Annual Concrete Forum 2023

Theme: Towards Climate-Friendly Concrete Construction

Innovations in Low Carbon Technology

Topic: PCM Energy Storage Technology： Green Concrete Construction

Ir Dr Tommy Lo

Chairman of Materials Division

HKIE THE HONG KONG INSTITUTION OF ENGINEERS 香 港 工 程 師 學 會

Materials Division 材 料 分 部

PCM Energy Storage Technology: Green Concrete Construction

1) Climate-Friendly / Net Zero

2) PCM Energy Storage Material: Active Solution towards Carbon Neutrality

3) Application of PCMs-enhanced energy storage technology
   a) Building Envelopes
   b) Building Facilities
   c) Underground Structures
   d) PCMs-enhanced concrete energy storage pile
   e) Cold Energy Storage System

4) PCMs-enhanced concrete energy storage pile

5) Study on use of PCM-HSB concrete for high performance in energy piles

6) Conclusions

Climate-Friendly / Net Zero

Climate change is a global issue increasingly affecting human health, socio-economic development, population migration, food security, and terrestrial and marine ecosystems. To address the increasing number of extreme climate disasters, countries have started to set specific targets to decrease carbon emissions.

The European Union (EU)' s Green Deal, launched in 2020, aims to make the EU climate-neutral by 2050[1]. As the world' s largest emitter of greenhouse gases, China also announced action against climate change, aims to reach peak carbon emissions by 2030 and become carbon neutral by 2060[2].

The global temperature will be stabilized when carbon dioxide emissions reach net zero. For 1.5°C (2.7°F), this means achieving net zero carbon dioxide emissions globally in the early 2050s; for 2°C (3.6°F), it is in the early 2070s

[1]European Commission (2019), The European Green Deal. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640&qid=1660118669836.

[2]Mallapaty, S. (2020). How China could be carbon neutral by mid-century. *Nature* 586, 482 – 483. doi:10.1038/d41586-020-02927-9

Climate-Friendly / Net Zero

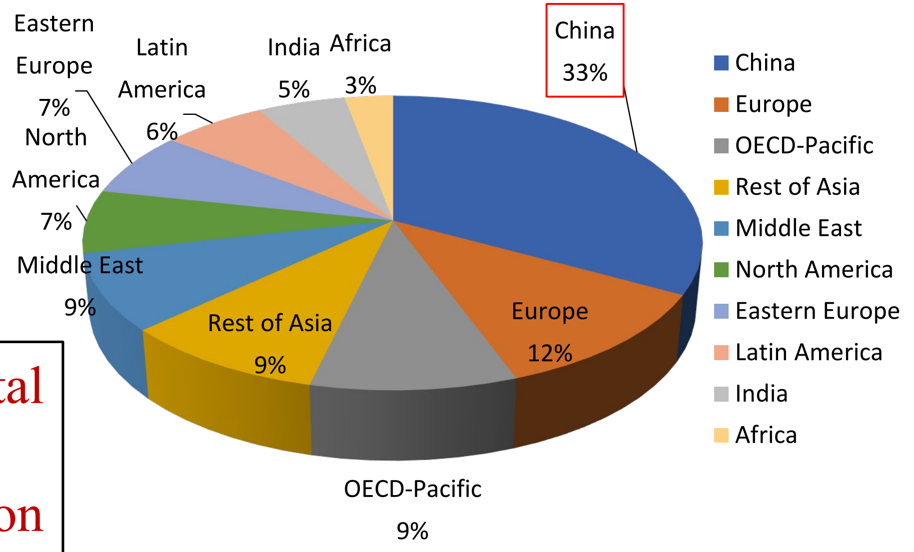
2009 Annual Concrete Seminar
Concrete Science on Global Warming: Role of Building Materials

For construction:

- Global cement industry contributes 5% of total global carbon dioxide
  (Marland G, Boden T, Brenkert A. 1998)
- China contributes 33% of the global CO_2 emissions from Cement Production
  (Hendrick C. A., et al., 2004)

Current Status (2022)

- The cement industry alone is responsible for almost 7% of the world's CO_2 emissions.
  (United Nations Economic Commission for Europe, 11 November 2022)
- China shares 29.2% of the emissions
  (GHG emissions of all world countries - JRC/IEA 2023 Report)



- The share of cement industry of China contributing to the total global CO_2 emission increases from 1.65% to 2.0%
- Using less cement is getting more important in CO_2 emission control

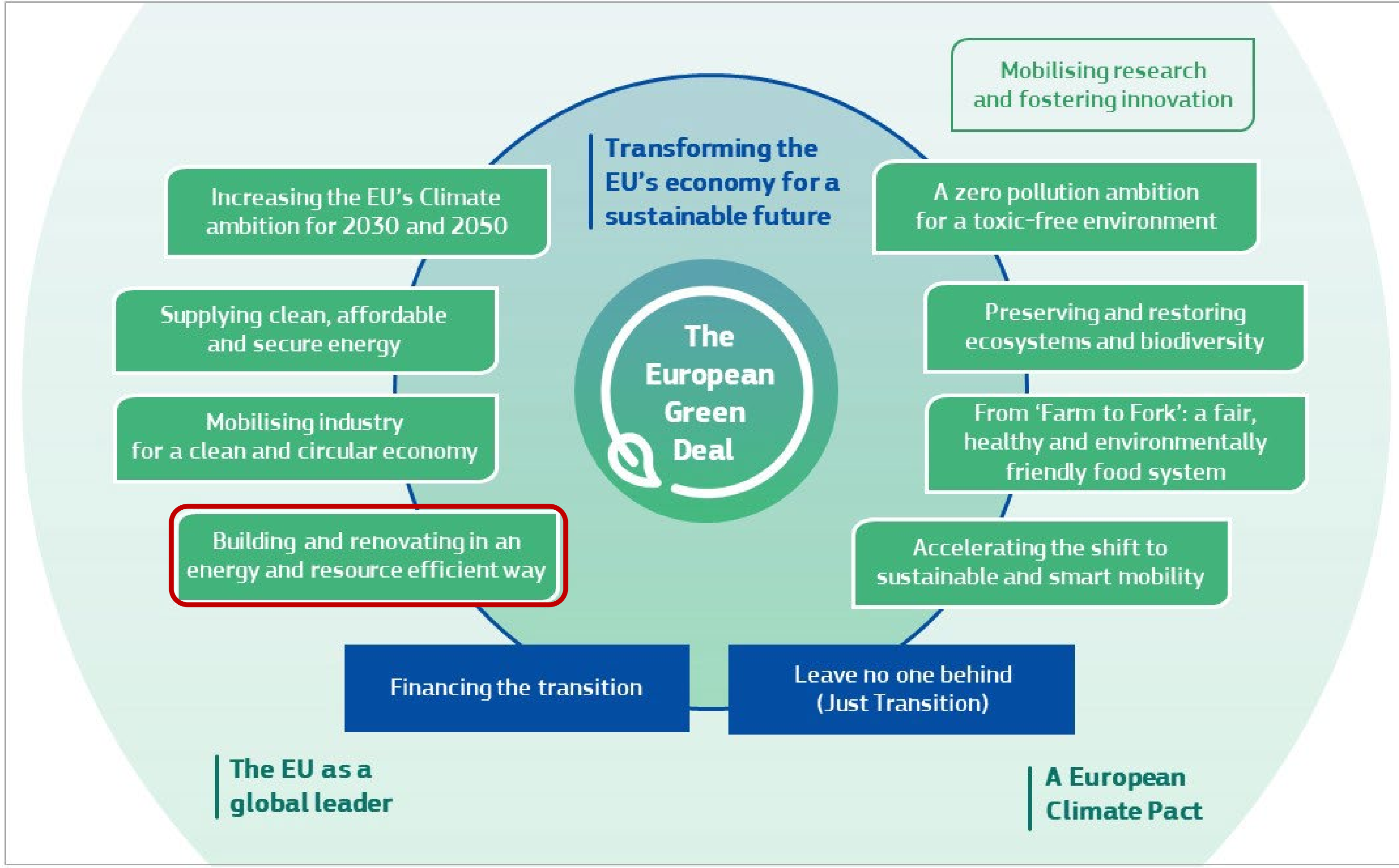
Climate-Friendly / Net Zero

For Construction, mitigation measures mainly by using cement replacement materials like PFA, GGBS

- aiming at using less cement and thus reduction in carbon emission in the construction stage
- only benefit once

What Materials Engineer can do ?

Building and renovating in an energy and resource efficient way



Climate-Friendly / Net Zero

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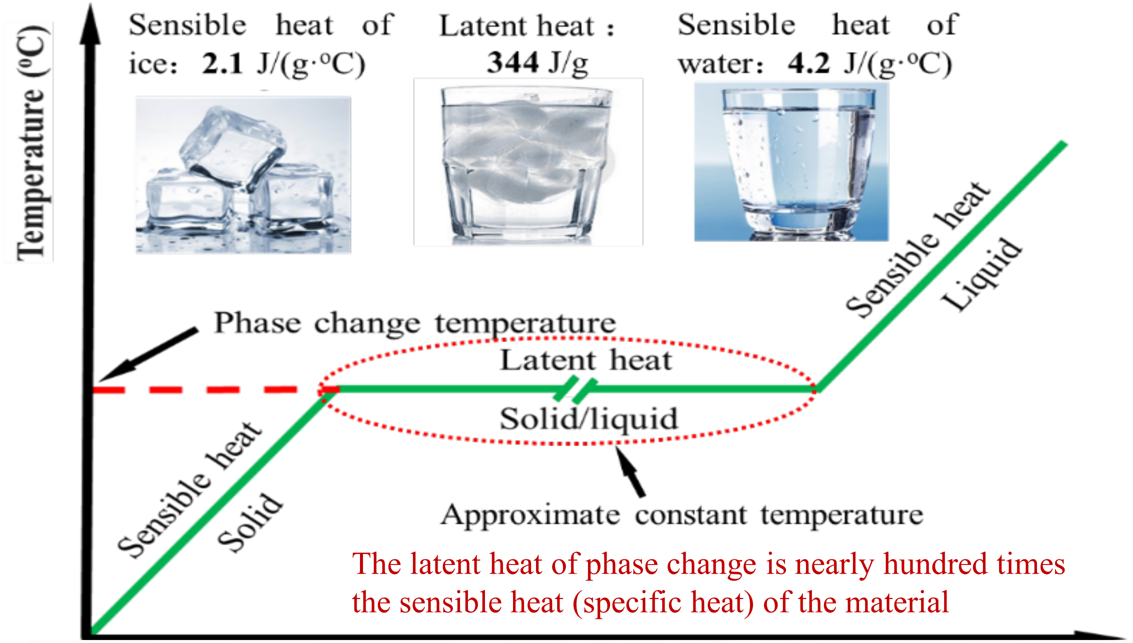
Greenhouse Gases emissions can be **classified into three scopes**: (The Hong Kong Exchanges and Clearing Ltd (HKEx) ESG Reporting Guide Dec. 2019)

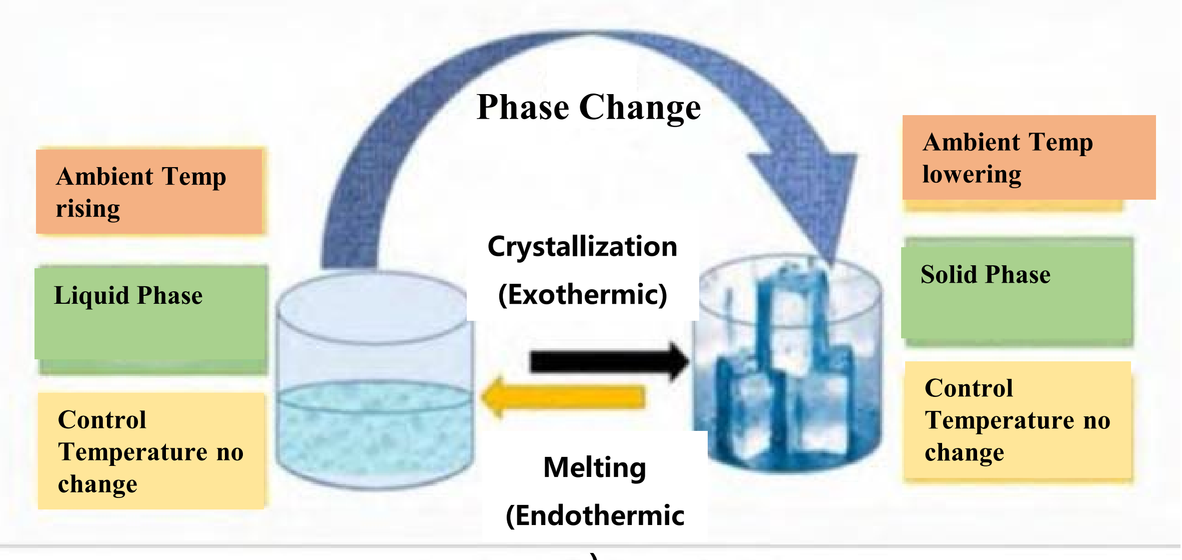
- ☐ **Scope 1** – Direct emissions from operations that are owned or controlled by the company;
- ☐ **Scope 2** – "**Energy indirect**" emissions resulting from the generation of **purchased or acquired electricity**, heating, cooling and steam consumed within the company;
- ☐ **Scope 3** – All other indirect emissions that occur outside the company, including both upstream and downstream emissions.
  (Reporting on Scope 3 emissions is not required as part of this KPI)

Note: GHGs include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.

PCM Energy Storage Material: Active Solution towards Carbon Neutrality

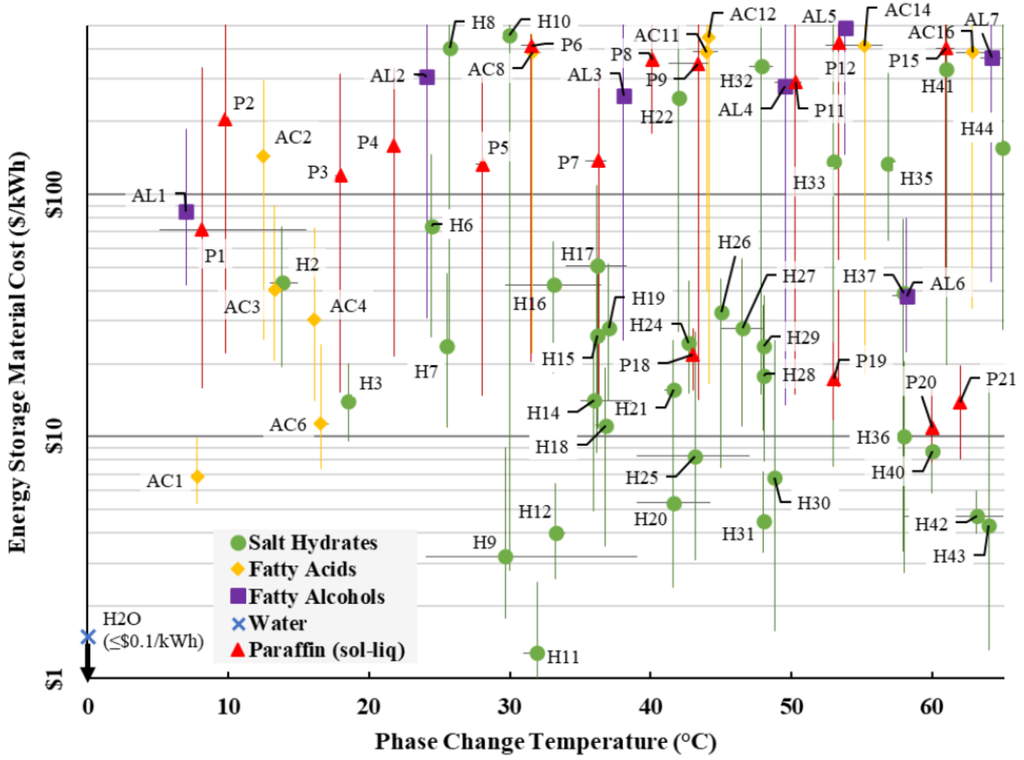
Phase Change Material (PCM) can regulate / saving energy consumption in building





Four PCM classes for potential use in building systems:

1) inorganic salt hydrates
2) organic fatty acids
3) organic fatty alcohols
4) organic paraffin waxes.



