Thermal storage properties of lightweight concrete incorporating phase change materials with different fusion points in hybrid form for high temperature applications
Sukontasukkul, Piti; Sangpet, Teerawat; Newlands, Moray; Yoo, Doo Yeol; Tangchirapat, Weerachart; Limkatanyu, Suchart

Published in:
Heliyon

DOI:
10.1016/j.heliyon.2020.e04863

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Link to publication in Discovery Research Portal

Citation for published version (APA):
Sukontasukkul, P., Sangpet, T., Newlands, M., Yoo, D. Y., Tangchirapat, W., Limkatanyu, S., & Chindaprasirt, P. (2020). Thermal storage properties of lightweight concrete incorporating phase change materials with different fusion points in hybrid form for high temperature applications. Heliyon, 6(9), [e04863]. https://doi.org/10.1016/j.heliyon.2020.e04863
In this study, the thermal storage properties of lightweight concrete incorporating two types of phase change materials (PCM) with two different fusion points were investigated. Two types of PCM, polyethylene glycol (PEG) and paraffin (PRF), were impregnated into porous aggregates using high temperatures. The PCM aggregates were mixed with concrete at different proportions of PEG/PRF aggregates from 0/100 to 100/0 with 25% intervals. The experimental series consisted of thermal property tests (such as thermal conductivity, specific heat, and latent heat), and some basic properties (such as compressive strength, density, water absorption, and abrasion resistance). The results showed that incorporating PCM aggregates into lightweight concrete helped increase the workability, lower the moisture absorption, and increase the mechanical properties. For thermal properties, both thermal conductivity (k) and specific heat were found to depend strongly on the state of PCM. The latent heat of lightweight concrete with PCM aggregates in hybrid form were found to be higher than that of single type PCM aggregates.

1. Introduction

For some engineering applications such as curing room for precast concrete components or concrete blocks, concrete structures may be required to store large amounts of heat inside at a high temperature for long periods of time. In order to do that, such structures are usually constructed with thick, massive walls to extend the duration of heat transfer and maintain a stable high temperature inside. However, this structural form is often not economical because increased mass comes with additional self-weight loadings on foundations and footings.

To enhance insulation properties of walls without compromising the thickness, materials with high energy storage such as phase change materials (PCM) can be used. PCMs are materials capable of storing heat during their phase changing transition. In the process of heating up, the PCM's phase changes from solid to liquid and heat is stored in form of latent heat. Conversely, during the process of cooling down, liquid PCM reverses back to a solid phase and the latent heat is released back to the surrounding environment.

PCMs can be divided into 3 groups: organic, inorganic, and eutectic (combination between organic and inorganic). They are available in a range of fusion temperatures and with a varying latent heat storage capabilities and the selection depends on application requirements. For household use in countries in cold regions, a fusion temperature of 20–25 °C is more suitable. For some applications such precast concrete or aerated concrete block manufacturing, in which the curing process requires high temperatures up to about 60–70 °C for a certain period of time, a higher fusion point PCM will be more desirable.
PCMs have been used as a heat storage medium in several construction materials such as gypsum boards, masonry blocks, plastering mortar or concrete, etc. For example, Hawes et al. [1] investigated properties of PCM in both gypsum boards and masonry blocks. The PCM used in the manufacturing of gypsum boards was directly mixed with gypsum in liquid form by immersion at 80 °C for several minutes. They found that PCM gypsum boards exhibited higher density, lower moisture absorption (by about 33%), and higher energy storage (by around 11 times) compared to conventional boards. For concrete blocks, they used PCM in both powder and liquid forms (immersion). Similar results to the gypsum boards were obtained with moisture absorption reducing and energy storage increased by 200–230%.

Salyer and Sirca [2] inserted PCM in dry form into the hollow core space of concrete blocks. This allowed them to experiment with the energy storage of PCM in large quantities. Thermal storage of over 1,000,000 BTU was obtained in a building with dimensions of 10 × 12 × 3 m constructed with PCM-hollow core concrete blocks. They also investigated the effect of PCM on thermal storage of plaster boards [3]. Some other notable research on plaster board incorporating micro encapsulated PCM can be found in references [4, 5] and [6, 7].

In the case of plastering mortar, Sá et al. [7] investigated thermal enhancement of plastering mortar incorporating phase change materials. The PCM was prepared in the form of micro encapsulated spheres and mixed with plastering mortar. Their thermal enhancement was achieved at a PCMs content of 25% by mass fraction which yielded enthalpy of 25,000 BTU in a building with dimensions of 10 × 12 × 3 m constructed with PCM-hollow core concrete blocks. They also investigated the effect of PCM on thermal storage of plaster boards [3]. Some other notable research on plaster board incorporating micro encapsulated PCM can be found in references [4, 5] and [6, 7].

