat in form of latent heat during phase transition and this ability plays an important role on the decreasing the TC. It causes the temperature to remain constant until all PCM changes into liquid state, the rate of heat transfer slows down, lowering the thermal conductivity. Similar finds are also reported by Cao et al [17]. In their study, the thermal conductivity of concrete with melted PCM in microencapsulate form was found to reduce by 38% (from about 1.25 to 0.9 W/m^{o}C) when the PCM concentration increased from 0 to 2.7 % by weight of concrete.

The relationship between the PCM-LWA replacement percentage and thermal conductivity can be expressed by equation 3 and equation 4 below.

Thermal Conductivity under solid state:

$$TC_{25} = 0.0038(\%A_{PCM}) + 0.495 \quad (3)$$

Thermal Conductivity under liquid state:

$$TC_{55} = -0.0016(\%A_{PCM}) + 0.6126 \quad (4)$$

where TC_{25} is the thermal conductivity measured under at 25°C (solid PCM), TC_{55} is the thermal conductivity measure at temperature of 55°C (melted PCM), $\%A_{PCM}$ is the replacement percentage of PCM-LWA over the LWA.

3.3.4 Enthalpy storage

The enthalpy storage of concrete mixed with PCM aggregates is plotted in Fig. 9. At the temperature below the PCM melting point, the enthalpy storages of all concretes are in similar range within a narrow gap between 0.260 MJ/m^2 to 0.315 MJ/m^2 (at 41°C). The total heat storage in this range of temperature is the direct result of the sensible heat.

Within the PCM active range (42 ^{o}C to 46 ^{o}C), the enthalpy storage increases for all specimen types due to the effect of energy storage in the PCM during the phase changing process (latent heat). The maximum enthalpy is reached at a temperature of 45°C. The enthalpy storage is found to increase from 57 % to 86% depending on the PCM aggregate content. The total heat at this range is assumed to be consisting of two parts: latent heat and sensible heat.

At temperatures higher than 45°C, the enthalpy storage begins to decrease slowly with increasing temperature. This shows that most of the PCM is melted at 45°C and the effect of latent heat begins to cease after this although to varying degrees. The enthalpy storage of the concrete with higher PCM aggregate contents appears to decrease at slower rate than those with lower PCM aggregate content. This phenomenon indicates that the PCM remains active even beyond the perceived PCM active range. The enthalpy storage approaches near constant values at different temperatures depending the PCM aggregate content (51 ^{o}C, 51 ^{o}C, 53 ^{o}C and 55°C for 75L/25P, 50L/50P, 25L/75P and 0L/100P, respectively). At temperatures of 55°C, when the enthalpy storage of all concrete types drop to the narrow level between 0.333 MJ/m^2 to 0.406 MJ/m^2, it is believed that there is no latent heat effect remaining. However, it must be noted that the enthalpy storage of concretes with melted PCM is essentially higher than those with solid PCM by a range of 30 % to 38%