Jason Hirschey, et al. "Review of Low-Cost Organic and Inorganic Phase Change Materials with Phase Change Temperature between 0°C and 65°C. 6th International High Performance Buildings Conference, Purdue, May 24-28, 2021.

PCM Energy Storage Material: Active Solution towards Carbon Neutrality

Phase Change Material (PCM) can regulate / saving energy consumption in building

Next Generation Materials Technology

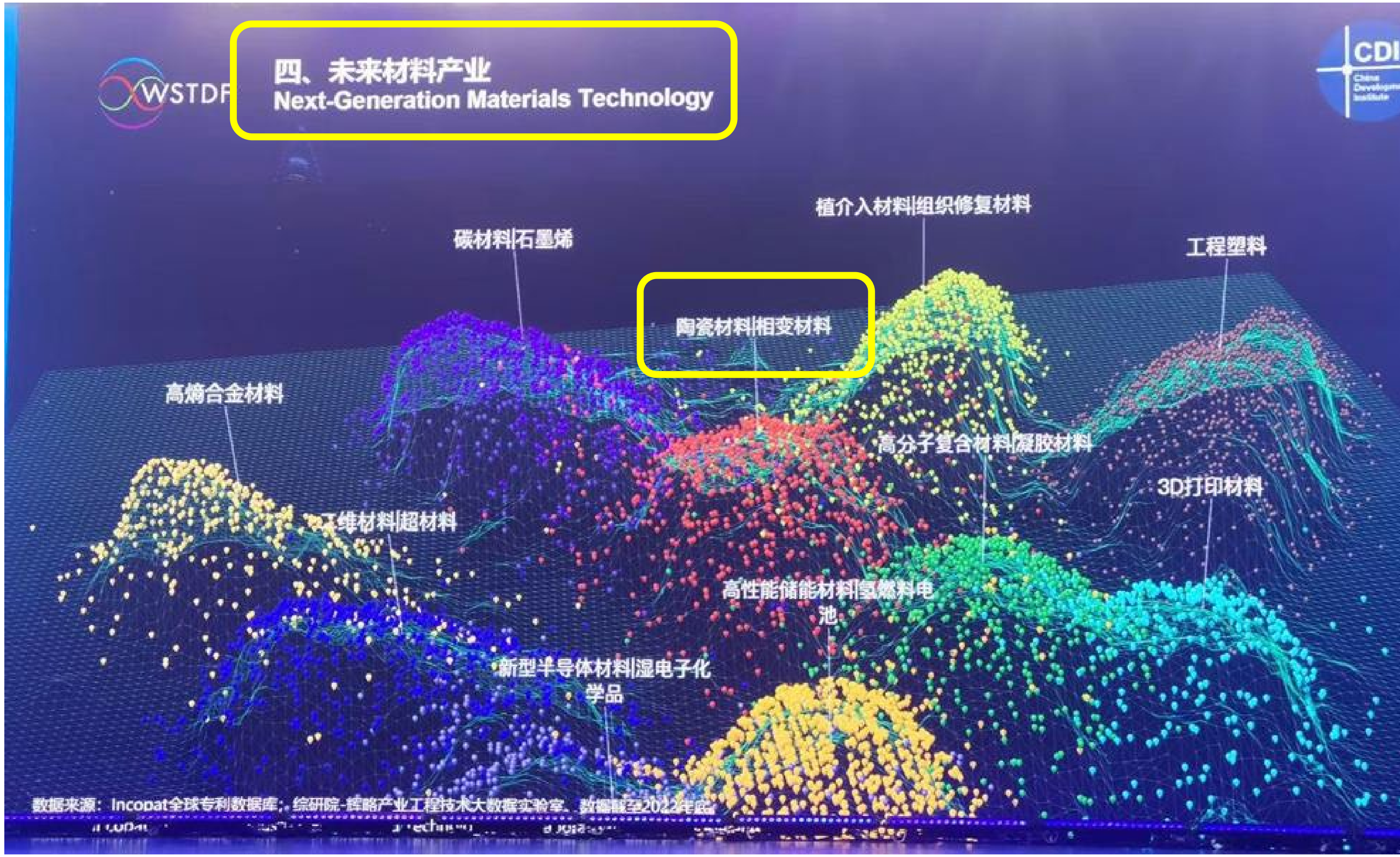
Phase Change Materials

As materials engineer

- ways to apply
- where to apply

Apply approach

- surface absorption by particle
- macro-encapsulated in carrier
- in system/tubes



Qu Jian, "Ten future industry development in the Guangdong-Hong Kong-Macao Greater Bay Area". The 5th World Science and Technology Development Forum, 23-25 Nov 2023. China Development Institute, Shenzhen, China.

First introduced in 2015 Annual Concrete Seminar

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SCCT Annual Concrete Seminar 2015
Concrete: From Production to Recycling
29 April 2015

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

Dr Tommy Y Lo
Associate Professor
Architecture and Civil Engineering Department
City University of Hong Kong

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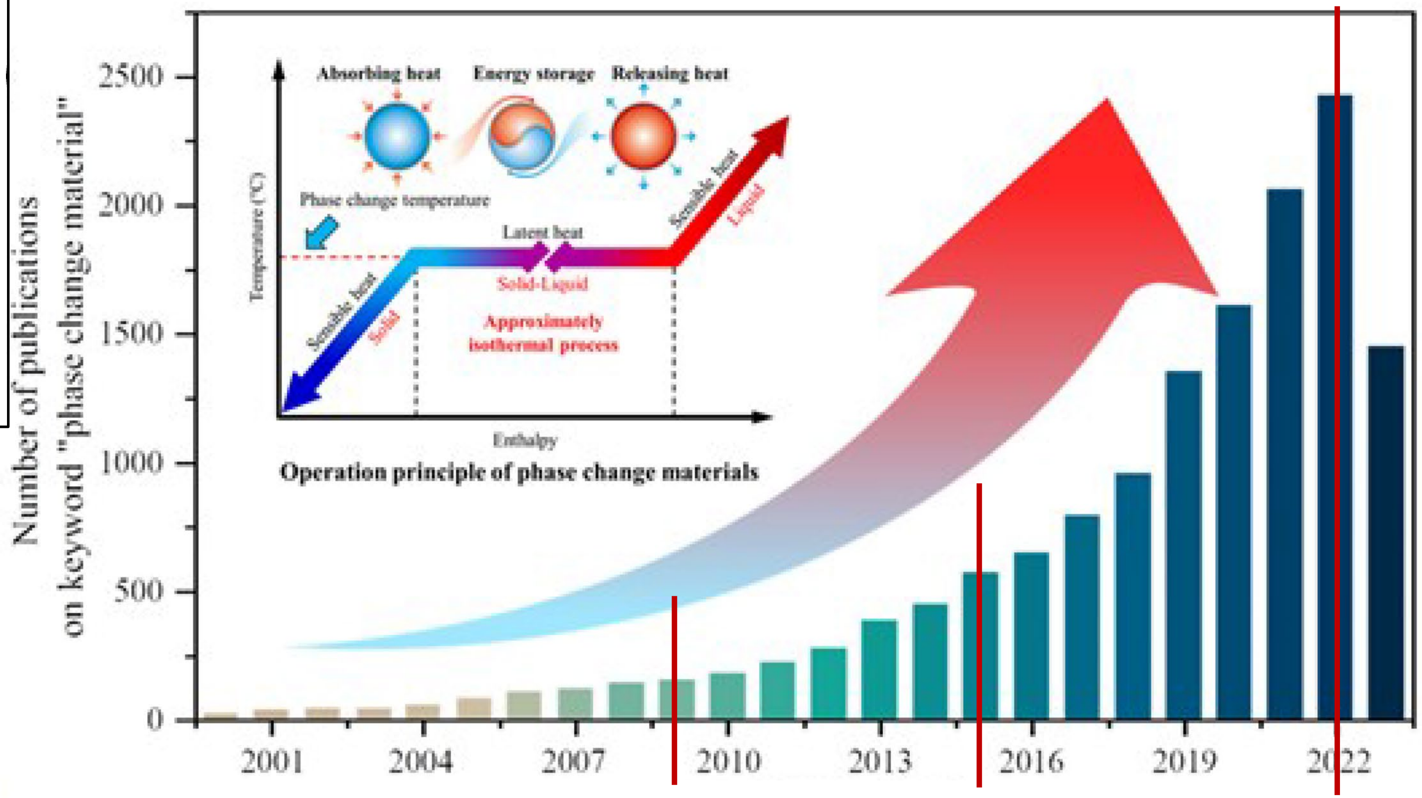
PCM Research Team

Ir Dr Tommy Lo (CityU of Hong Kong)

Prof Hongzhi Cui, Dr Haibin Yang (Shenzhen University, China)

Dr Shazim Ali Memon (Nazarbayev University, Kazakhstan)



Number of publications on the keyword "phase change material" from 2000 to 2023 (data as of September 2023 from Web of Science) increase sharly

First introduced in 2015 Annual Concrete Seminar

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

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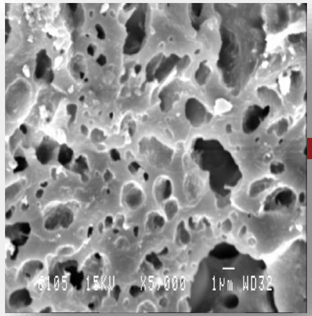
Macro-encapsulated PCM (Phase Change Material)

PCM (70%) in Porous Lightweight Aggregate



储能陶粒

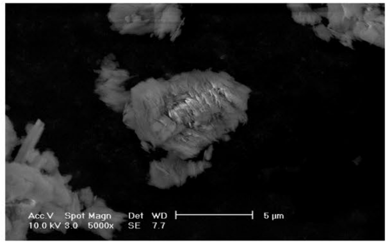
Form-stable composite PCMs

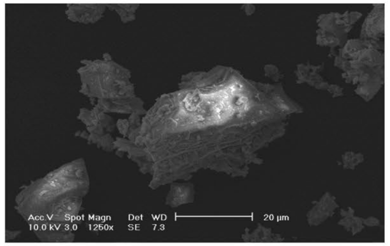
PCM (Lauryl Alcohol (LA)/Paraffin) in Mineral Admixture / Cement

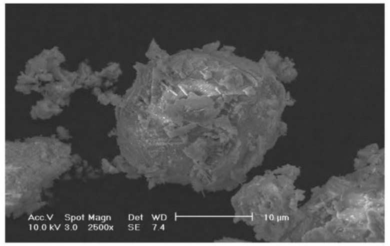
- PCM – KO (Kaolin)
- PCM - GGBS (Ground granulated blast furnace slag)
- PCM – CE (Cement)

储能粉体

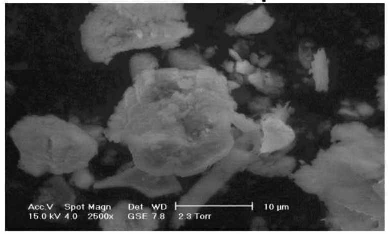
Kaolin	GGBS	Cement

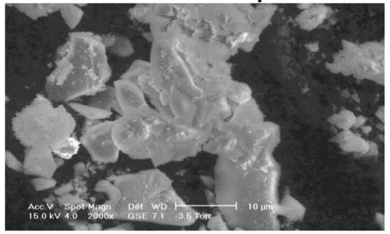


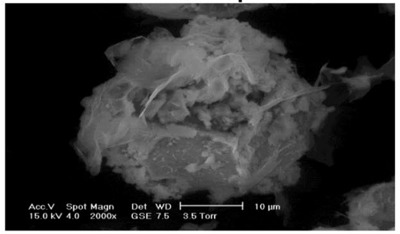




LA-Kaolin composite	LA-GGBS composite	LA-CE composite





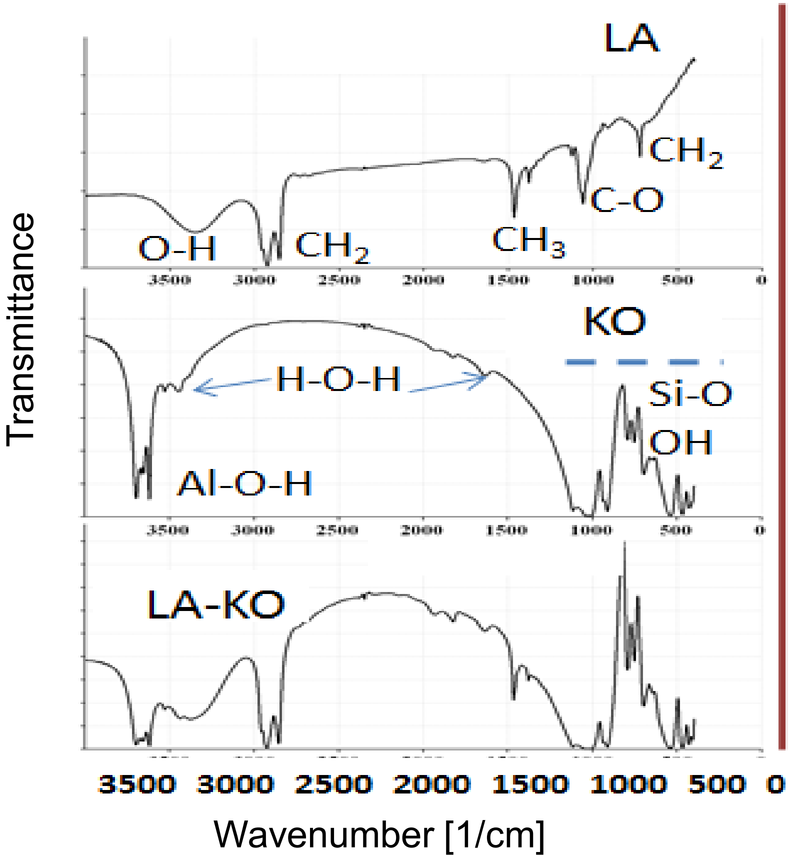


LA= 24%; Paraffin = 18%	LA=11%; Paraffin = 9%	LA= 9%; Paraffin = 7%

First introduced in 2015 Annual Concrete Seminar

Chemical Compatibility of PCM

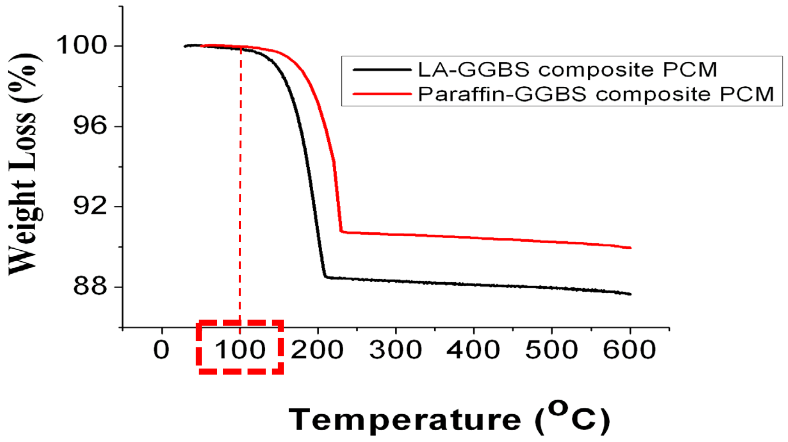
Fourier transformation infrared spectrum analysis (FT-IR)



- 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 absorption in nature – Chemically compatible.