In the case of plastering mortar, Sá et al. [7] investigated thermal enhancement of plastering mortar incorporating phase change materials. The PCM was prepared in the form of micro encapsulated spheres and mixed with plastering mortar. Their thermal enhancement was achieved at a PCMs content of 25% by mass fraction which yielded enthalpy of 25,000 BTU in a building with dimensions of 10 × 12 × 3 m constructed with PCM-hollow core concrete blocks. They also investigated the effect of PCM on thermal storage of plaster boards [3]. Some other notable research on plaster board incorporating micro encapsulated PCM can be found in references [4, 5] and [6, 7].

In the case of concrete materials, several methods of incorporating PCM have been proposed. At the beginning, PCM was directly mixed with concrete mixture as a constituent material. However, some drawbacks were observed related to the changes in concrete properties, the interactions between cement paste and PCM, and the PCM leakage [9]. To deal with the leakage problem, the encapsulation technique was introduced [10, 11, 12, 13]. However, because of the poor bond between PCM microcapsules and high porosity, a drop of strength was commonly observed [14].

Our recent studies [15] investigated the use of porous aggregates as PCM carriers instead of microencapsulated spheres. The polyethylene glycol (PEG) with fusion points of around 42–46 °C was impregnated into lightweight aggregates using heat and pressure. This technique allowed PCM to be incorporated in larger volumes of up to about 8.1% of total weight. A latent heat of about 4,800 to 7,200 J/kg was observed depending on the volume of PCM aggregate.

In this study, the thermal properties on lightweight concrete mixed with two types of PCM with two different fusion points was investigated. Since the application of this study aims to develop high insulation lightweight concrete suitable for concrete structures subjected to high temperatures, two types of PCM with high fusion points were used (PEG with fusion point of 56–59 °C and paraffin with fusion point of 56–59 °C). The use of two PCMs allows the latent heat to be stored at two temperature ranges. The PCM aggregates were prepared by impregnating liquid PCM into porous concrete using high temperatures. Concrete samples were prepared with different proportions between both PCM aggregate types (0:100, 25:75, 50:50, 75:25, and 100:0). The thermal properties such as thermal conductivity, specific heat, and latent heat were determined including some basic properties such as compressive strength, density, water absorption, and abrasion resistance.

2. Experimental procedure

2.1. Materials

Materials used in this study consisted of Portland cement type I (ASTM C150), fine aggregate passing sieve no.4, and lightweight aggregate with properties given in Table 1. Two types of phase change materials (PCMs) with different fusion points were used: Paraffin 6035 (PRF) and Polyethylene glycol 1450 (PEG) with properties as shown in Tables 2 and 3.

2.2. PCM aggregate preparation

The PCM aggregates were prepared by impregnating PCM into aggregates using high temperatures. The process began with heating the PCM (both PRF and PEG) to achieve a liquid state, submerging the lightweight aggregates into the liquid PCM, and then placing them in an oven at a temperature of 120 °C for 8 h. This process created PCM aggregates with impregnation percentages of 17.8% and 23.5% for PRF and PEG aggregates, respectively. The high temperature caused the viscosity of both PCMs to decrease (Figure 1) allowing the PCM to penetrate inside the aggregates. More details on PCM impregnation process are described elsewhere [15]. The properties of normal and PCM aggregates are compared in Table 4. The PCM aggregates exhibited a large reduction in porosity and an increase in density of around 30% compared to normal lightweight aggregates. The PCM impregnation also enhanced the abrasion resistance of aggregates by about 62–68%.

2.3. Mix proportion

The concrete mix proportion were set at 1:1.02:1.05:0.42 (Cement: Lightweight aggregate: Fine aggregate: Water). For concrete with single type PCM aggregates, the total content of normal lightweight aggregates was replaced with either PRF-PCM or PEG-PCM aggregates. For concrete with two types of PCM aggregates, the PEG-PCM aggregates were replaced with PRF-PCM aggregates in increments of 25% by weight ranging from 0 to 100%. More details are given in Table 5.