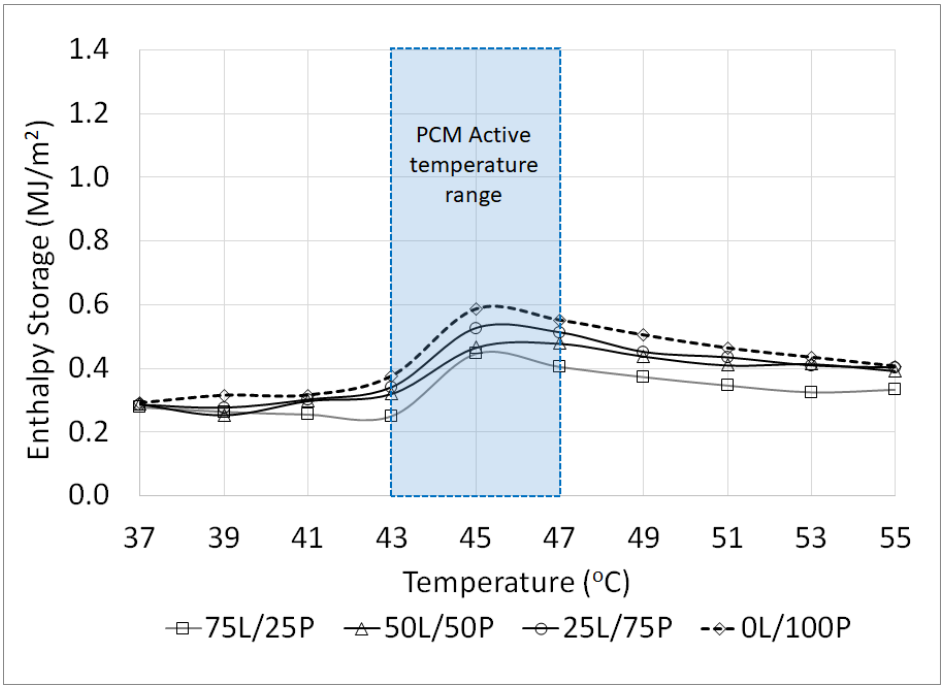


Fig. 9 Enthalpy Storage vs. Temperature

3.3.5 Specific heat

The specific heat is the amount of heat per unit mass required to raise the temperature of material by 1 °C. The specific heat can be calculated from the plot between accumulated enthalpy storage and temperature using the method described in Section 2.5.2. Test results are given in Table 6 and plotted in Fig. 10. According to the results, the specific heat of concretes with solid PCM (C_{pS}) are almost identical for all concrete types. The increasing PCM aggregate content from 25 % to 100% causes about 10% variation in specific heat (from 0.136 to 0.150 (MJ/m^2)/°C) which is considered low as compared to the PCM under liquid stage.

The specific heat is found to be higher under liquid state for all concrete types. Comparing at the same PCM aggregates content, C_{pM} is higher than C_{pS} by a range of 24 % to 55% for various concretes. Similar to the C_{pS}, the C_{pM} also increases with the PCM aggregate content. The increase of PCM aggregate from 25 % to 100% yields a 28% increase of the C_{pM} (from 0.168 to 0.214 (MJ/m^2)/°C).