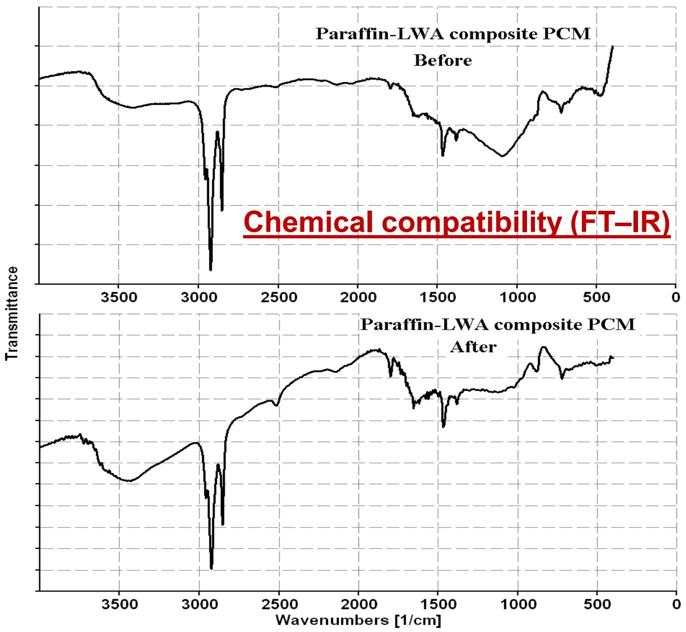
Thermal Stability of PCM

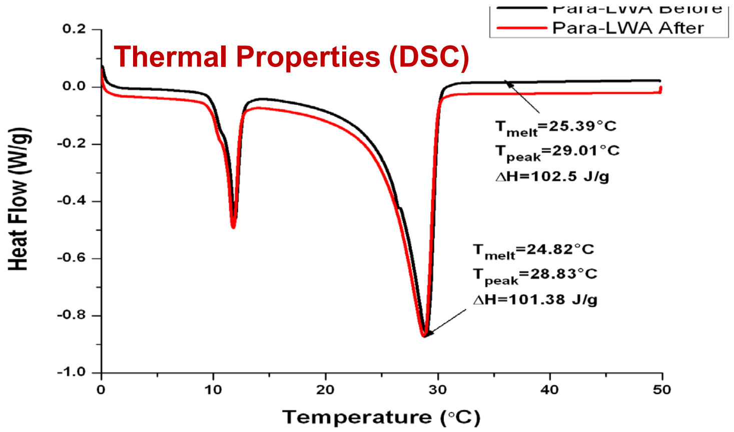
Thermal gravimetric analyzer(TGA)



- 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 (1000 cycles)



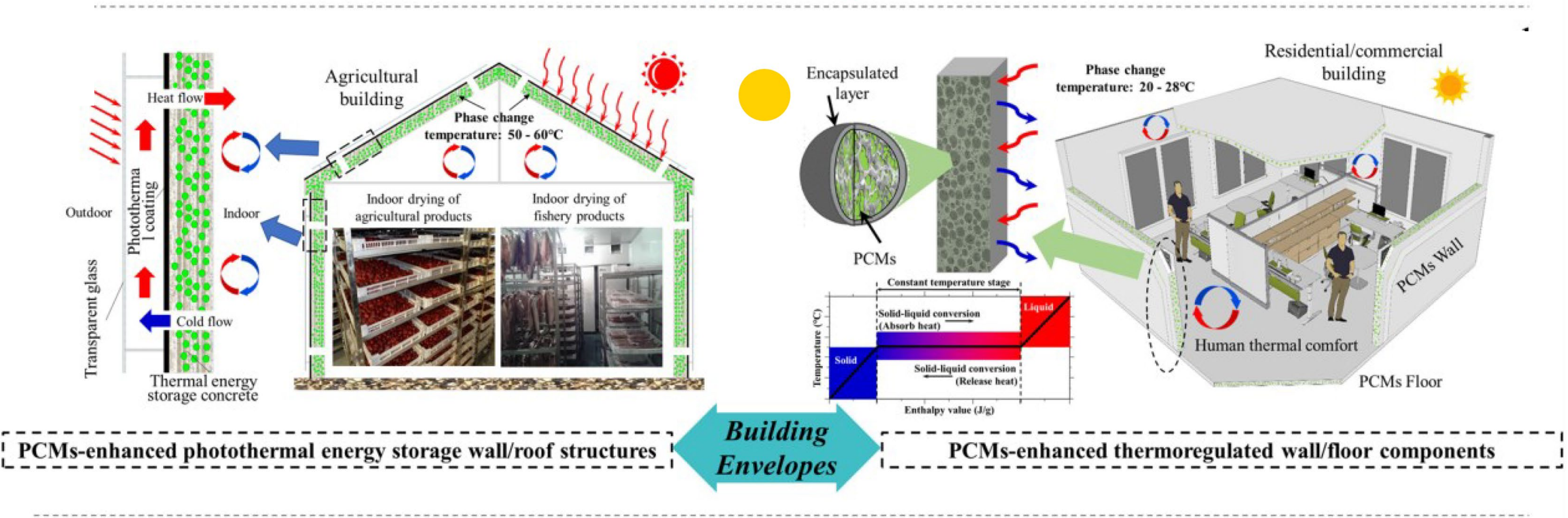


- Thermally reliable in terms of phase change behavior, the difference in thermal properties before and after thermal cycles is small.

Application of PCMs-enhanced energy storage Technology

(a) Building Envelopes

PCMs-enhanced photothermal energy storage wall/roof structures
PCMs-enhanced thermoregulated wall/floor components

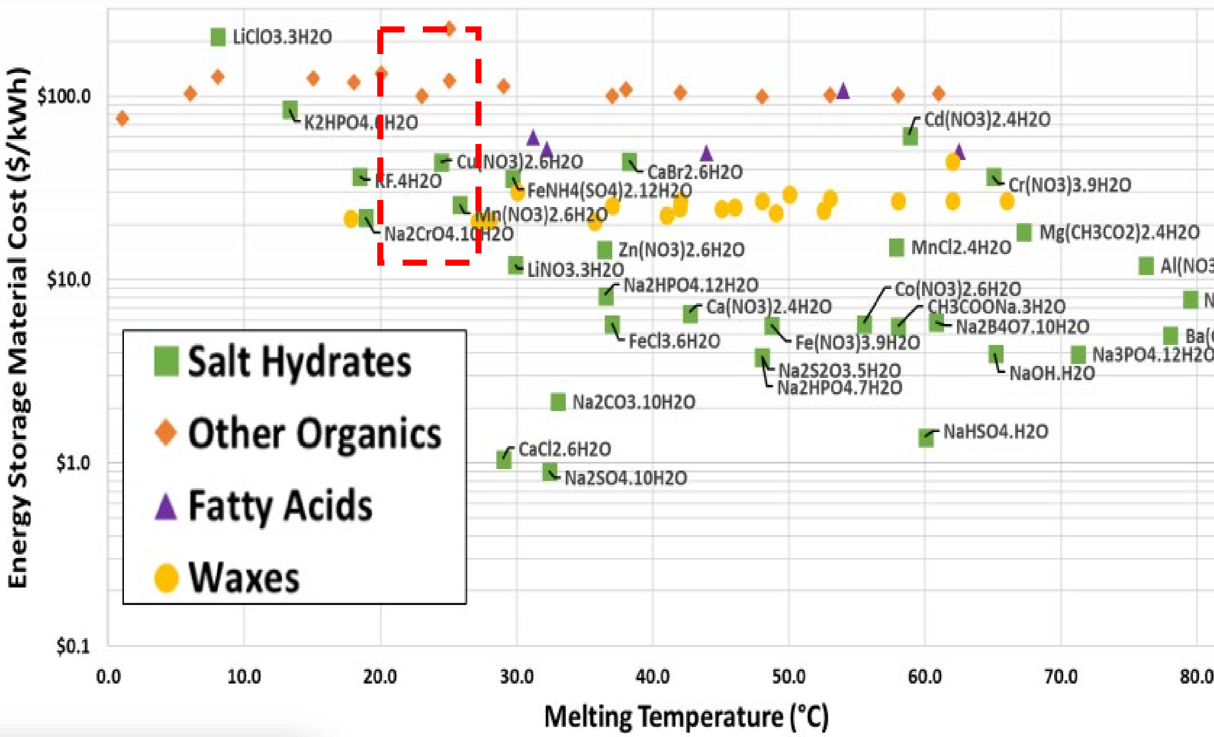


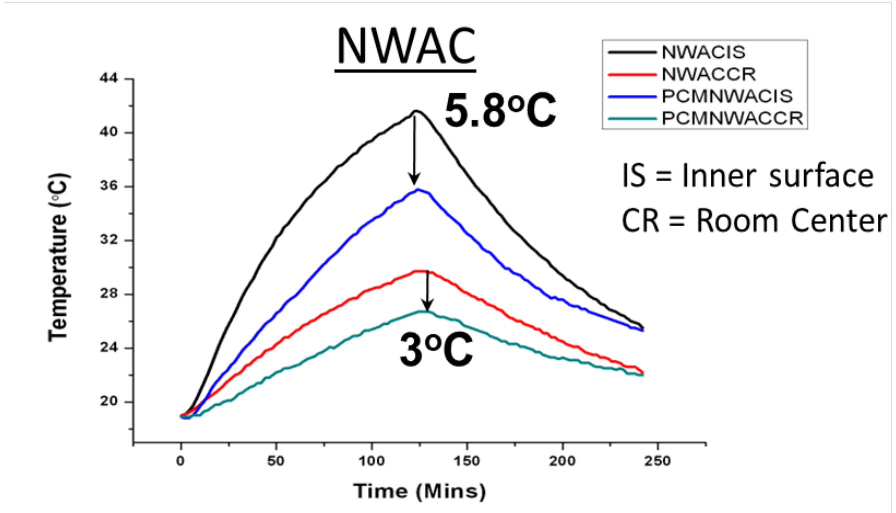
Application of PCMs-enhanced energy storage Technology

Thermal Comfort

Building envelopes (thermal comfort)

PCM enhanced energy storage concrete used for building envelopes can regulate room temperatures, maintaining them within the thermal comfort range of 20-28°C, and facilitates the harnessing of solar energy (with the capability to meet hot water demand in the range of 29-68°C) within buildings. Selection of PCM materials shall match with the design thermal comfort zone.





Energy storage concrete house model

Application of PCMs-enhanced energy storage Technology

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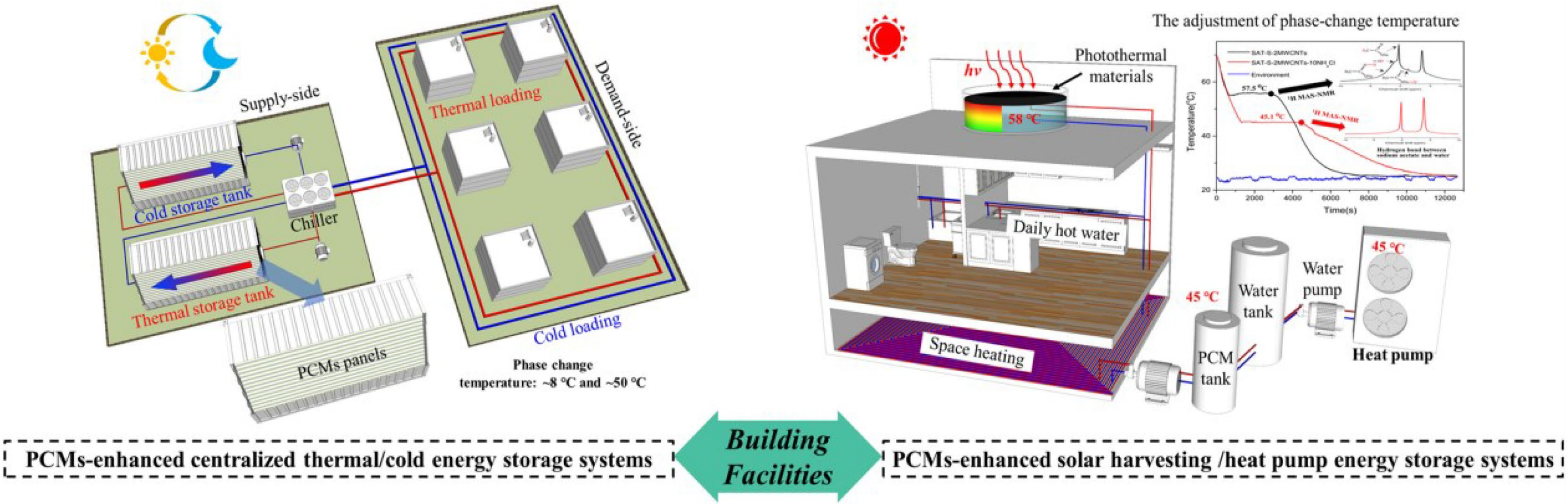
(b) Building Facilities

PCMs-enhanced centralized thermal/cold storage systems

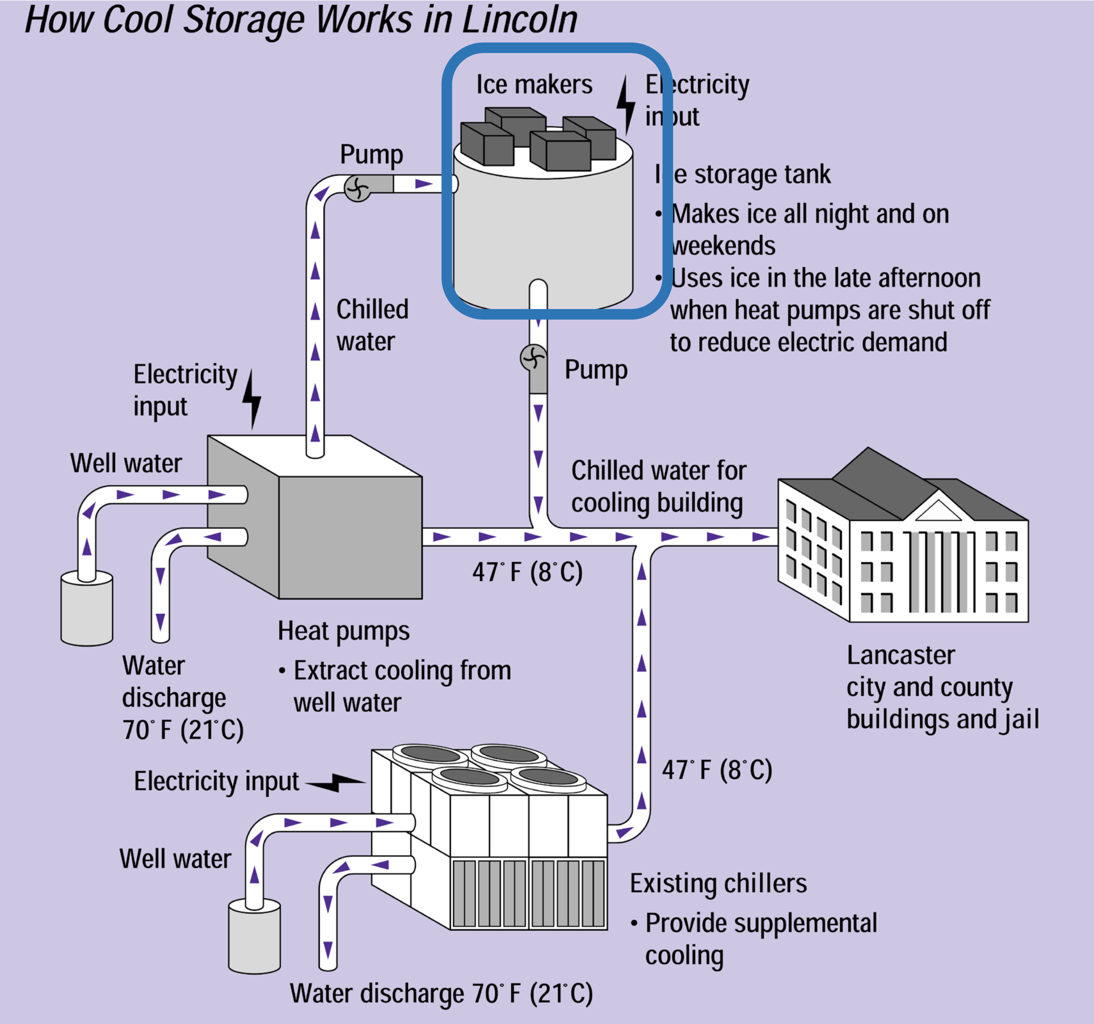
PCMs-enhanced solar harvesting/heat pump energy storage systems



Application of PCMs-enhanced energy storage Technology

Cold Energy Storage System with PCM

Cold energy storage tank (Lincoln Electric, US)



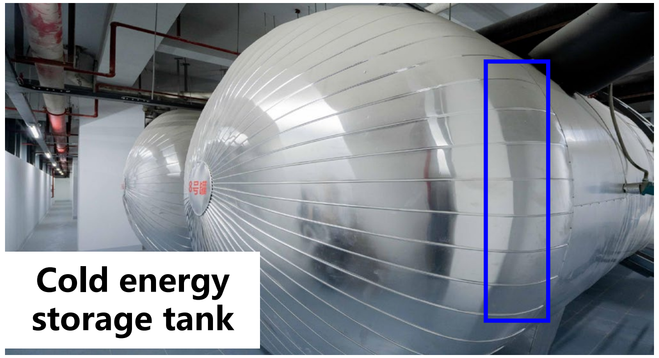
Keep It Cool with Thermal Energy Storage Energy, https://www.nrel.gov/docs/legosti/old/20176.pdf

In 1989, Lincoln Electric System uses an ice storage system to cool inlet air on a 57-megawatt turbine. On a day with a temperature of 100°F (38°C), the cooling increases the turbine's capacity by 25% compared to that with no inlet cooling, and at no net increase in operating costs.