2.4. Specimen preparation

The specimens were prepared by dry mixing all ingredients for a few minutes and, after adding water, the mixing continued for another few minutes. After mixing finished, the fresh concrete was poured into steel molds in layers, with the number of layers depending on the specimen type. Three specimen types were prepared: cubes with dimensions of 150 × 150 × 150 mm for compression and abrasion tests (EN12390-3), prisms with dimensions of 100 × 100 × 350 mm for flexural test (ASTM C78), and square panels with dimensions of 200 × 200 × 50 mm for thermal test (ASTM C518 and ASTM C1784). Each layer was compacted with a steel rod for 25 times and vibrated on a shaking table. After completing the top layer, excessive concrete was removed and the specimens were covered with plastic sheets. The specimens were cured in the specified environment and then removed from the molds after 28 days. After complete curing, the specimens were tested for the specified properties.

2.5. Experimental series

Each type of concrete panel was subjected to series of test as follow:

- Density test (ASTM C138)
- Water absorption test (ASTM C642)
- Abrasion resistance (ASTM C779)
- Compressive strength (EN12390-3 2002)
- Flexural strength (ASTM C78)
- Steady-state thermal transmission properties by means of heat flow meter apparatus (ASTM C518-17)
2.5.1. Thermal properties test and data analysis

Two thermal properties (thermal conductivity and latent heat) were investigated using a heat flow meter apparatus constructed at King Mongkut's University of Technology North Bangkok (Figure 2). The apparatus consisted of two hot plates installed with two heat flux sensors and eight K-type thermocouples on both sides. To prevent temperature leakage, an insulating wool with thickness of 50 mm was used in covering around the specimen edges. All sensors and thermocouples were connected to and collected by an automatic data acquisition box.

2.5.1.1. Thermal conductivity.

Since the melting temperatures of the two PCMs were different, the two temperature tests were proposed to measure the thermal conductivity of concrete containing PCM aggregates at different stages. The first temperature was selected at 25 °C, which was the temperature low enough to keep both PCM in solid phases. This temperature yielded the thermal conductivity concrete with PCMs in solid stage. On the opposite end, to obtain the thermal conductivity of

Table 1. Properties of lightweight aggregates.

| Specification             | Unit | Value |
|---------------------------|------|-------|
| Maximum particle size     | mm   | 10    |
| Unit weight               | kg/m³| 732   |
| 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 paraffin 6035.

| Specification         | Unit | Value       |
|-----------------------|------|-------------|
| Melting Point         | °C   | 57.2–59.9   |
| Specific Gravity      | at 25 °C | 0.89        |
| Latent Heat           | kJ/kg| 189         |
| Thermal Conductivity  | W/(m.K) | 0.21        |
| Specific Heat         | J/kg.K | 2100       |
| Oil Content           | max% | 0.4         |
| Penetration           | at 25 °C | 10.0–17.0  |
| Color                 |      | 30          |
| UV Absorption         |      | 1.3         |

Source: Dalian Chemical Group Co., Ltd.

Table 3. Properties of Polyethylene Glycol type 1450.

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

Source: Dow Chemical Co., Ltd.

- Thermal storage properties of phase change materials and products (ASTM C1784 – 14)

2.5.1. Thermal properties test and data analysis

Two thermal properties (thermal conductivity and latent heat) were investigated using a heat flow meter apparatus constructed at King Mongkut's University of Technology North Bangkok (Figure 2). The apparatus consisted of two hot plates installed with two heat flux sensors and eight K-type thermocouples on both sides. To prevent temperature leakage, an insulating wool with thickness of 50 mm was used in covering around the specimen edges. All sensors and thermocouples were connected to and collected by an automatic data acquisition box.

2.5.1.1. Thermal conductivity.

Since the melting temperatures of the two PCMs were different, the two temperature tests were proposed to measure the thermal conductivity of concrete containing PCM aggregates at different stages. The first temperature was selected at 25 °C, which was the temperature low enough to keep both PCM in solid phases. This temperature yielded the thermal conductivity concrete with PCMs in solid stage. On the opposite end, to obtain the thermal conductivity of
concrete with all PCMs in liquid stage, a testing temperature of 65 °C was selected which was higher than the melting points of both PCMs.

To begin a test, the two heat plates were set to have equal temperatures. After the heat flux became constant, a new target temperature was set on one of the hot plates. The difference in temperature on both sides allowed the heat to transfer through the sample. The test was stopped as soon as the steady-state was reached. The total heat required for the sample to reach equilibrium (steady-state) at the new target temperature was measured. The thermal conductivity can be calculated by Eq. (1).

\[
\lambda_T = \frac{q}{L} \left( \frac{\Delta T}{L} \right)
\]

where \( \lambda_T \) is thermal conductivity at any temperature (W/m \cdot K), q is heat flux (W/m²), L is the distance between the heat plates (m) and \( \Delta T \) is temperature difference across the specimen (K).