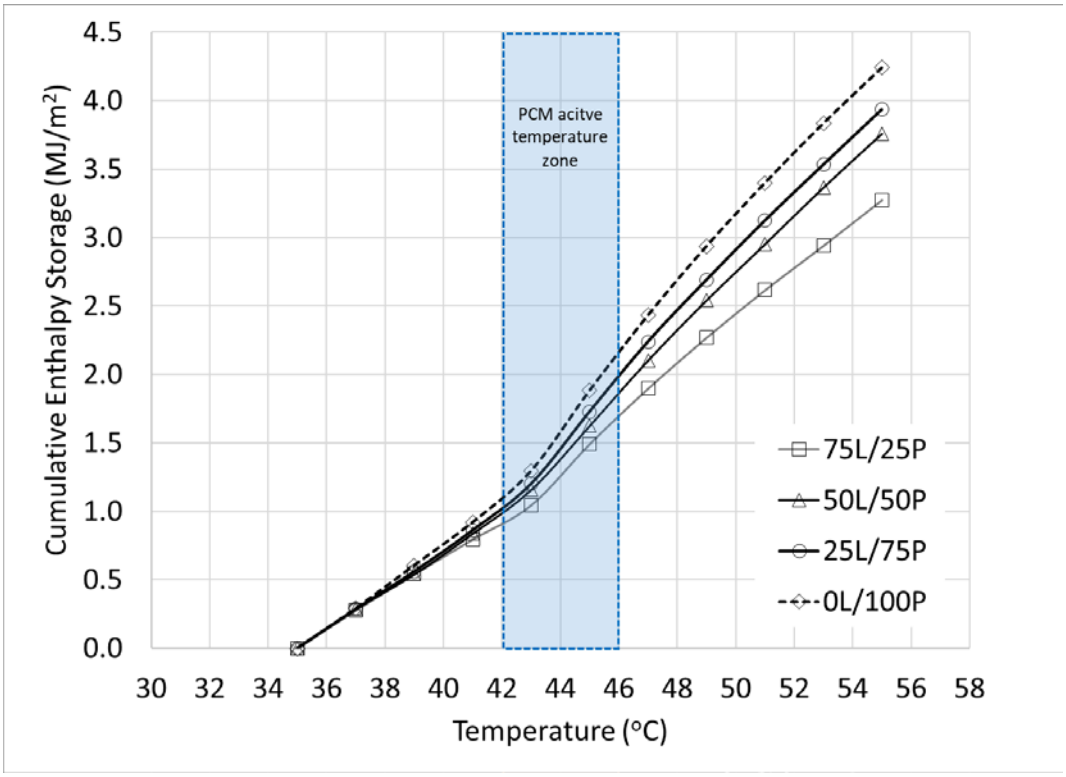


Fig. 10 Cumulative enthalpy storage vs. Temperature

3.3.6 Latent heat

The results on latent heat along with the total heat and sensible heat storages during the PCM active range are given in Table 6. All of them are clearly affected by the PCM aggregate content by varying degrees. For the sensible heat, the increase of about 20% is observed. Since the sensible heat is strongly related to the specific heat (both C_{pS} and C_{pM}), the increase in specific heat due to PCM, especially in the $C_{pM,}$ provides some impact on the sensible heat storage.

The latent heat storage, on the other hand, is the thermal property that is influenced by the PCM content. Therefore, the latent heat storage is expected to rise with the increasing amount of PCM aggregates. In this study, the peak latent heat (7,722 J/kg) is observed in 0L100P (PCM content of 7.8%). With the PCM aggregate replacement increasing from 25 %

to 100%, an increase of the latent heat by 64% (from 0.447 MJ/m^2 to 0.635 MJ/m^2) is observed. The increase of latent heat with respected to PCM aggregate content clearly demonstrated the possibility of incorporating high contents of PCM into concrete without compromising other properties.

Although the latent heat capacity of concrete at 7.722 kJ/kg seems high when compared to ordinary concrete, it still looks relatively small when compared to the latent capacity of pure PCM at about 150 kJ/kg. This can be explained as follows. The amount of PCM used in the concrete is approximately about 8% of the concrete weight. Therefore, the latent heat obtained is less when compared to pure PCM. In addition, the unit weight of PCM concrete is higher than PCM itself, when dividing the latent heat storage by weight of concrete, it gives less latent heat per unit weight. The reported results are in line with work by Jayalath et al [20]. In their study, the PCM with latent heat capacity of about 100 kJ/kg in encapsulated form was mixed with cement mortar up to 55% by weight. They observed the latent heat capacity ranged from 0.546 kJ/kg to 4.724 kJ/kg which is also small compared to the latent heat of the PCM. Ramakrishnan et al [21] also conducted thermal tests on PCM impregnated into expanded perlite aggregates. They found the latent heat capacity of the concrete mixed with PCM aggregates varied from 35 J/g to 61 J/g depending on the surface coating condition as compared to PCM of 133 J/g.

For total heat storage, an increase of 35% from 1.36 MJ/m^2 to 1.83 MJ/m^2 with increasing PCM aggregate content was observed. Since the total heat storage is the summation of latent heat and sensible storage, the increase of both contribute to the increase in total heat storage.

Based on the results, linear relationships between the PCM aggregate replacement percentage and heat storage can be expressed by Equations 5, 6 and 7 (Fig.11).

$$h_t = 0.62(\%A_{PCM}) + 1.22 \quad (5)$$

$$h_s = 0.23(A_{PCM}) + 0.88 \quad (6)$$

$$h_l = 0.39(A_{PCM}) + 0.35 \quad (7)$$

where A_{PCM} is the percentage replacement of PCM aggregate over the conventional lightweight aggregate.

Table 6 Total heat, Specific heat and Latent heat

	Unit	**75L25P**	**50L50P**	**25L75P**	**0L100P**
Total Heat/sq.m	MJ/m^2	1.36	1.56	1.68	1.83
Specific heat of solid PCM	$(MJ/m^2)/^oC$	0.136	0.139	0.142	0.150
Specific heat of melted PCM	$(MJ/m^2)/^oC$	0.168	0.202	0.206	0.214
Sensible heat/sq.m	MJ/m^2	0.910	1.024	1.043	1.092
Latent heat/sq.m	MJ/m^2	0.447	0.539	0.637	0.735
Latent heat capacity	J/kg	4,847	5,828	6,781	7,722