During the summer, heat pumps remove heat from the buildings and transfer it to underground water wells. During the cooler late evening and early morning hours, when electricity is less expensive, the heat pumps act as high-efficiency ice makers. This ICE/PCM is stored to cool the buildings during the afternoon, the peak demand period. Chillers are available to provide supplemental cooling on the hottest days and may also be used for cooling buildings in off-peak periods while the heat pumps are making ice.

Application of PCMs-enhanced energy storage Technology

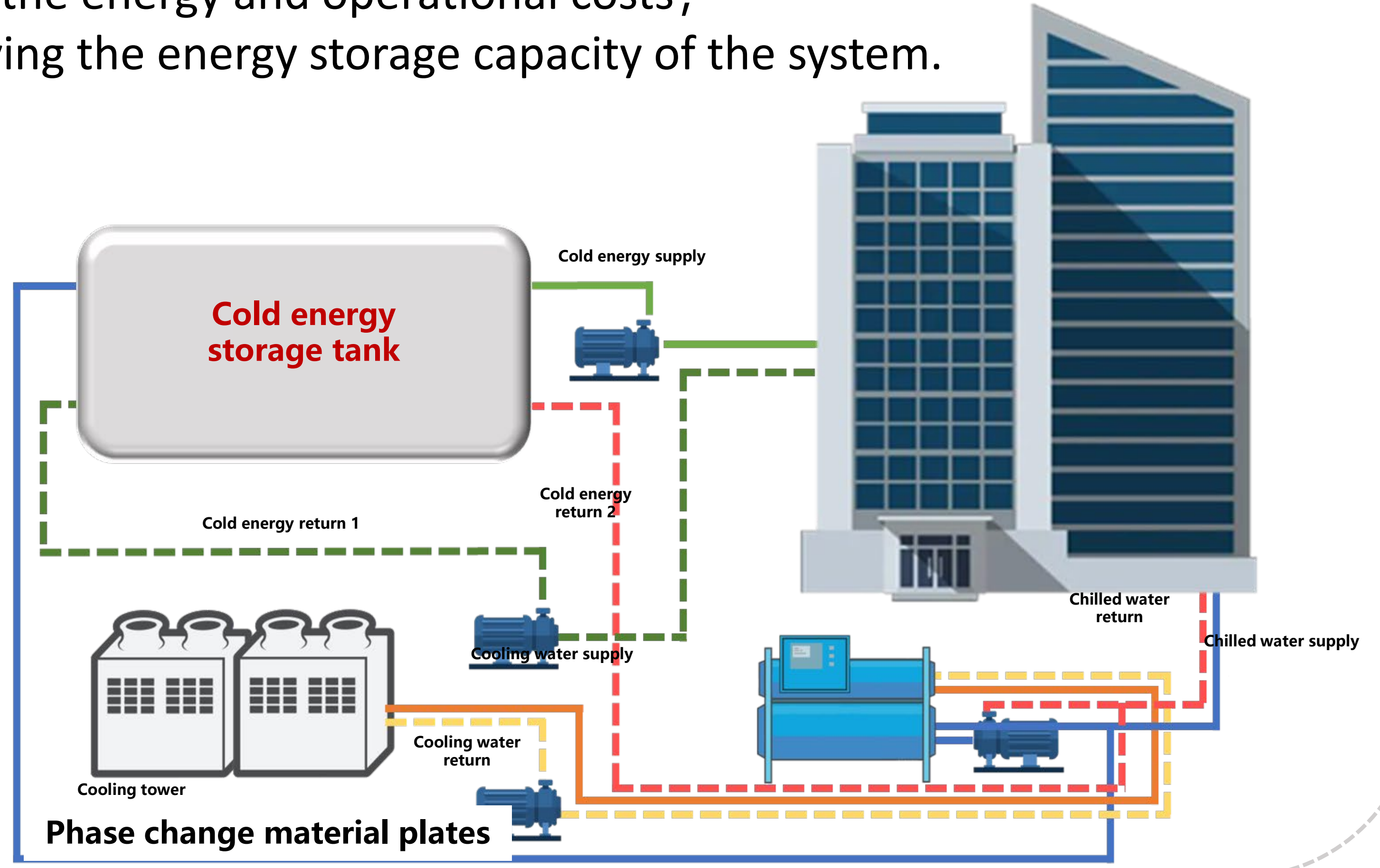
Cold Energy Storage System with PCM



Cold energy storage tank

Phase change material plates

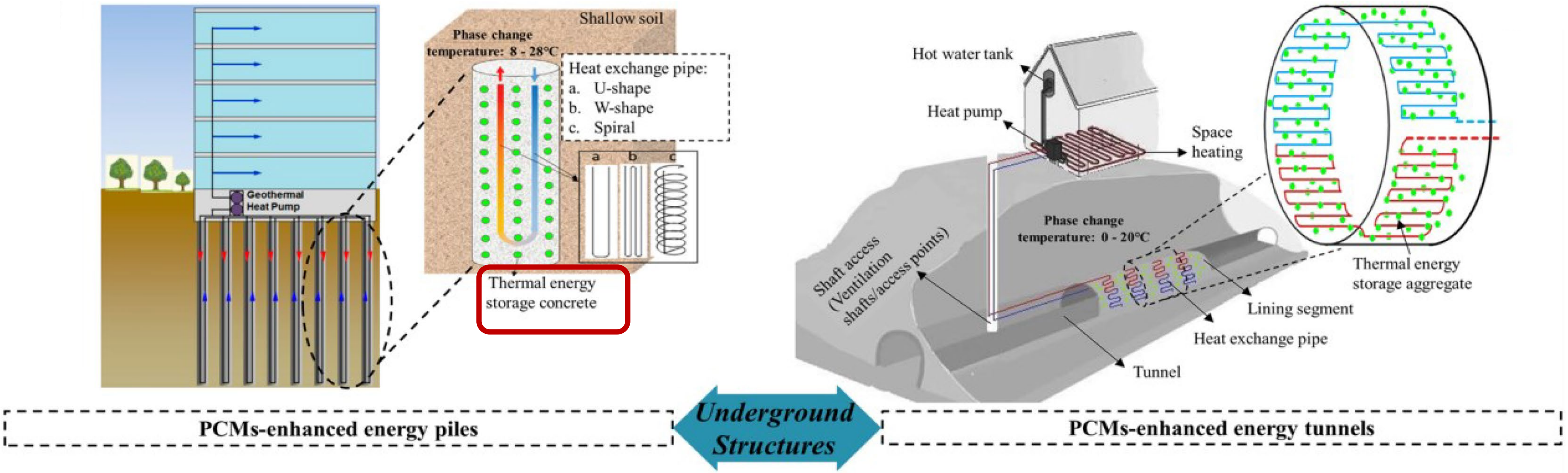
- Saving the energy and operational costs;
- Improving the energy storage capacity of the system.



Application of PCMs-enhanced energy storage Technology

(c) Underground Structures

PCMs-enhanced energy piles and
PCMs-enhanced energy tunnels



Application of PCMs-enhanced energy storage Technology

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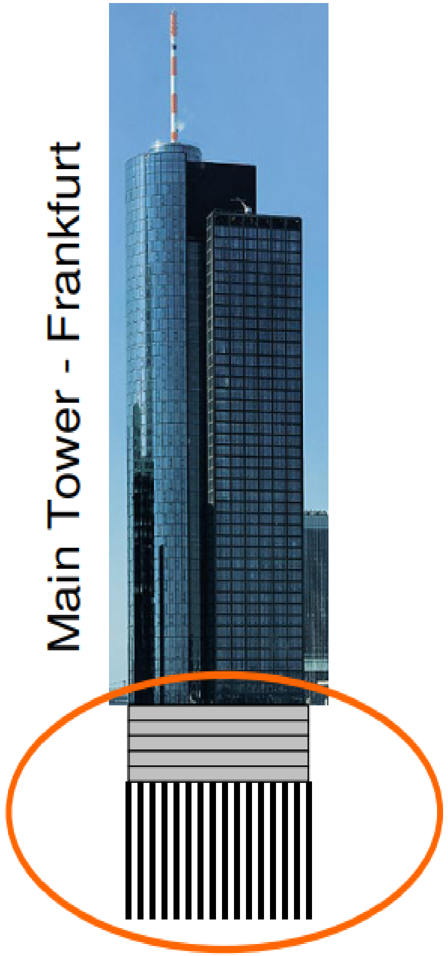
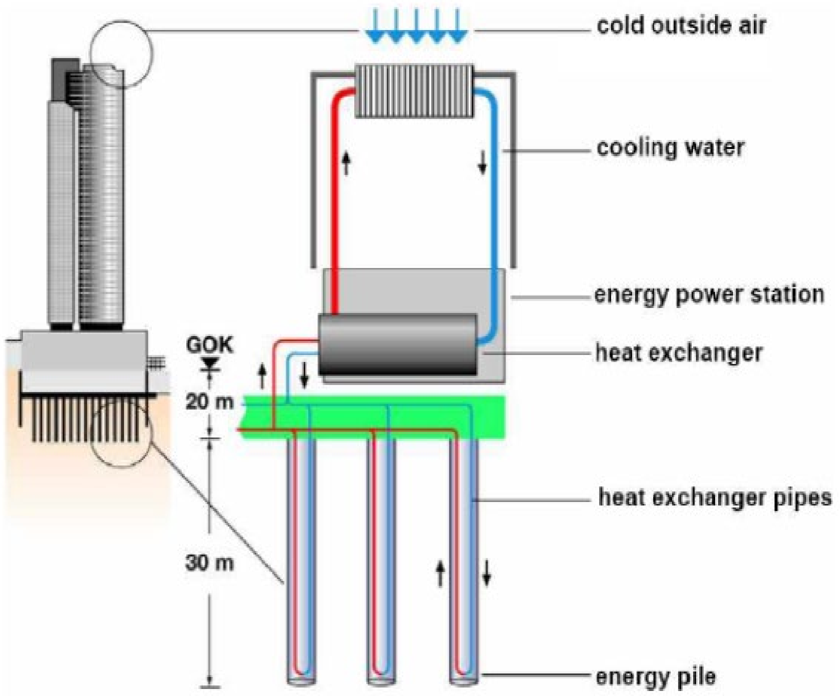
PCMs-enhanced concrete energy storage pile





223 Energy piles were installed
Power : 500kW
Courtesy R. Katzenbach TUD

The `Main Tower`, with a height of 198 m, is one of Europe`s highest and most innovative office buildings.

The building has a pile foundation which is at the same time a component of the energy supply concept: The piles are equipped with heat exchanger tubes, so that the soil can be utilized for heat supply down to a depth of 50 m.

There are several interfaces between foundation work and technical facilities. The number of cogeneration units required for supply of the building could be reduced accordingly.

Hude, N von der, and Kapp, C. "Use of energy piles in the Main Tower high-rise building, Frankfurt". Scientific and Technical Information. U.S. Department of Energy. Mar 01, 1998. https://www.osti.gov/etdeweb/biblio/640865

PCMs-enhanced concrete energy storage pile

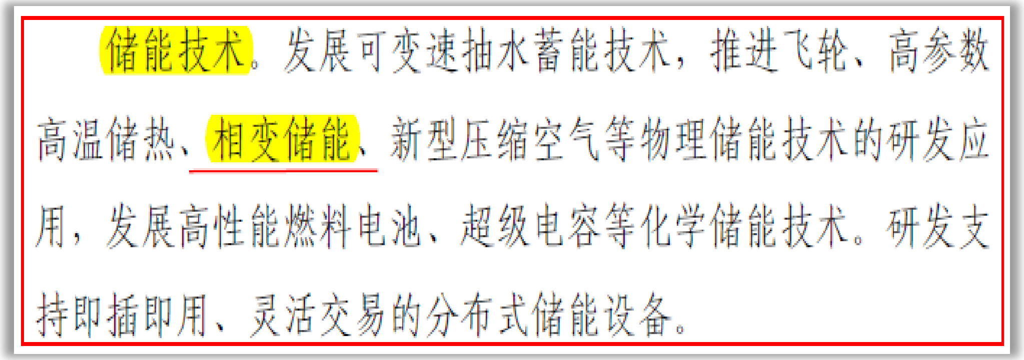
National Policy - Green Construction

2017年初，国家发展改革委、国家能源局联合印发《能源生产和消费革命战略（2016—2030）》，进一步明确到2030年能源革命的总体目标和战略任务。

能源生产和消费革命战略

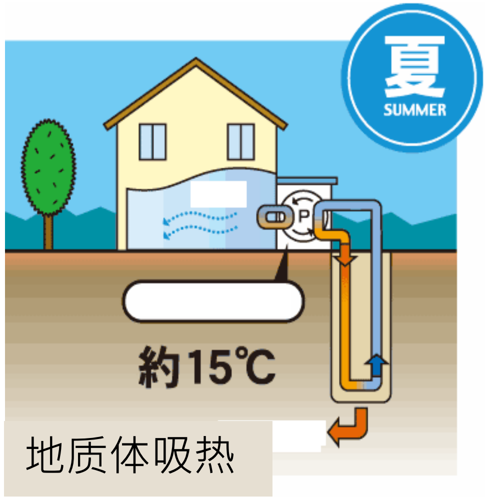
（2016—2030）

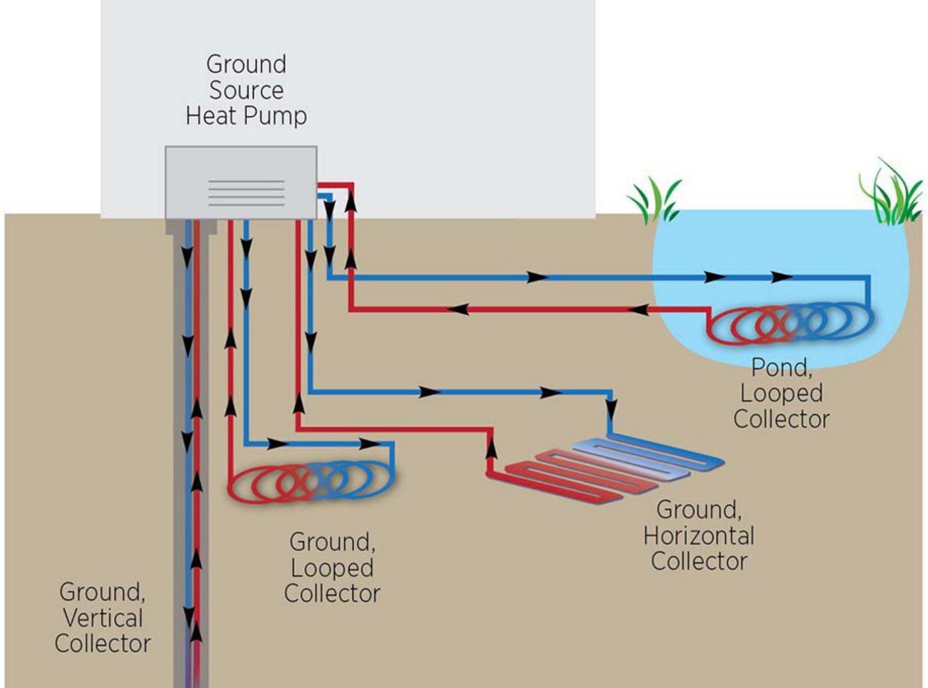
（公开发布稿）



储能技术。发展可变速抽水蓄能技术，推进飞轮、高参数高温储热、相变储能、新型压缩空气等物理储能技术的研发应用，发展高性能燃料电池、超级电容等化学储能技术。研发支持即插即用、灵活交易的分布式储能设备。