### Table 4. Comparison of normal lightweight and PCM Aggregate properties.

| Properties            | Normal Agg. | PCM Agg. |
|-----------------------|-------------|----------|
| Water Absorption (%)  | 16.0        | 0.20     | 0.17     |
| Bulk specific gravity (Dry Basis) | 1.068     | 1.297    | 1.304    |
| Abrasion Resistance (Percent Weight Loss, %) | 31.7       | 12.1     | 10.3     |

### Table 5. Mix proportions of reference and PCM aggregate concretes.

| No. | Type          | Weight per Unit Volume (kg/m³) |
|-----|---------------|-------------------------------|
|     | Normal LW Agg. | PEG-Agg. (P1) | PRF-Agg. (P2) | Fine Agg. | Cement | Water |
| 1   | 100L          | 488              | 0              | 0         | 550     | 477    | 200   |
| 2   | 100P₁/₀P₂     | 144              | 149             | 550       | 477     | 200    |
| 3   | 75P₁/25P₂     | 298              | 298             | 550       | 477     | 200    |
| 4   | 50P₁/50P₂     | 446              | 446             | 550       | 477     | 200    |
| 5   | 25P₁/75P₂     | 149              | 149             | 550       | 477     | 200    |
| 6   | 0P₁/100P₂     | 0                | 0               | 550       | 477     | 200    |

Note: L = Normal lightweight aggregate; P₁ = PEG PCM aggregate; P₂ = PRF PCM aggregate.

2.5.1.2. Latent heat. The latent heat can be determined by measuring energy storage in a material over a range of temperatures. The selected range of temperatures must cover the melting range of PCM and divide into steps of 1 or 2 °C. The test began by setting initial temperatures of both hot plates to be identical, and then both heat plates were set to a new identical temperature. The heat flow was measured simultaneously until the temperatures of the hot plates and specimen became identical and the steady-state was achieved. The steady-state is 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 required to move the temperature up each step was measured and recorded. Similar processes were repeated until the steady state of the final temperature was achieved.

In this study, the temperature range was set from 35 °C to 65 °C with 2 °C incrementing steps to cover the melting temperature of both PRF aggregates.
and PEG. The phase states of each PCM over the entire range of temperature are demonstrated in Table 6 below.

To determine a specific heat, a graph between the cumulative enthalpy storage (CES) and temperature (T) was plotted, then the baseline was drawn by performing a linear regression using the first data and subsequent data points with the regression coefficient ($R^2$) smaller than 0.995. The slope of the line connecting the first to the last data point with $R^2$ greater than 0.995 was defined as the specific heat values (Figure 2a).

In the case of a material containing a single type PCM, two specific heats are commonly determined: $C_{ps}$-specific heat under solid state PCM and $C_{pl}$-specific heat under liquid state PCM. Then latent heat can be calculated using Eqs. (2), (3), (4), (5), and (6).

To obtain the latent heat, the total heat ($H_t$) is defined as being equal to the summation of enthalpy ($\Delta H$) over the assigned temperature range (Eq. (2)).

$$H_t = \sum_{i=1}^{n} \Delta H_i$$  

(2)

In temperature region where the PCMs are not active (i.e. not melting), the total heat or enthalpy stored in the specimen is assumed equal to the sensible heat ($H_s$) (Eq. (3)).

$$H_t = H_s$$  

(3)

In the region where a PCM is melting, the latent heat takes affect and the total heat is assumed equal to the combination of sensible ($H_s$) and latent heats ($H_l$) (Figure 2b).

$$H_t = H_s + H_l$$  

(4)

Over the temperature range where PCM is melting, the sensible heat ($H_s$) can be determined using an average specific heats below and above the active range of the PCM using Eq. (5).

$$H_s = \frac{(C_{ps} + C_{pl})(T_f - T_l)}{2}$$  

(5)

Based on Eq. (3), The latent heat is the difference between the total heat and the sensible heat as expressed by Eq. (6).

$$H_l = H_t - H_s = \sum_{i=1}^{n} \Delta H_i - \frac{(C_{ps} + C_{pl})(T_f - T_l)}{2}$$  

(6)

where $\Delta H$ is the enthalpy ($J/m^2$), $T_f$ is an upper temperature limit of the PCM active Range (°C), $T_l$ is a lower temperature limit of the PCM active Range (°C).