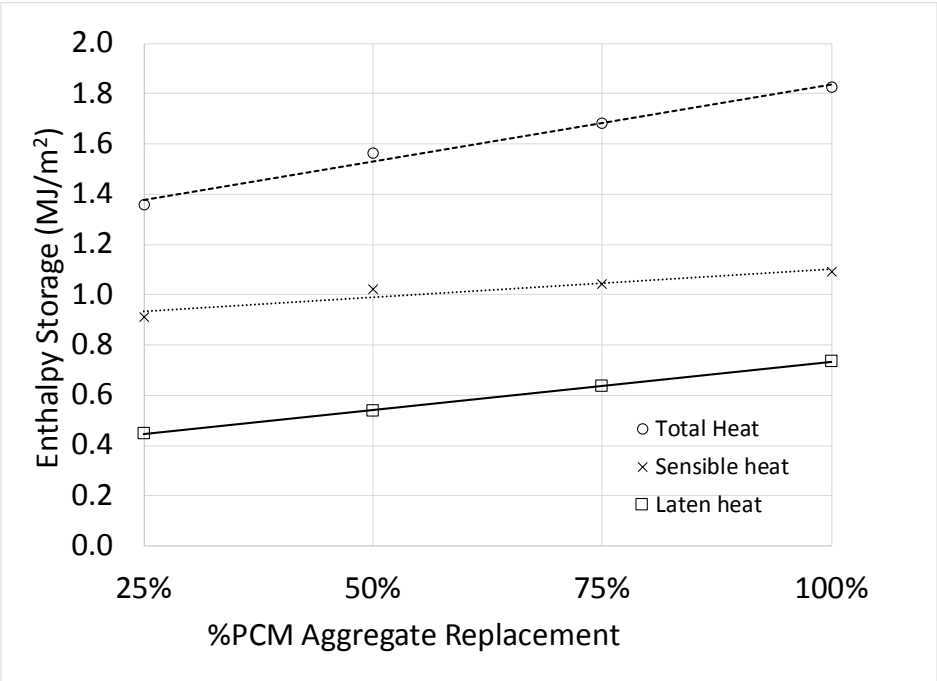


Fig. 11 Relationships between PCM Aggregate Replacement Percentage and Heat Storage

4. Conclusions

In this study, the thermal properties essential for lightweight concrete mixed with aggregates impregnated with PCM (polyethylene glycol 1450) were determined. The rate of replacement of conventional porous aggregates with PCM impregnated aggregates ranged from 25 % to 100% (equivalent to 2.1 to 7.8% by weight of concrete).

Thermal conductivity tested under solid state PCM (TC_S or TC_{25}) was found to increase with the PCM aggregate content from 0.448 W/m^{o}C to 0.841 W/m^{o}C due to the increase in solid content where solid PCM is replacing voids inside the aggregates. Under liquid state PCM, the TC_M or TC_{55} was found to decrease with increasing PCM aggregate content from 0.647 W/m^{o}C to 0.456 W/m^{o}C due to the effect of energy storage during the PCM's phase changing process.

For latent heat and sensible heat storage, both were found to increase with the PCM aggregate content to varying degrees. A 20% increase is observed in the sensible heat, mainly due to the increasing specific heat (especially in the C_{pM}) with PCM aggregate content. The specific heat is relatively constant for all types of concrete when tested under PCM solid state. However, a large increase in specific heat is observed when concretes are tested under PCM liquid state.

Latent heat is found to increase significantly (by 64%) when the PCM aggregates replacement rate rises from 25 % to 100%. The effect of energy storage during phase changing of PCM plays an important role on increasing latent heat storage.

The improvement in both mechanical and the latent heat properties with the increasing PCM content indicates the possibility of incorporating high contents of PCM into concrete without compromising other required properties. In this study, a maximum latent heat of 7,722 J/kg and compressive strength of 25.4 MPa was found in lightweight concrete with a PCM content of 7.8% by weight of concrete.

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References

[1] Rao, V. V., Parameshwaran, R., & Ram, V. V., PCM-mortar based construction materials for energy efficient buildings: A review on research trends. Energy and Buildings, 158 (2018), 95-122.