在中国，2010年以来，中国浅层地热能利用量以年均 28%的速度递增。2017年底，实现供暖（制冷）建筑面积超过 5 亿平方米





PCMs-enhanced concrete energy storage pile

Study on use of PCM-HSB concrete for high performance in energy piles

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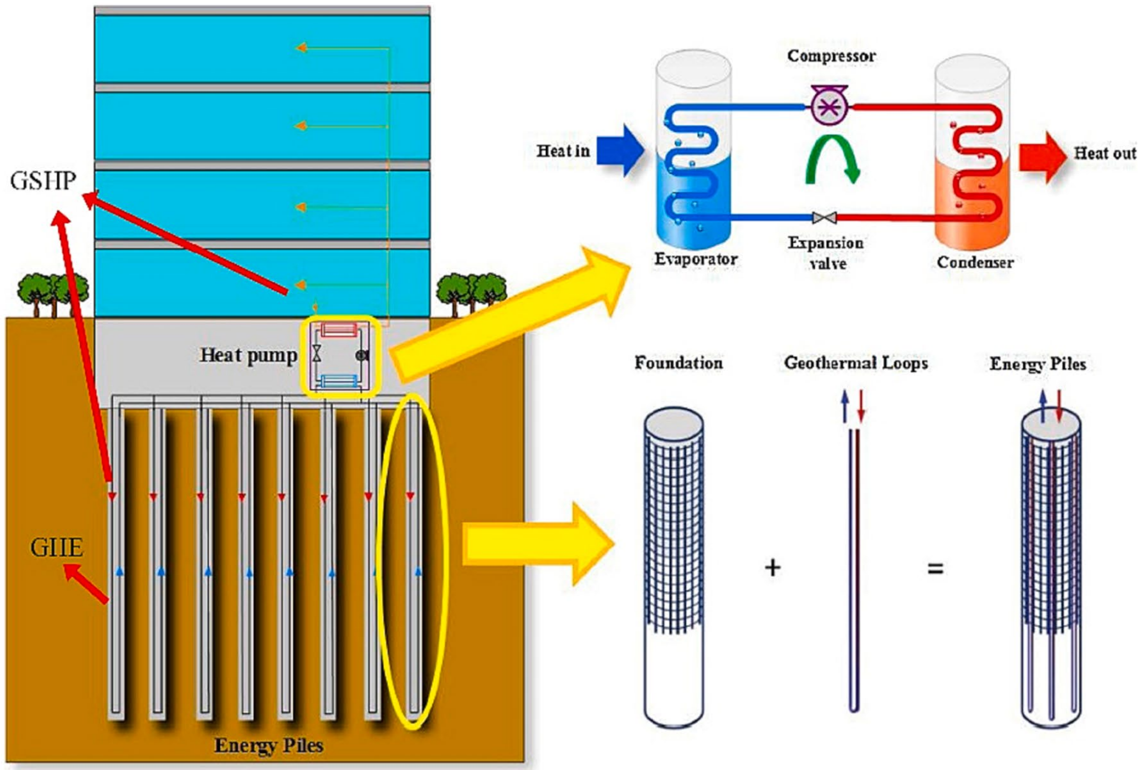
Brief

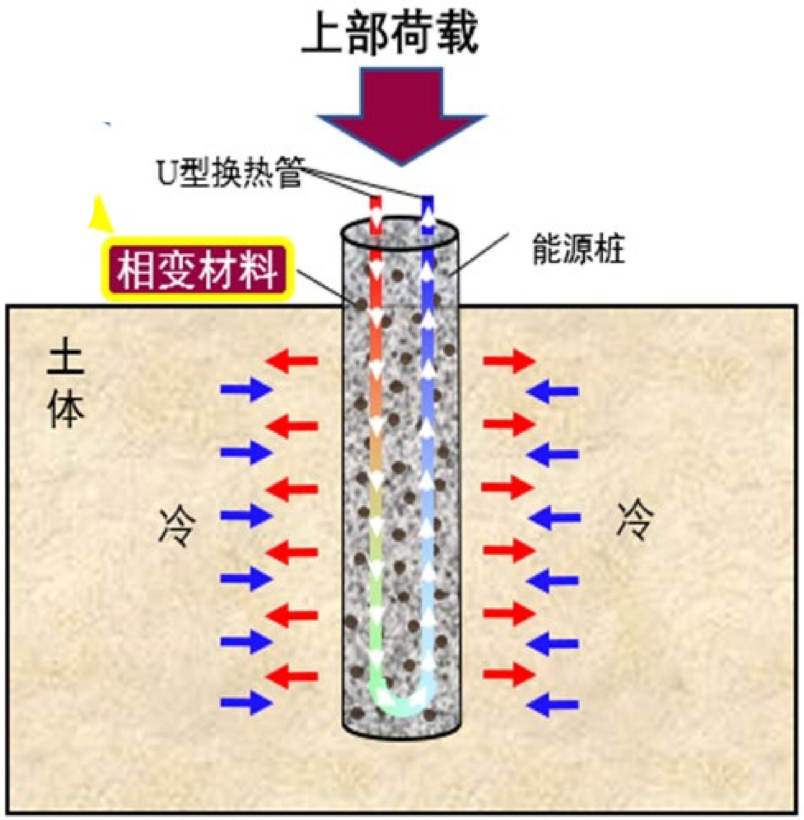
1) A hollow steel ball (HSB) is used to macro-encapsulate the phase change materials (PCM) to form PCM-HSB aggregates.
2) To improve the thermal and mechanical properties of concrete. Steel fibres was added.
3) The test results demonstrated that the thermal conductivity and compressive strength of the PCM-HSB concrete significantly increased with an increase in the steel fibre content and HSB thickness. The addition of 0.35% steel fibre improved the thermal conductivity of the PCM-HSB concrete by 71% due to the bridge function of the scattered steel fibres in the concrete matrix.
4) The proposed fibre reinforced PCM-HSB can significantly improve the heat capacity and bearing capacity of concrete, which can ensure



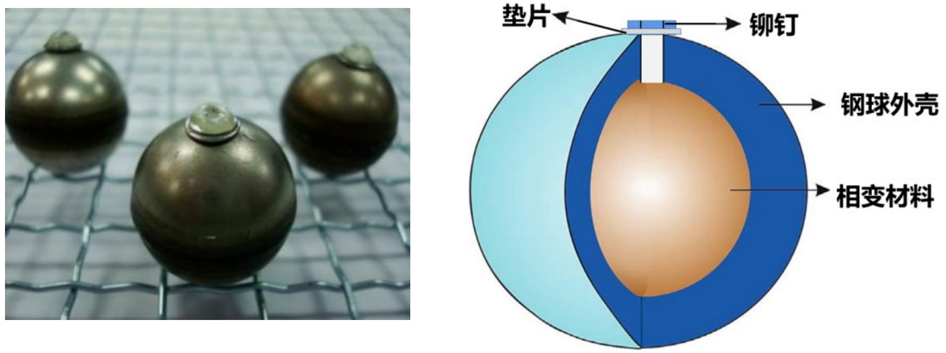
Hongzhi Cui, et al. "Study on the thermal and mechanical properties of steel fibre reinforced PCM-HSB concrete for high performance in energy piles". Construction and Building Materials. 350 (2022) 128822

Study on use of PCM-HSB concrete for high performance in energy piles

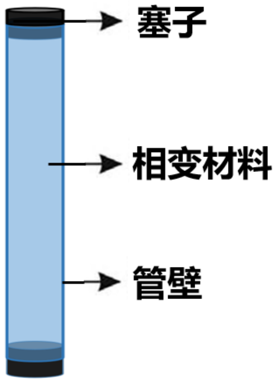
PCM energy pile heat exchange diagram



macro-encapsulate phase change materials



Stainless steel pipe



Study on use of PCM-HSB concrete for high performance in energy piles

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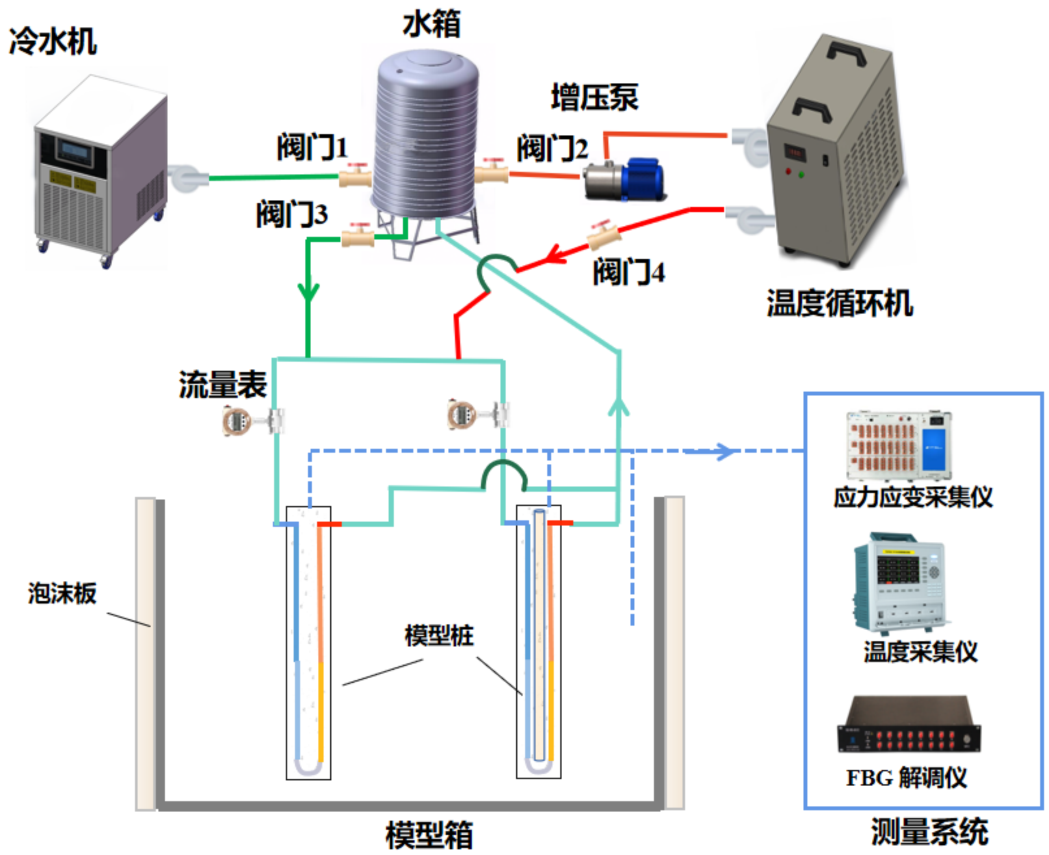
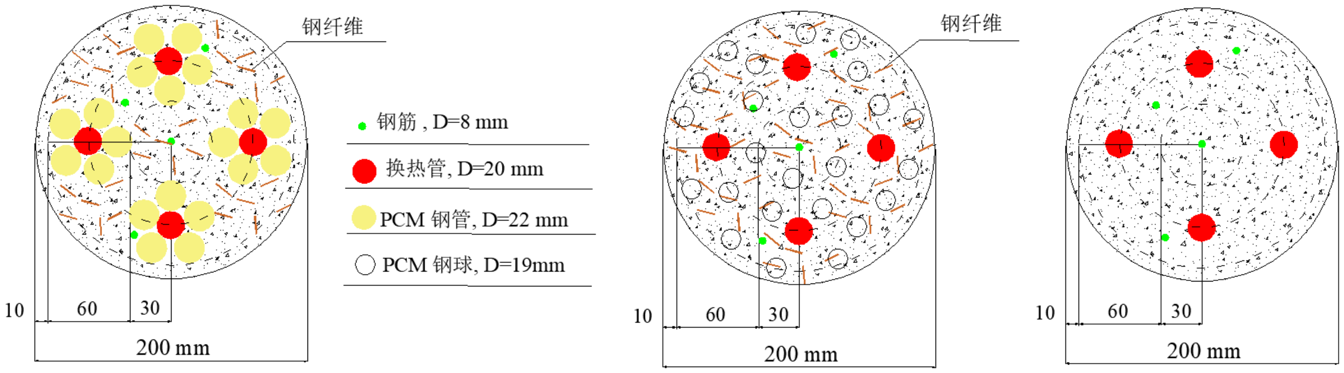