In the case of concrete containing two types of PCMs, the phase state of PCM is divided into 3 states as shown in Table 6. Based on the phase state of PCM, three specific heats can be determined as $C_{ps}$, $C_{pl}$, and $C_{pl/s}$ as shown in Figure 3, where $C_{ps}$ refers to the specific heat with both PEG and PRF in solid state, $C_{pl}$ is the specific heat with PEG in liquid and PRF in solid state, and $C_{pl/s}$ is the specific heat with both PEG and PRF in liquid state. The latent heat can then be calculated by Eq. (7).

$$H_l = H_t - H_s = \sum_{i=1}^{n} \Delta H_i - \frac{(C_{ps} + C_{pl/s})(T_{f1} - T_{l1})}{2} - \frac{(C_{pl} + C_{pl})(T_{f2} - T_{l2})}{2}$$  

(7)

### Table 6. State of PCMs on temperature range.

| Temperature range, °C | Phase State of PCM |
|-----------------------|---------------------|
| 35-42                 | PEG (P1)            |
| 42-46                 | PRF (P2)            |
| 46-56                 | Solid               |
| 56-59                 | Melting             |
| 59-65                 | Liquid              |

Figure 3. Specific heats at concrete containing PCM in hybrid form.

3. Results and discussion

3.1. Workability

The workability of concrete was determined by a slump test and the results are given in Figure 4. Considering concrete containing single PCM aggregate type, the concrete with 100% PEG (100P1/0P2) exhibited larger slump than that with 100% PRF (0P1/100P2) by about 20 mm. This is partly due to a slightly higher absorption of PRF aggregates (0.20%) as compared to PEG aggregates (0.17%), which allow them to absorb a more water, hence lowered the workability. Another reason could be from the impregnation percentage itself. Since the PEG can be impregnated into aggregates at a higher level than the PRF (by around 5%), this meant that the excessive PCM may have coated the outer surface of PEG aggregates. This coating may have improved the surface smoothness, leading to better particle mobility and higher slump.

In the case of concrete with two PCM types, the slump was directly affected by the variation of PEG and PRF aggregate contents. Since the slump of PEG aggregate was better than that of PRF aggregate, replacing the PEG aggregate with PRF aggregates reduced the slump gradually with increasing PRF aggregate content (Figure 3). The relationship between slump and percentage PRF aggregate content is demonstrated by Eq. (6).

$$S = -0.216(\%PRF) + 50.6$$  

(8)
where $S$ is slump (mm), $\%_{APRF}$ is the replacement percentage of PRF aggregate over PEG aggregate (%) ranging from 0 to 100%.

### 3.2. Density and absorption of concretes

Results on the density and absorption of concretes are shown in Figure 5. The density of control lightweight concrete was observed to be 1747 kg/m$^3$. The density increased to about 1853–1903 kg/m$^3$ when normal aggregates were replaced with PCM aggregates. The densities of PCM aggregate concrete were found to depend on the ratio between PEG/PRF aggregates. The maximum density of 1903 kg/m$^3$ was observed in concrete containing 100% PEG aggregate and decreased gradually with the increasing portion of PRF aggregates. The lowest density was observed in concrete containing 100% PRF aggregate at about 1853 kg/m$^3$. This is because the specific gravity of PEG aggregates is higher than that of PRF aggregates (Table 4) and by gradually replacing portions of PEG aggregates with PRF aggregates, the density decreased.

In the case of absorption, the normal lightweight concrete (100L) exhibited the highest absorption of 2.20% due to the high porosity and absorption of lightweight aggregates. By replacing the entire amount of normal aggregates with PCM aggregates, the absorption decreased to about 1.75–1.90%. This because PCM aggregates are much denser with less porosity than normal aggregates (Table 4).

Comparing between two types of PCM aggregates, the absorption was found to increase with the increasing PRF aggregate ratio. The mix with 100% PEG aggregates exhibited the lowest absorption of about 1.75%. The absorption then increased gradually with the increasing PRF aggregate content to the highest at about 1.90% in the mix containing 100% PRF aggregate. The increase in absorption was because the absorption of PRF aggregates was higher than that of PEG aggregates by about 17.6% (Table 4).

### 3.3. Abrasion resistance

The abrasion resistance was tested in accordance to ASTM C779. The specimen was subjected to abrasion by pressing dressing wheels, with bearing weight of 7.5 kg, on the horizontal surface of specimen for the period of 30–60 min. The specimen’s weight before and after testing were measured and used in determining weight loss percentage over the original weight.

