Preparation and Characterization of Phase Change Material for Thermal Energy Storage in Buildings

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Background

Energy Consumption

➢ Global Issues
  – The energy demand increases as the growth of economic.
  – The conventional fossil energy sources are exhausting
  – The usage of fossil fuel is related to emission of harmful gases making people worried about environment issues.

➢ Building Sector
  – It is the dominant energy consumers around the world with a total of 30% share of the overall energy consumption.
  – The energy demand for buildings have increased very rapidly due to population growth enhancement of building services and thermal comfort levels.*

Background

Energy Issue:
- Carbon audit (system control)
- Green label (system control)
- Use of replacement materials with lower embodied CO$_2$ emission (materials)

Research Direction (Topic):
2009  Role of Building Materials, global warming/Urban Heat Island effect (SCCT)
  ➢ Possible Alternative Materials on reduction in CO$_2$ Emissions in Building Design
  ➢ Review contribution of building finishes materials on Urban heat island effect
  ➢ Characterise building finishes materials in terms of their total energy released after heat
2011  Study of Rice Husk Ash as Green Cement Replacement Materials (Green Construction Materials, workshop Nami/HKIE Mat’ls divn)
2013  Study of Fine Recycled Glass in Concrete as filler and Cement Replacement Materials (SCCT)
2015  Study of Phase Change Materials (potential application in Buildings)
Background

**Publications:** Study of Phase Change Materials


Phase change material (PCM) works on the principle that as the temperature increases, the material stores energy with phase changing from solid to liquid phase within a defined temperature range; and then, when the temperature decreases, it releases heat with phase changing from liquid to solid phase.
Phase change material (PCM) has a large latent heat, it absorbs or releases large amounts of latent heat in a narrow phase change temperature range, thus to regulate the indoor temperature of buildings.

Different desirable indoor temperatures can be achieved in buildings by using PCM with suitable selected phase change temperatures.
PCM used in Building

- More and more PCMs have been used in building, such as, interior walls, ceilings.
- Thermal energy storage concrete is prepared by integrating PCM with it.

PCM used in Building
Functional Structural PCM Wall

Solar air collector system

Solar air collector system used in wall and roof for drying in industrial building
Combining the characteristics of PV, PCM and building wall. PV/PCM composite wall system (a) store solar energy (b) increasing the efficiency of PV panel (c) regulate indoor temperature.
Laboratory Study

- **Part 1: Form-stable composite PCM**
  - PCM in Mineral Admixture and Cement
    - PCM - Kaolin (KO)
    - PCM - Ground granulated blast furnace slag (GGBS)
    - PCM - Cement (CE)

- **Part 2: Macro-encapsulated PCM**
  - PCM in Porous Lightweight Aggregate
    - Paraffin – Ceramisite Lightweight Aggregate Concrete
Part 1: Form-stable composite PCM
PCM in Porous Mineral Admixture and Cement

Selection of PCM

<table>
<thead>
<tr>
<th>Lauryl Alcohol (LA)</th>
<th>Paraffin</th>
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<tbody>
<tr>
<td>• Phase change temperature in Human comfort zone</td>
<td>• Chemically inert</td>
</tr>
<tr>
<td>• High latent heat storage capacity</td>
<td>• Non-corrosive</td>
</tr>
<tr>
<td>• Economical</td>
<td>• Innocuous (not harmful)</td>
</tr>
</tbody>
</table>

Porous Mineral Admixture & Cement

- Kaolin (KO)
  - World production 28Mtonnes/year, China’s share 11%
- Ground granulated blast furnace slag (GGBS)
  - China produces 30Mtons/year, Use in concrete 7Mtons/year
- Cement (CE)
Preparation of PCM (Lauryl Alcohol/Kaolin)

Schematic of Vacuum Impregnation setup
PCM was successfully held by the porous structure through capillary force and surface tension of the materials. KO has the best absorbing capacity of PCM.
Chemical Compatibility
- Fourier transformation infrared spectrum analysis (FT-IR)

- The peak in the FT-IR spectrum correspond to different functional group. Without new peaks appear, the interaction between components of the composite PCM of LA-KO is physical in nature – Chemically compatible. So the composite method of LA-KO is only physical absorption.