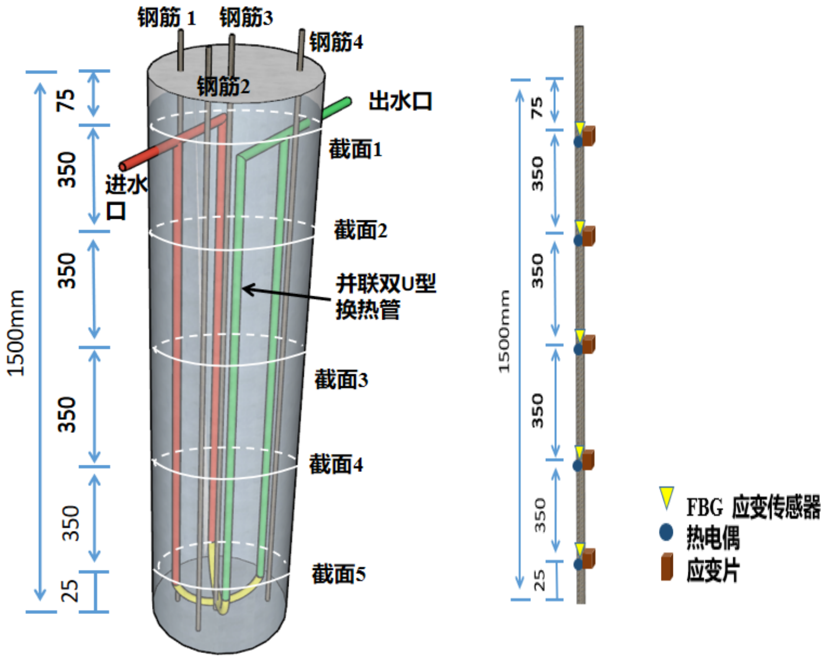
Energy pile test system model

Study on use of PCM-HSB concrete for high performance in energy piles

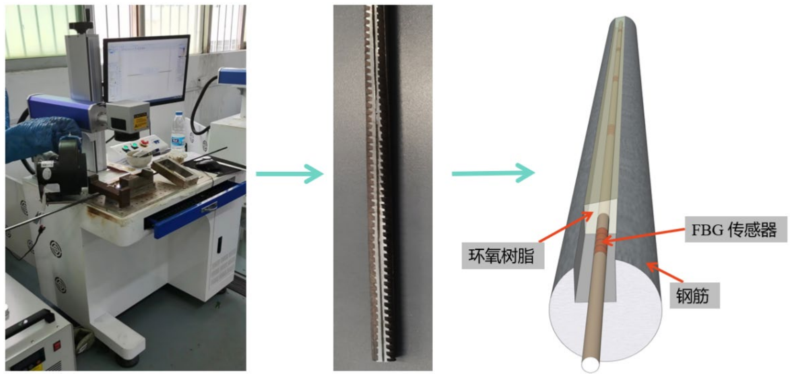
Energy Piles Design



钢管相变桩截面位置　　钢球相变桩截面位置　　普通桩截面位置



传感器粘贴　　钢筋和 PCM 钢管固定　　浇桩　　三根模型桩养护完成



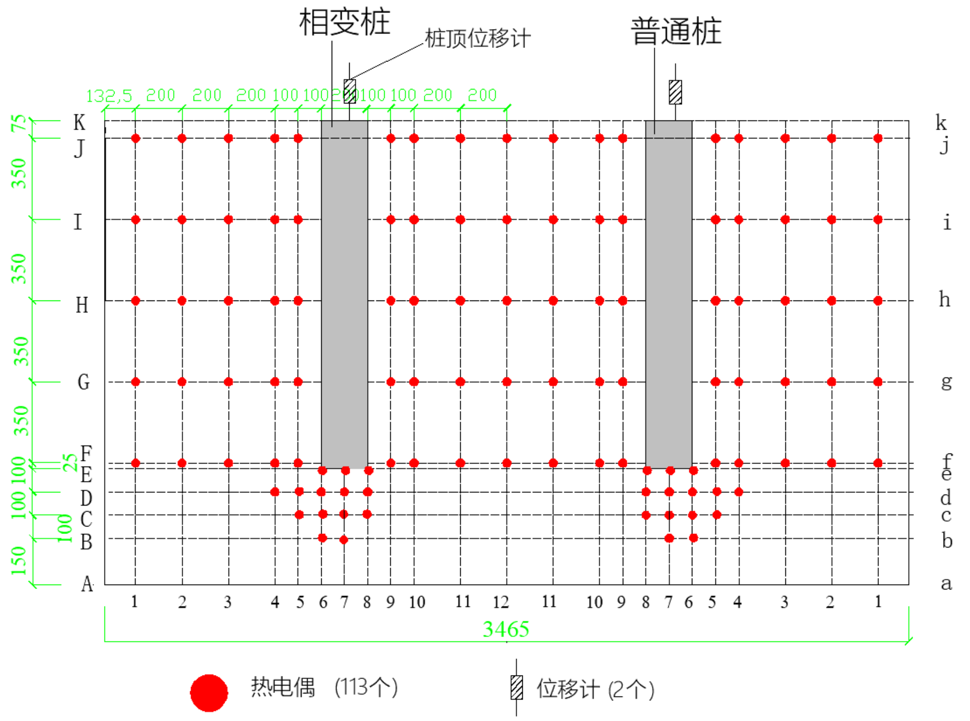
激光刻槽　　刻槽后的钢筋　　粘贴FBG 应变裸纤

Study on use of PCM-HSB concrete for high performance in energy piles

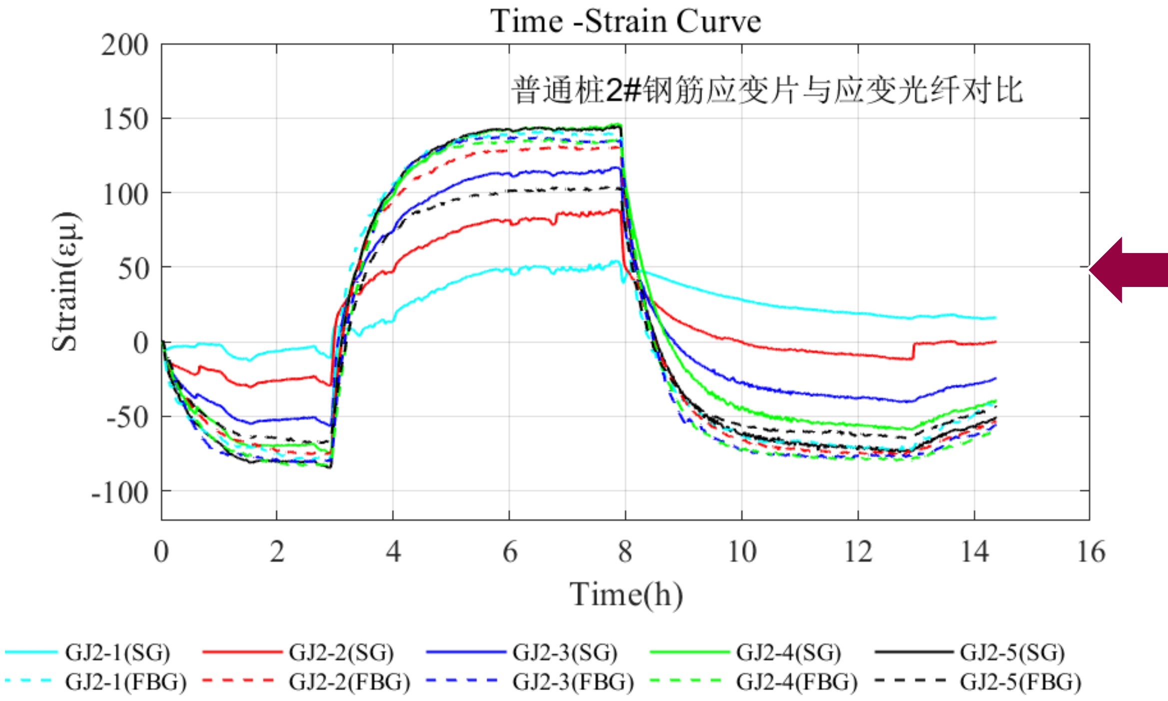
Concrete Mix Proportion (1m³) in Energy Piles

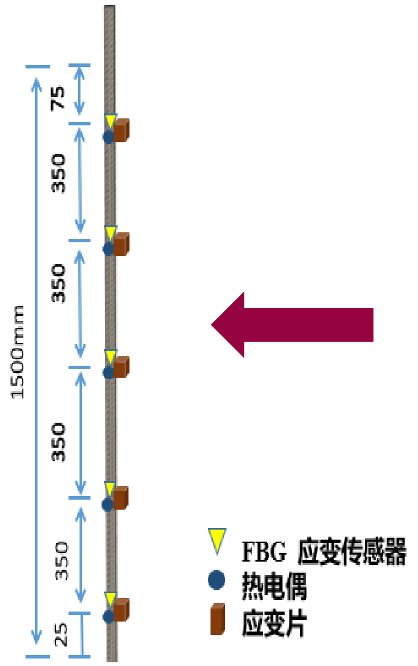
材料	水 (kg)	水泥 (kg)	粉煤灰 (kg)	砂 (kg)	5-10 mm 碎石 (kg)	10-19 mm 碎石 (kg)	相变钢球 (kg)	钢纤维 (kg)	减水剂 (%)
普通混凝土	162.8	407.1	174.5	659	110	864	—	—	0.250 %
普通钢纤维混凝土	162.8	407.1	174.5	649	974	—	—	39	0.44%
钢纤维相变钢球混凝土	162.8	407.1	174.5	649	110	302.4 (864*0.35)	314.6	39	0.229 %

Locations of Thermocouple



Study on use of PCM-HSB concrete for high performance in energy piles





Comparison of the measurement results of a steel bar strain gauge and strain fiber in the pile

应变片测量的温度影响系数

- 电阻片的热膨胀
- 温度对电阻本身的影响
- 导线受热长度的影响

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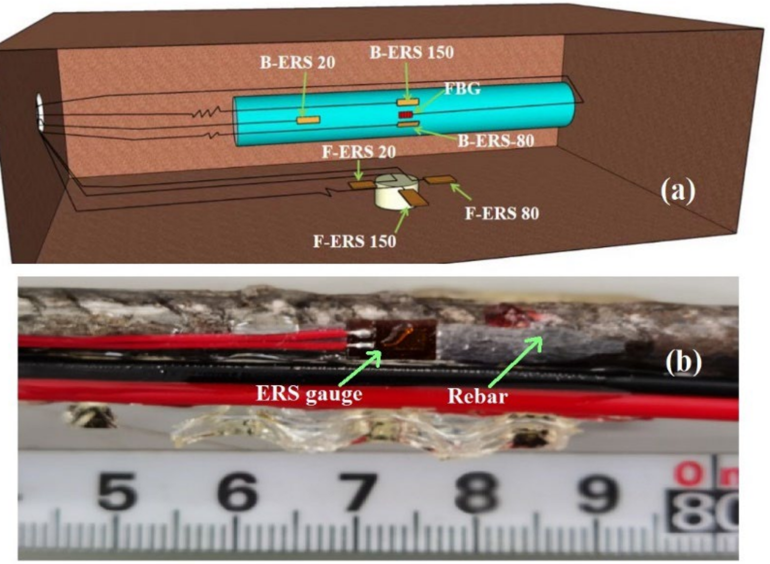
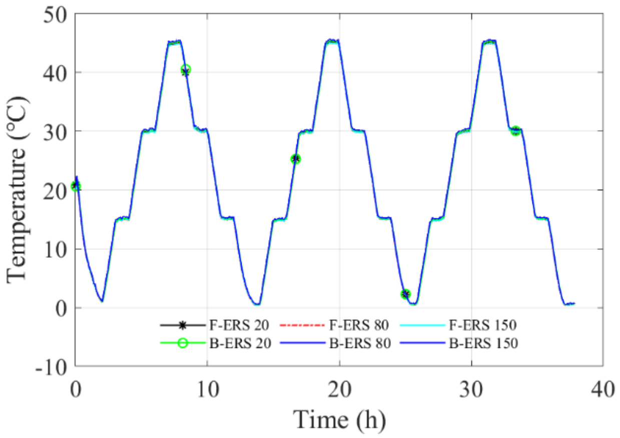
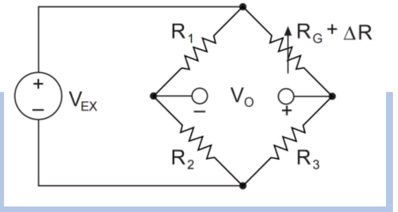
Temperature calibration of strain gauges



Strain gauge position



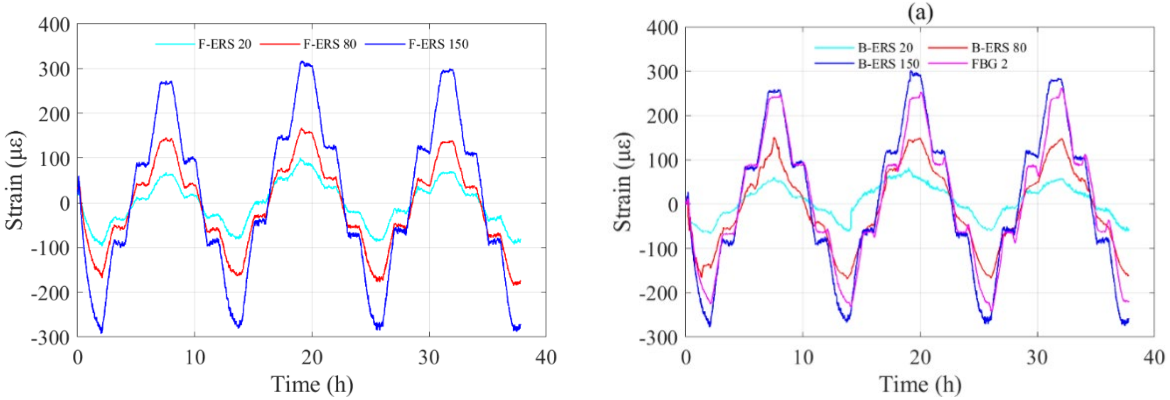
Temperature change during calibration



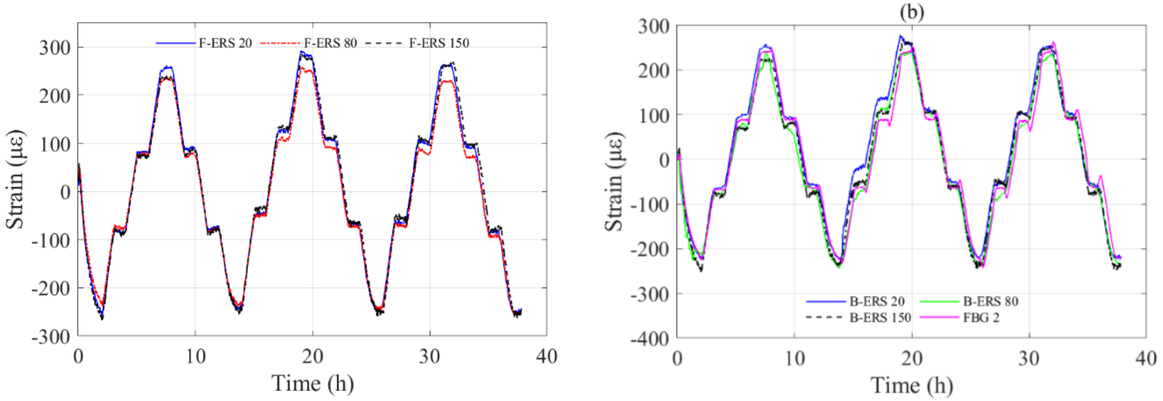
➢ 应变片温度输出计算公式：

$$\varepsilon_{T/O} = \frac{\left(\frac{\Delta R}{R_G}\right)_{T/O}}{GF} = \frac{\left(\frac{\Delta R}{R_G}\right)_{gauge} + \left(\frac{\Delta R}{R_G}\right)_{cable}}{GF}$$

➢ 应变片自身以及连接导线的温度输出均会对应变测量造成严重的影响



Readings of strain gauge and strain fibre before correction



Strain readings after correction

Study on use of PCM-HSB concrete for high performance in energy piles

Results of energy piles in the air (5 hours)

Test No.	运行模式	流速（m³/h)	环境温度（°C)
1	14 °C (3h)-40 °C (5h)-14 °C (5h)-自然回温	0.1	24.7
2	14 °C (3h)-40 °C (5h)-自然回温	0.05	24.5
3	14 °C (3h)-40 °C (5h)-自然回温	0.1	21.2
4	14 °C (3h)-40 °C (5h)-自然回温	0.15	24.3
5	14 °C (3h)-35 °C (5h)-11 °C (5h)- 自然回温	0.1	25.3
6	14 °C (3h)-40 °C (5h)-6 °C (5h)-自然回温	0.1	26.1