The weight loss percentage of all specimen types were observed to be between 1.5 % and 3.5 % (Figure 6). The concrete with normal lightweight aggregate exhibited maximum weight loss percentage of 2.5%. With PCM aggregates, the weight loss percentage reduced to between 1.5 % and 2.2 % depending on the ratio between $P_1$ and $P_2$ (Figure 5).

Concrete with 100% PEG aggregate (100P1/0P2) exhibited the lowest weight loss percentage of about 1.5%. The weight loss percentage increased gradually with increasing PRF aggregate ratio. The highest weight loss among concrete with PCM aggregates was observed in concrete containing 100 PRF aggregate (0P1/100P2), the reason being that the abrasion resistance of PRF aggregate was poorer than that of PEG aggregates by about 20% (Table 4) and by replacing PEG aggregate with PRF aggregate, the weight loss percentage increased by a similar proportion.

### 3.4. Compressive strength

The influence of aggregate type on compressive strength is shown in Figure 7. The lowest compressive strength of 18.7 MPa was observed in concrete containing 100% of normal lightweight aggregate (100L). The strength then increased to between 25.4 MPa and 29.2 MPa in concrete containing PCM aggregates. The increase in strength was due to the reduction of porosity in aggregates as they were filled up with PCMs.

The lowest strength among the PCM concretes was with 100% PEG aggregates. With the increasing proportion of PRF aggregates, unlike other properties, the compressive strength increased. The strength was highest at 29.2 MPa in concrete containing 100% of PRF aggregates. The lower strength with PEG is believed to be the direct result of the excessive PCM coating at surface of PEG aggregates hence creating a weaker bond between aggregate and cement paste.
3.5. Thermal properties

3.5.1. Thermal conductivity coefficient of concretes

The thermal conductivity coefficient \( k \) of concrete was tested under 2 different temperatures in order to study the effect of PCM state (liquid and solid) on \( k \). The 1st temperature of 25 °C was selected because it was lower than the fusion points of both PCMs. This temperature aimed to test for the \( k \) of concrete at 25 °C \( (k_{25}) \) or with PCMs in solid state. The 2nd temperature of 65 °C was selected because it was higher than the fusion points of both PCMs. The temperature, in this case, aimed to measure the thermal conductivity coefficient of concrete at 65 °C \( (k_{65}) \) or with both PCMs in liquid state. The results of both tests are shown in Figure 8.

For plain lightweight concrete (100L), \( k_{25} \) and \( k_{65} \) were 0.448 and 0.647 W/m°C, respectively. Since 100L contained no PCM aggregates, there was no influence of PCM on the \( k \) values. The increase in \( k \) with the increasing test temperature was the direct result of the thermal coefficient itself because the thermal coefficient is known to be sensitive to the testing temperature.

In the case of concrete with PCM aggregates tested at 25 °C, \( k_{25} \) was observed in a similar range between 0.829 - 0.842 W/m°C. They appear to be higher than that of 100L by about 40%. The reason should be the effect of PCM in filling up pores inside aggregates. Since, the PCMs are in solid state at this temperature, the filling of PCM reduced the porosity and hence, increased the thermal conductivity of concrete.

For those with PCM aggregates tested at 65 °C, \( k_{65} \) was found in the range of 0.447–0.465 W/m°C. This is about 40% lower than the \( k_{65} \) of 100L. The decrease was the direct effect of PCM phase changing transition. As the temperature increased to 65 °C, both PCMs underwent the phase transition from solid to liquid state, while heat was also stored inside the PCMs during this transition. This stored heat interrupted the normal heat conductivity process and caused the heat to transfer at a slower rate and hence, decreased the \( k_{65} \) values.

3.5.2. Specific heat of concretes

The specific heat refers to the amount of energy required to raise the temperature of a unit mass of a material up to a certain level (usually 1 °C). For concrete containing one type of PCM, two specific heats can be...
Regardless of PCM type and content, both CpS and CpL were found in the OP1/100P2. Both concretes exhibited similar behaviours when subjected to this graph are shown in Table 7.

The PCM range of 0.146–0.214

| Concrete Containing Hybrid PCM. | | | |
|---|---|---|---|
| 100P1/0P2 | Single | 0.153 | - | 0.204 |
| 75P1/25P2 | Hybrid | 0.153 | 0.198 | 0.206 |
| 50P1/50P2 | Hybrid | 0.146 | 0.195 | 0.212 |
| 25P1/75P2 | Hybrid | 0.147 | 0.187 | 0.214 |
| 0P1/100P2 | Single | 0.150 | - | 0.214 |

Note:
- CpS is the specific heat where both PCMs are in solid state.
- CpL/S is the specific heat where one PCM is in solid state and another is still in solid state.
- CpL is the specific heat where both PCMs are in liquid state.