- Also, according to the test result, LA and paraffin both are chemically compatible with KO, GGBS and cement.
Thermal stability
– Thermal gravimetric analyzer (TGA)

- When the test temperature is below 100°C, no obvious weight loss was observed. So the composite PCMs are thermal stable in its working temperature (<=100°C).
Thermal reliability

- The composite PCM is necessary to be thermally reliable over large number of melting and freezing cycles.
  - Chemical compatibility (FT-IR)
  - Thermal Properties (DSC)

The test results indicate chemical structure and thermal properties of the composite PCM don’t change after numbers of thermal cycles (18-26°C).
Thermal performance – Energy storage cement paste panel

PCM panels test showed reduced indoor temperature, right-shifted temperature curves and reduced temperature fluctuations.

Form-stable composite PCMs are Potential Thermal energy storage materials for Building applications.
Part 2: Macro-encapsulated PCM
PCM in Porous Lightweight Aggregate

Ceramic porous lightweight aggregate as carrier of macro-encapsulated PCM.
Preparation of PCM-LWA composite

Left: Vacuum impregnation set-up  
Right: LWA in the melted paraffin

The PCM: paraffin  
Phase change temp.: 24 °C  
Latent heat: 103 J/g.

- Use vacuum impregnation method to obtain the macro-encapsulated PCM.
Macro-encapsulated Paraffin-LWA

Properties of the LWA, ceramisite

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>600 kg/m³</td>
</tr>
<tr>
<td>Porosity (MIP)</td>
<td>77.75%</td>
</tr>
<tr>
<td>Water absorbing capacity by simple immersion (1hr)</td>
<td>18%</td>
</tr>
<tr>
<td>Water absorbing capacity by vacuum immersion (1hr)</td>
<td>73.85%</td>
</tr>
<tr>
<td>PCM absorbing capacity by vacuum immersion (1hr)</td>
<td>70%</td>
</tr>
</tbody>
</table>

- The maximum mass percentage of the PCM absorbed is about 70%. Compared with PCM absorbed in the form-stable PCM, it is very high.
Since paraffin had no effect on hydration reaction, the leak paraffin (if any) adhering on the aggregate surface will pose problem to cement hydration and lower the mechanical strength of concrete.

PCM-LWA trial coated with epoxy
Limitation: poor thermal conductivity of epoxy

Low coefficient of thermal conductivity of the epoxy sealer
\[ K=0.227 \, \text{w/(m·k)} \]

Concrete: \( K=0.886 \, \text{w/(m·k)} \)
Cement paste: \( K=0.912 \, \text{w/(m·k)} \)

Macro-encapsulated PCM coated by epoxy

Low coefficient of thermal conductivity of the epoxy coat affected heat storage since heat can’t get through the epoxy layer into the PCM inside the aggregate.
Graphite (Carbon powder) $K=398 \text{ W/mK}$

Copper powder $K=401 \text{ W/mK}$

Control samples

- Graphite and copper powder that with high thermal conductivities were added into epoxy in order to improve thermal conductivity.
Test results show that graphite has better thermal modification than copper powder.

When 20 wt% of graphite powder is added to epoxy, the thermal conductivity would increase to 0.627 W/mK.
Surface Morphology

30% graphite (100X)

Graphite (Flake)

Copper powder (particle)

30% copper powder (100X)
Graphite with its inter connected flakiness shape achieve better thermal conductivity than copper.
Limitation: poor epoxy/cement interface

- The interface between LWA and epoxy is acceptable, but the interface between sealed epoxy and cement paste matrix is very poor.
Improving epoxy/cement Interface with Silica Fume

- Using **silica fume** to increase interface bond between PCM-LWA and cement-based matrix.
Preparation of Macro-encapsulated PCM-LWA

Paraffin-LWA

Modified Macro-encapsulated Paraffin-LWA

Surface Coat with epoxy and graphite powder

Surface Coat with silica fume
Chemical compatibility and thermal stability Check

- Macro encapsulated Paraffin-LWA is chemically compatible.