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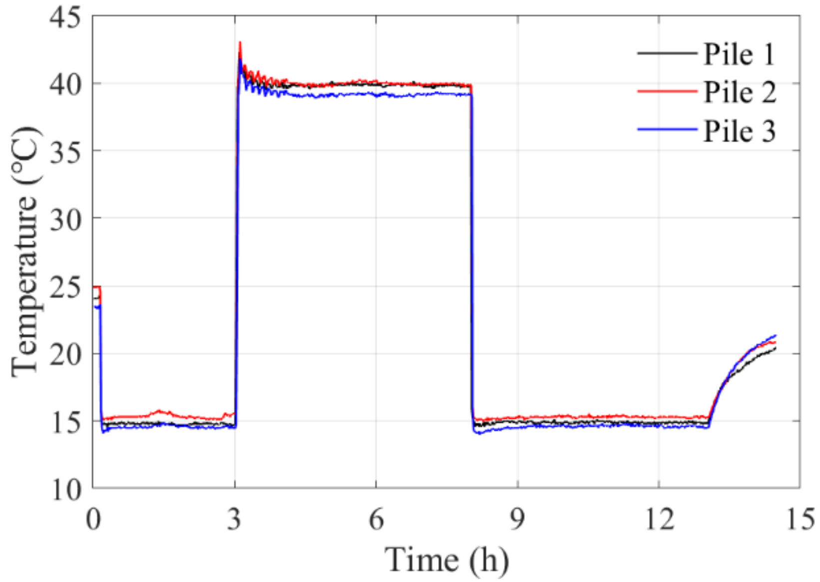
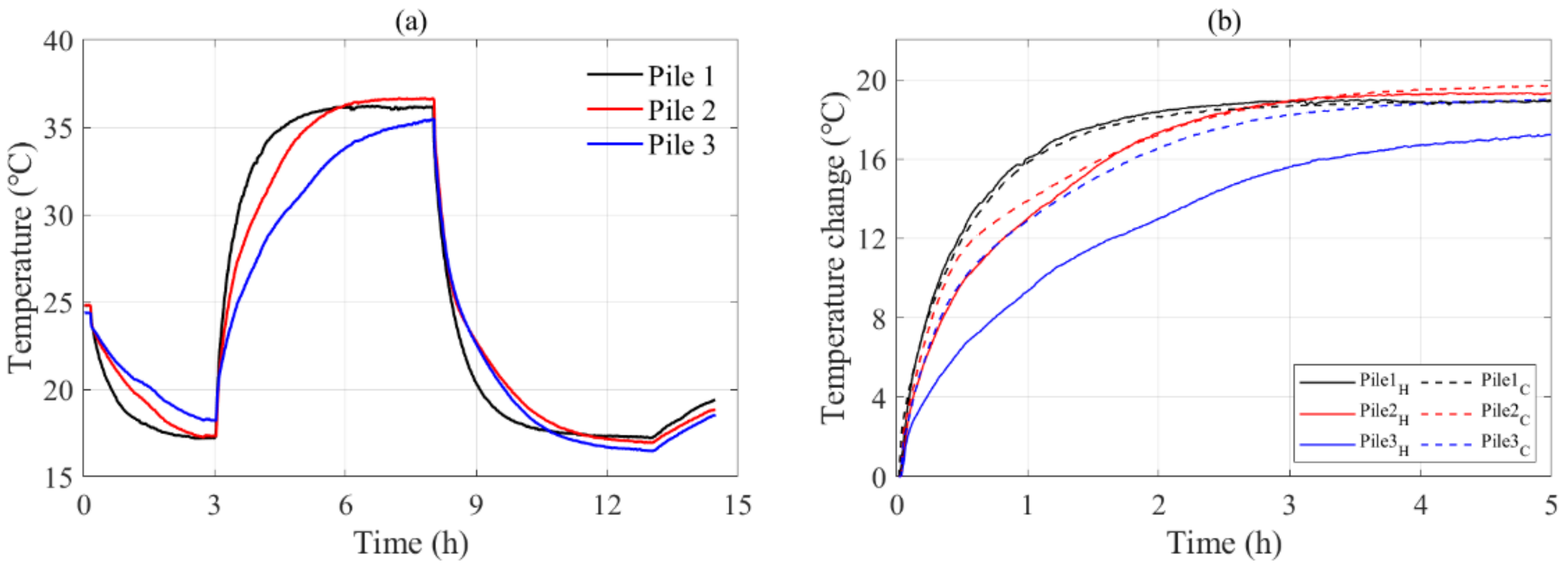
Changes in the average temperature of the pile





Temperature curve at the water inlet of the heat exchange pipe in the energy pile

- The average temperature change of Pile 1 and Pile 2 are roughly the same under heating and cooling conditions.
- The average temperature change of Pile 3 under the cooling condition is 2°C faster than the temperature change during heating.

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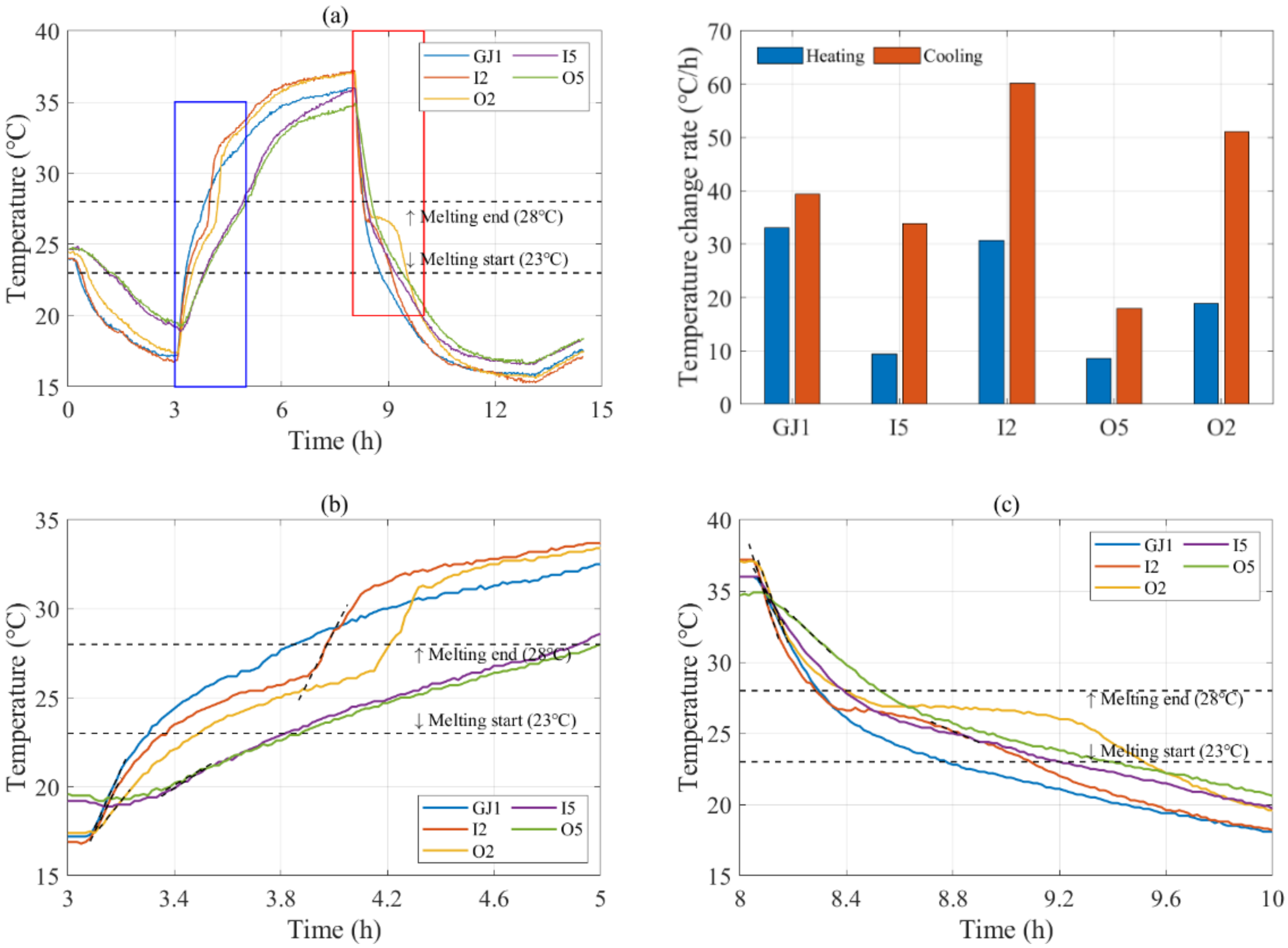
Performance of Pile 3



- During cooling down, the temperature change rate is significantly greater than when heating up.
- The phase change process takes shorter time when the temperature rises. The duration of the phase change interval at I2 and O2 is 0.55 and 0.7 hours respectively. The corresponding durations when the temperature drops are 0.85 and 1.15 hours respectively.

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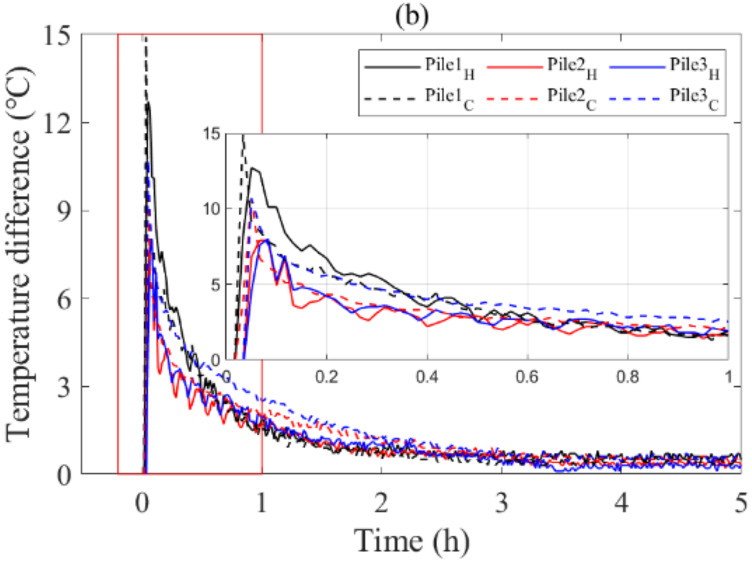
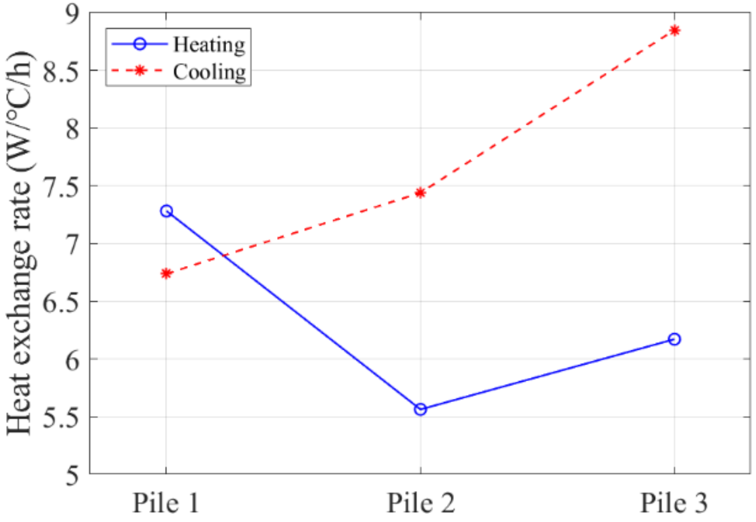
Temperature difference and heat exchange between inlet and outlet

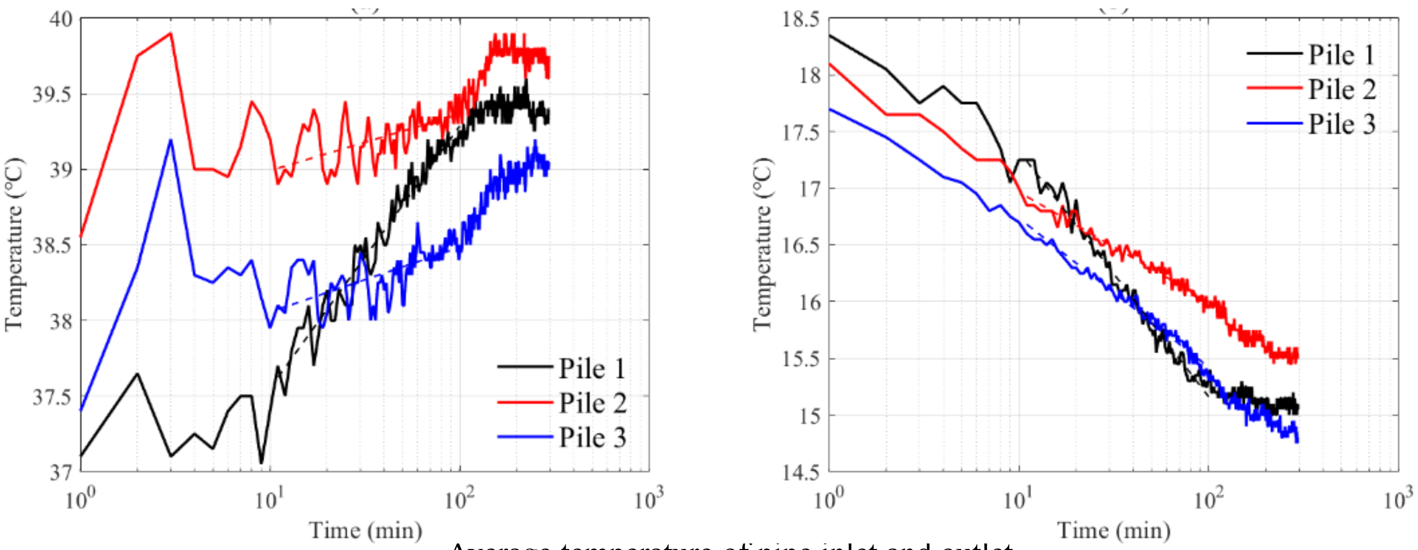


Temperature difference between inlet and outlet

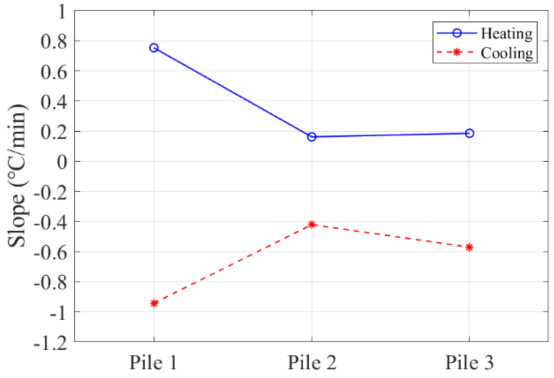


Heat exchange

- The average heat exchange of Pile 1 under heating conditions is 1.31 and 1.18 times the average heat exchange of Pile 2 and Pile 3 respectively.
- Under cooling conditions, the heat exchange of Pile 3 was 1.31 and 1.19 times the average heat exchange of Pile 1 and Pile 2 respectively.
- The unit heat exchange of Pile 2 and Pile 3 under cooling conditions is 33.7% and 43.4% higher than their respective unit heat exchanges under heating conditions.
- The absolute value of the slope of the average water inlet and outlet temperature curve of Pile 3 under the cooling condition is twice greater than that under the heating condition