The results are shown in Table 8 and Figure 11 in form of the relation between enthalpy and temperature is shown in Figure 10 and Table 8.

The specific heat of concrete with hybrid PCMs depended strongly the PCM state and the PEG/PRF ratio in each concrete type. The value of CpL/S fell intermediately between CpS and CpL regardless of the concrete type. In this specific case of CpL/S, the concrete was tested under the condition of PEG in a liquid state and PRF in a solid state. The phase of PEG in aggregates that underwent change from solid to liquid state caused the CpL/S to increase to be slightly higher than CpS. As the PEG aggregate content decreased, the value of CpL/S also decreased. This can be seen by the decreasing of CpL/S from 0.198 to 0.187 MJ/m²/°C with the decrease of PEG/PRF ratio from 75/25 to 25/75. As the temperature continuously increased, the concrete then approached a temperature high enough to cause both PCMs to change phase to liquid state, this was a region where the Cp became the highest and CpL was measured.

3.5.3. Latent heat of concrete

The latent heat can be measured from the enthalpy storage over ranges of PCM active temperature using Eqs. (2), (3), (4), (5), (6), and (7). The results are shown in Table 8 and Figure 11 in form of the relation between enthalpy storage and temperature. In term of heat profile, the graph can be divided into 5 regions based on temperature ranges.

- The first region was when both PCMs were in solid state and the temperature was in the range of 35–41 °C. Since the PCMs were still in a solid state, there was no effect of latent heat. The heat storage in this zone was a sensible heat of concrete with both PCMs in solid state.
- The second region occurred in the melting temperature range of PEG (41–49 °C). In this region, the PEG began to melt and stored heat in form of latent heat. The latent heat storage for each concrete type depended strongly on the ratio of PEG aggregates.
- After all the PEG melted entirely, the concrete shifted to the third region where latent heat had no influence the heat storage. The heat stored in this region was considered the sensible heat storage of concrete with one melted PCM and one solid PCM.
- As the temperature continued to increase to the melting range of PRF (55–61 °C), the PRF began to melt and stored latent heat. The latent heat storage depended on the ratio of PRF aggregates in each concrete type.

Figure 10. Influence of P1:P2 ratio and temperature on Cumulative Enthalpy of Concrete Containing Hybrid PCM.
The last region occurred when both PCMs were in liquid state (temperature higher than 61 °C). The heat storage observed in this region was the sensible heat of concrete with both PCMs in aggregates in liquid state.

The use of PCM aggregates enhanced the properties of concrete in several aspects. These included the effect of PCM filling voids in aggregates caused the aggregates to become denser and less absorptive which led an improvement in workability, an increase in density, and a decrease in moisture absorption. The compressive strength and abrasion resistance also increased when conventional aggregates were replaced with PCM aggregates.

Table 8 shows the results in terms of values of total, sensible and latent heats. Both 100P1/0P2 and 0P1/100P2 concretes which contained single type PCM aggregates were subjected to one region of heat with respected to the melting point of their PCM (either 43–47 or 55–59 °C, for PEG and PRF type). The latent heat of 0.54–0.55 MJ/m² was observed. For concrete containing hybrid PCM aggregates, higher latent heat of 0.80–0.83 MJ/m² was observed. This is because both type of concretes were subjected to heat in two regions (both 43–47 or 55–59 °C). This indicated that the use of concrete with PCM in hybrid form provide higher latent heat and become more effective in storing heat than those with single type PCM.

4. Conclusions

- The use of PCM aggregates enhanced the properties of concrete in several aspects. These included the effect of PCM filling voids in aggregates caused the aggregates to become denser and less absorptive which led an improvement in workability, an increase in density, and a decrease in moisture absorption. The compressive strength and abrasion resistance also increased when conventional aggregates were replaced with PCM aggregates.
- The thermal conductivity (k) of PCM lightweight concrete was found to depend strongly on the state of PCM. The k25 (k of PCM in solid state) increased with the PCM aggregate content due to the reduction in void content which was replaced by the solid PCM. The k65 (k of PCM in liquid state), on the other hand, decreased with the PCM aggregate content due to the effect of latent heat during phase changing process. The k25 and k65 were found in the range of 0.829–0.842 and 0.447–0.465 W/m °C, respectively.
- For both types of concrete (single and hybrid PCM aggregate), the specific heat was found to increase as the state of PCM. The concretes with PCM in liquid form yielded higher specific than those with PCM in solid form.
- For the PCM aggregate in hybrid form, at the intermediate temperature region where the concrete containing both solid and liquid PCM, the specific depended strongly on the quantity of PCM in liquid form. The concretes with higher content of liquid PCM aggregates yielded higher specific heat that those with lower content of liquid PCM.
The latent heat of concrete with PCM aggregates in hybrid form were found to be higher than those with single type PCM aggregates. This indicated that concrete with PCM in hybrid form can be more effective in storing heat at high temperature than concrete with singly type PCM aggregates.