[2] Diana Ürge-Vorsatz, Luisa F. Cabeza, Susana Serrano, Camila Barreneche, Ksenia Petrichenko, Heating and cooling energy trends and drivers in buildings, Renewable and Sustainable Energy Reviews, 41 (2015): 85-98.

[3] Energy Policy and Planning Office, Ministry of Energy, Energy Statistic of Thailand 2018, 2018.

[4] Sharma, SK., Zero energy building envelope components: a review, Int. J. Eng Res Appl., 3, no.2(2013): 662–675.

[5] Abhat A., Low temperature latent heat thermal energy storage, Heat storage materials, Solar Energy, 30 (1983): 313–332.

[6] Lorsch H.G., Kauffman K.W., Denton J.C., Thermal energy storage for heating and air conditioning, future energy production system, Heat Mass Transfer Proc., 1 (1976): 69–85.

[7] Abhat A, et al., Development of a modular heat exchanger with an integrated latent heat storage, Report no. BMFT FBT 81-050, Germany Ministry of Science and Technology Bonn, 1981.

[8] Hale D.V., Hoover M.J., O'Neill M.J., Phase change materials handbook. Alabama Marshal Space Flight Center, 1971.

[9] Telkes M., Solar house heating—a problem of heat storage, J. Heat Ventilating, 44 (1947): 68–75.

[10] Oliver A., Thermal characterization of gypsum boards with PCM included: Thermal energy storage in buildings through latent heat, Energy and Buildings, 48 (2012): 1-7.

[11] Silva T., Vicente R., Rodrigues F., Samagaio A., Cardoso C., Performance of a window shutter with phase change material under summer Mediterranean climate conditions. Applied Thermal Engineering 84 (2015): 246-256.

[12] Cunha S., Lima M., Aguiar J., Influence of adding phase change materials on the physical and mechanical properties of cement mortars, Construction and Building Materials, 127 (2016): 1-10.

[13] Sukontasukkul P., Sutthiphasilp T., Chalodhorn W. and Chindaprasirt P., Improving thermal properties of exterior plastering mortars with phase change materials with different melting temperatures: paraffin and polyethylene glycol, Advances in Building Energy Research (2018), DOI: 10.1080/17512549.2018.1488614

[14] Boh B., Sumiga B., Microencapsulation technology and its applications in building construction materials, RMZ—Materials and Geoenvironment, 55, no.3 (2008): 329–44.

[15] Hawlader M.N.A., Uddin M.S., Khin M.M., Microencapsulated PCM thermal energy storage system, Applied Energy, 74 (2003): 195–202.

[16] Ling T-C, Poon C-S, Use of phase change materials for thermal energy storage in concrete: An overview, Construction and Building Materials, 46 (2013): 55-62.

[17] Cao V.H., Pilehvar S., Salas-Bringas C., Szczotok A.M., Rodriguez J.F., Carmona M., Nodar Al-Manasir, Kjøniksen A., Microencapsulated phase change materials for enhancing the thermal performance of Portland cement concrete and geopolymer concrete for passive building applications, Energy Conversion and Management, 133 (2017): 56-66.

[18] Sakulich, A. R., & Bentz, D. P., Incorporation of phase change materials in cementitious systems via fine lightweight aggregate, Construction and Building Materials, 35 (2012), 483-490.

[19] Sukontasukkul, P., Intawong, E., Preemanoch, P. Chindaprasirt, P., Use of paraffin impregnated lightweight aggregates to improve thermal properties of concrete panels, Materials and Structures 49 (2016): 1793.

[20] Amitha Jayalath, Rackel San Nicolas, Massoud Sofi, Robert Shanks, Tuan Ngo, Lu Aye, Priyan Mendis, Properties of cementitious mortar and concrete containing micro-encapsulated phase change materials, Construction and Building Materials, 120 (2016): 408-417. https://doi.org/10.1016/j.conbuildmat.2016.05.116.

[21] Ramakrishnan, S., Sanjayan, J., Wang, X., Alam, M., & Wilson, J. (2015). A novel paraffin/expanded perlite composite phase change material for prevention of PCM leakage in cementitious composites. Applied Energy, 157, 85-94.