- No weight degradation appears below 100°C, so the macro encapsulated Paraffin-LWA is thermally stable in its working temperature.

**Chemical compatibility (FT–IR)**

**Thermal stability - TGA**

70.76%
Thermal reliability – 1000 cycles

Chemical compatibility (FT–IR)

- Paraffin-LWA composite PCM Before
- Paraffin-LWA composite PCM After

Wavenumber [1/cm]

- Transmittance

Thermal Properties - DSC

- Phase change temperature range of Paraffin-LWA is about 24-30 °C.
- It is thermally reliable in terms of phase change behavior, the difference in thermal properties before and after thermal cycles is small.

Macro encapsulated Paraffin-LWA is thermally reliable in terms of chemical compatibility.
**Mix proportion of Thermal Energy Storage Concrete**  
- Compared NWAC and LWAC with and without Paraffin-LWA

<table>
<thead>
<tr>
<th>Mix designation</th>
<th>Cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>NWA (kg/m³)</th>
<th>LWA (kg/m³)</th>
<th>PCM-LWA (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NC</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>1087</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 NC-17%LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>910</td>
<td>43</td>
<td>-</td>
</tr>
<tr>
<td>3 NC-33%LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>728</td>
<td>85</td>
<td>-</td>
</tr>
<tr>
<td>4 NC-50%LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>546</td>
<td>126</td>
<td>-</td>
</tr>
<tr>
<td>5 NC-17%PCM-LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>910</td>
<td>-</td>
<td>80.08</td>
</tr>
<tr>
<td>6 NC-33%PCM-LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>728</td>
<td>-</td>
<td>160.16</td>
</tr>
<tr>
<td>7 NC-50%PCM-LWA</td>
<td>400</td>
<td>140</td>
<td>787</td>
<td>546</td>
<td>-</td>
<td>240.24</td>
</tr>
<tr>
<td>8 LC</td>
<td>400</td>
<td>140</td>
<td>507</td>
<td>-</td>
<td>316</td>
<td>0</td>
</tr>
<tr>
<td>9 LC-100%PCM-LWA</td>
<td>400</td>
<td>140</td>
<td>507</td>
<td>-</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>10 LC-50%PCM-LWA</td>
<td>400</td>
<td>140</td>
<td>507</td>
<td>-</td>
<td>158</td>
<td>300</td>
</tr>
</tbody>
</table>
The compressive strength after 28 days of NWAC with PCM-LWA is 33 - 53 Mpa.

The compressive strength of LWAC with 50% and 100% PCM-LWA is larger than 16 MPa, higher than mix without PCM-LWA.
Thermal performance – NWAC & LWAC (Indoor test)

Indoor temperature of the test chamber with energy storage concrete panel show lower indoor temperature.
Conclusions: Form-stable composite PCM

- PCMs can be vacuum impregnated into pores of mineral admixture or cement. Kaolin has the best storing capacity of PCM.
- Lauryl Alcohol and paraffin are both chemically compatible with KO, GGBS and cement.
- The form-stable composite PCMs are thermal stable and thermal reliable.
- The macro-encapsulated Paraffin-LWA also a chemical compatible, thermal stable and thermal reliable PCM material for thermal energy storage applications in buildings.
- The compressive strength after 28 days of NWAC with PCM-LWA is 33 - 53 MPa, which has an opportunity for structural purpose.
- The compressive strength of LWAC with 50% and 100% PCM-LWA is larger than 16 MPa, higher than mix without PCM-LWA.
- Indoor temperature of the test chamber with energy storage concrete panel show lower indoor temperature.
Conclusions: Macro-encapsulated PCM

- The macro-encapsulated Paraffin-LWA is chemical compatible, thermal stable and thermal reliable.
- The compressive strength after 28 days of NWAC with PCM-LWA is 33 - 53 MPa, which has an opportunity for structural purpose.
- The compressive strength of LWAC with 50% and 100% PCM-LWA is larger than 16 MPa, higher than mix without PCM-LWA.
- Indoor temperature of the test chamber with energy storage concrete panel show lower indoor temperature.
- Macro-encapsulated PCM-LWA is a promising candidate for thermal energy storage applications in buildings
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