Declarations

Author contribution statement

Piti Sukontasukkul: Conceived and designed the experiments; Wrote the paper.
Teerawat Sangpet: Performed the experiments.
Moray Newlands & Doo-Yeol Yoo: Analyzed and interpreted the data; Wrote the paper.
Weerachart Tangchirapat: Analyzed and interpreted the data.
Suchart Limkatanyu & Prinya Chindaprasirt: Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by King Mongkut’s University of Technology North Bangkok under contract no. KMUTNB-63-KNOW-024, the Thailand Research Fund under contract no. RTA6280012 (Suchart Limkatanyu) and DPG6180002 (Prinya Chindaprasirt).

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] D.W. Hawes, D. Feldman, Latent heat storage in building materials, Energy Build. 20 (1993) 77–86.
[2] I.O. Salyer, A.K. Sircar, A. Kumar, Advanced phase change materials technology: evaluation in lightweight solitie hollow-core building blocks, in: Proceedings of the 30th Intersociety Energy Conversion Engineering Conference, Orlando, 1995, pp. 217–224.
[3] I.O. Salyer, A.K. Sircar, Development of PCM Wallboard for Heating and Cooling of Residential Buildings. Thermal Energy Storage Research Activities Review, U.S. Department of Energy, New Orleans, 1989, pp. 97–123.
[4] D. Feldman, D. Banu, D.W. Hawes, Development and application of organic phase change mixtures in thermal storage gypsum wallboard, Sol. Energy Mater. Sol. Cell. 36 (2) (1995) 147–157.
[5] C.-m. Lai, R.H. Chen, C.-Y. Lin, Heat transfer and thermal storage behaviour of gypsum boards incorporating micro-encapsulated PCM, Energy Build. 42 (8) (2010) 1259–1266.
[6] C. Han, M. Grenet, A. Bontemps, R. Dendievel, H. Salle, Realization, test and modelling of honeycomb wallboards containing a phase change, Mater. Energy Buildings 43 (1) (2011) 232–238.
[7] A.V. Sà, M. Azenza, H. de Sousa, A. Samaglio, Thermal enhancement of plastering mortars with Phase Change Materials: experimental and numerical approach, Energy Build. 49 (2012) 16–27.
[8] P. Sukontasukkul, T. Sutthiphasilp, W. Chalodhorn, P. Chindaprasirt, Improving thermal properties of exterior plastering mortars with phase change materials with different melting temperatures: paraffin and polyethylene glycol, Adv. Build. Energy Res. 13 (2) (2019) 220–240.
[9] P. Schossig, H. Henning, S. Gschwander, T. Hausmann, Microencapsulated phase change materials integrated into construction materials, Sol. Energy Mater. Sol. Cells 89 (2005) 297–306.
[10] M.N.A. Hawlader, M.S. Uddin, M.M. Khin, Microencapsulated PCM thermal-energy storage system, Appl. Energy 74 (2003) 195–202.
[11] A. George, Hand book of thermal design, in: C. Guyer (Ed.), Phase Change thermal Storage Materials, McGraw Hill Book Co., 1989 (chapter 11).
[12] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi, T. Akiyama, Development of phase change materials based microencapsulated technology for buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 1373–1391.
[13] 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 (2007) 113–119.
[14] Y. Liu, M. Xie, X. Gao, Y. Yang, Y. Sang, Experimental exploration of incorporating form-stable hydrate salt phase change materials into cement mortar for thermal energy storage, Appl. Therm. Eng. 140 (2018) 112–119.
[15] P. Sukontasukkul, P. Uthalichiratt, T. Sangpet, K. Sithomphon, M. Newlands, A. Siripanichgorn, P. Chindaprasirt, Thermal properties of lightweight concrete incorporating high contents of phase change materials, Construct. Build. Mater. 207 (2019) 431–439.
[16] Emmerich Wilhelm, Trevor M. Letcher (Eds.), Heat Capacities: Liquids, Solutions and Vapours, Royal Society of Chemistry, Cambridge, U.K., 2010.