Average temperature of pipe inlet and outlet



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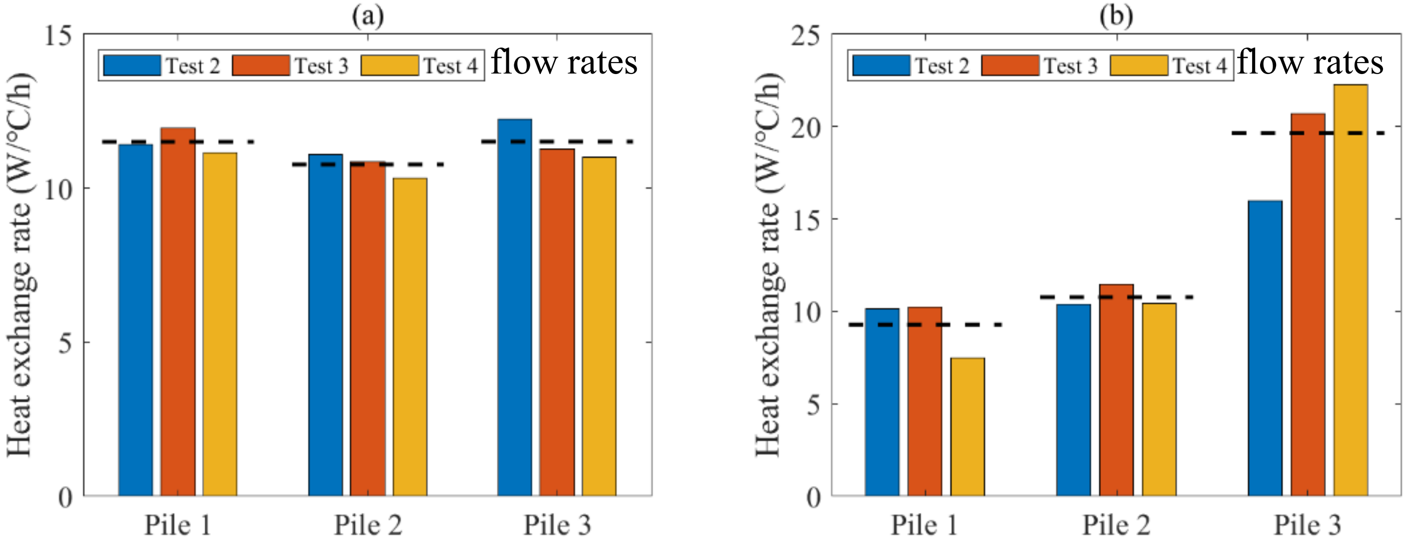
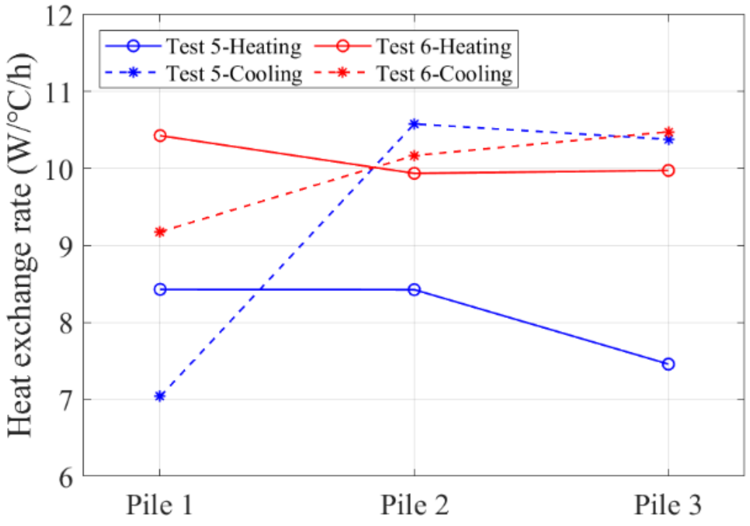
Temperature difference and heat exchange between water inlet and outlet



Comparison of heat exchange rate of each pile under different flow rates
(a) heating condition, (b) cooling condition at inlet and outlet

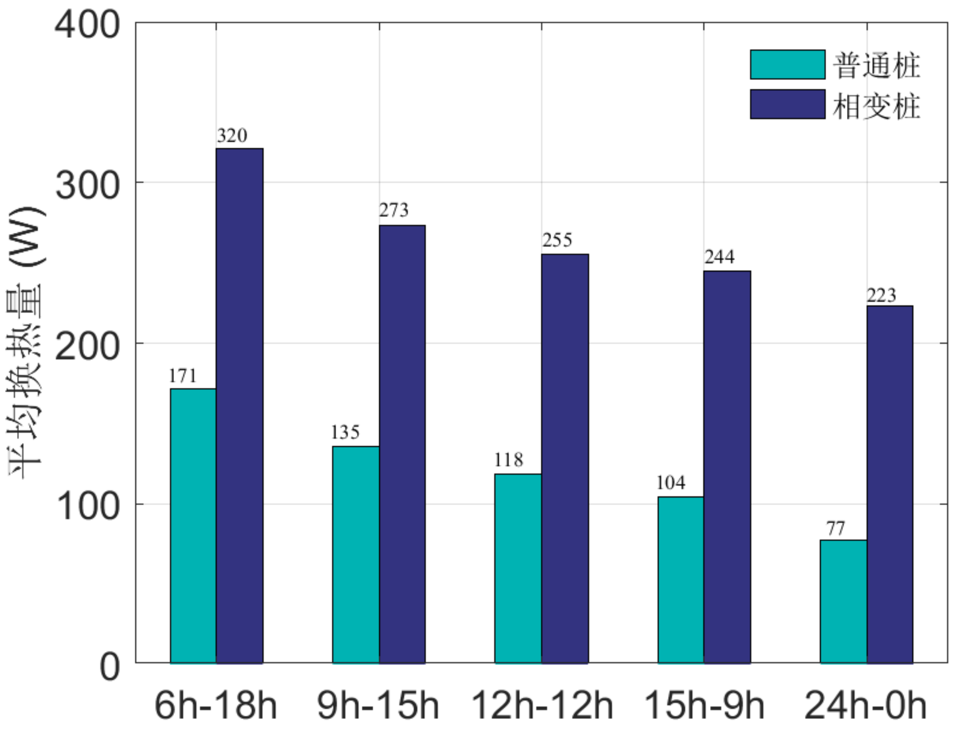


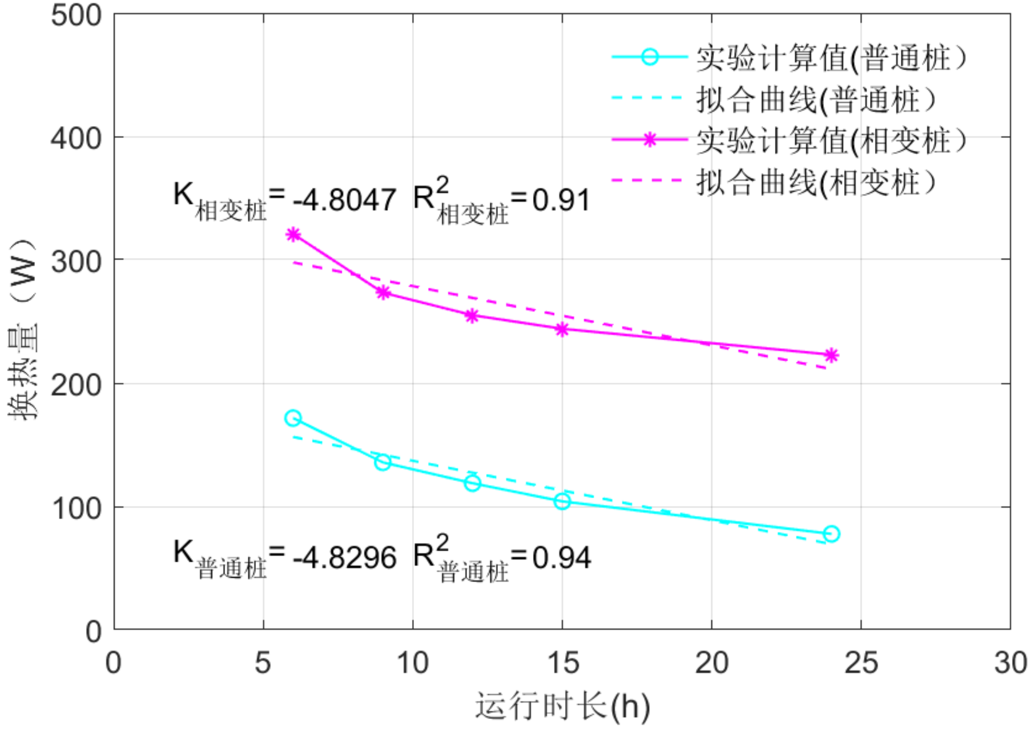
不同升降温幅度的影响

- The flow rate has little effect on the heat exchange efficiency, especially under heating conditions. The average heat exchange rate of the three piles in the different flow rate experiments is 10.64, 10.15 and 10.67 W/(°C·h) respectively, with a difference of less than 5%.
- Increasing the heating amplitude can effectively improve the heat exchange efficiency of energy piles, while increasing the temperature cooling amplitude has no significant effect on improving the heat exchange efficiency of energy piles, especially for phase change piles.

Study on use of PCM-HSB concrete for high performance in energy piles

Effect of running time on heat exchange efficiency

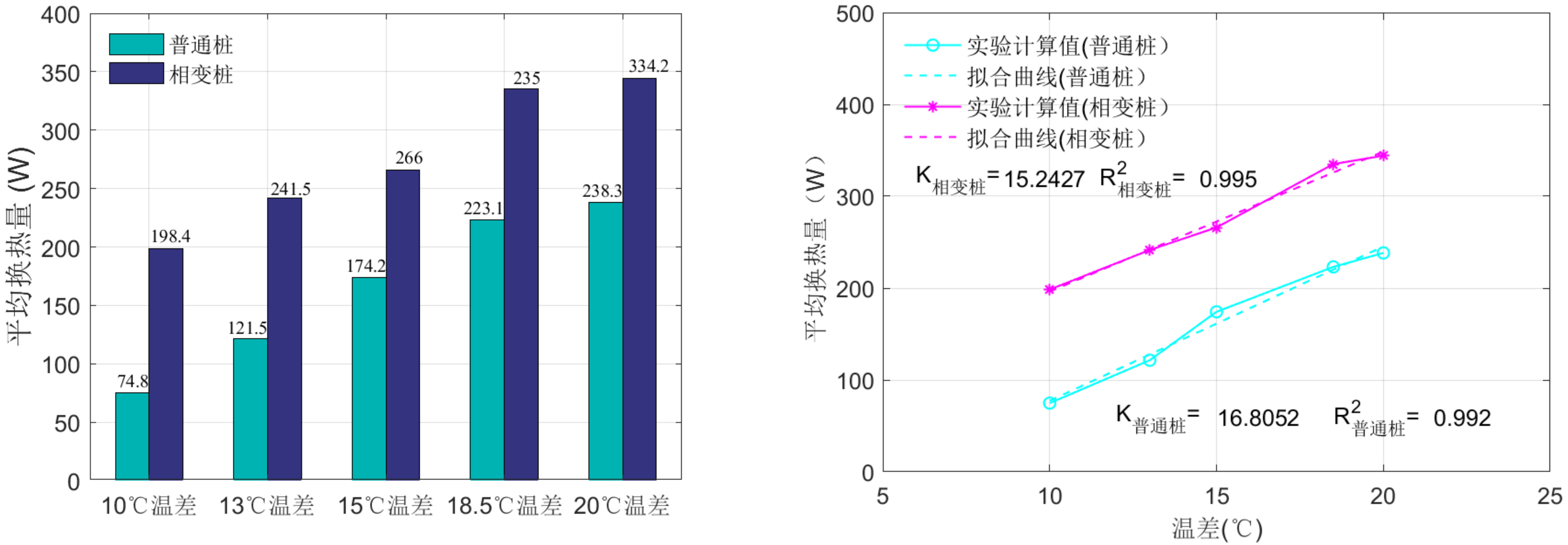




- ➢ As the running time increases, the heat exchange decreases. The relationship between running time and heat exchange is linear.

Study on use of PCM-HSB concrete for high performance in energy piles

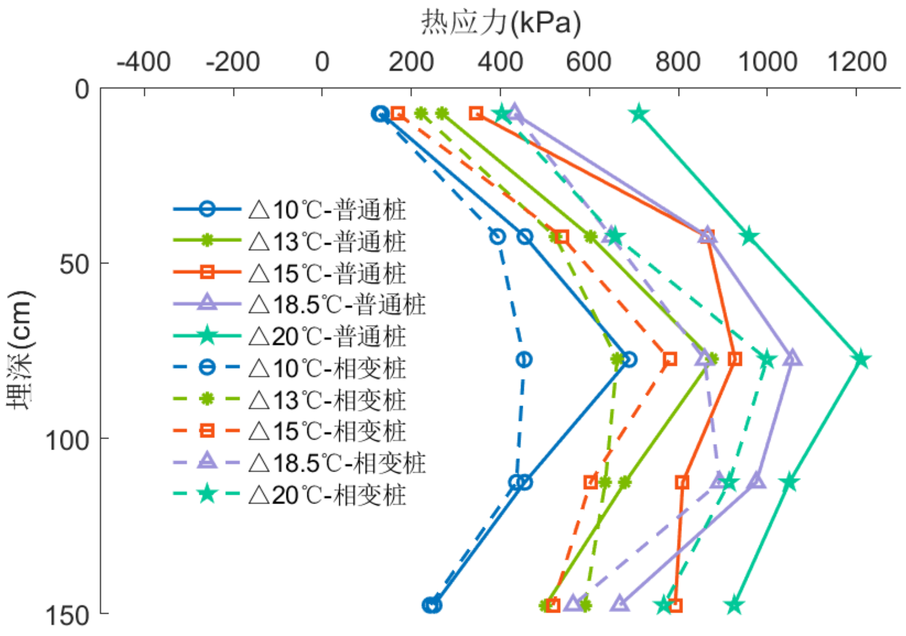
Effect of temperature difference on heat exchange efficiency

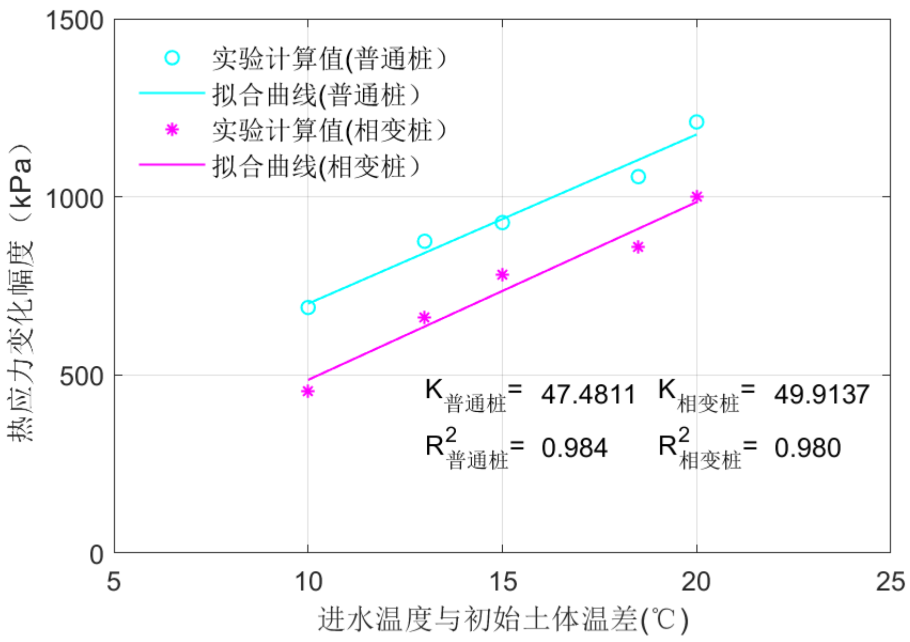


- There is a linear relationship between the average heat exchange of the energy pile and the temperature difference between the soil temperature. It can be seen that the average heat exchange of the phase change pile is higher than that of ordinary piles.

Study on use of PCM-HSB concrete for high performance in energy piles

Effect of temperature difference on thermal stress in piles





- ➢ The thermal stress of phase change piles is smaller than that of ordinary piles
- ➢ It is a linear relationship between the thermal stress in the pile and the temperature difference between the initial soil temperature and the heat exchange fluid.

Advantage of using PCM in energy pile

- There is a linear relationship between the average heat exchange of the energy pile and the temperature difference between the soil temperature.
- The average heat exchange of the phase change pile is higher than that of ordinary piles. The average temperature change of PCM pile under the cooling condition is 2°C faster than the temperature change during heating.
- The flow rate has little effect on the heat exchange efficiency, especially under heating conditions, with a difference of less than 5%.

Conclusions

1) Phase Change Materials (PCMs) Energy Storage Technology is an innovative material contributing active solution towards carbon neutrality.
2) PCMs serves as highly efficient thermal energy storage mediums, proficient in absorbing and releasing thermal or cold energy during the physical phase change.
3) The integration of PCMs into concrete changed the thermal energy storage capacity of building envelopes, thus introduced a novel temperature regulator for indoor temperature of buildings.
4) The experimental results on a competitive renewable energy exchange model study using PCM buried pipes within pile foundations demonstrated the feasible use of PCM to enhance ground-source heat pump systems and optimizing geothermal energy utilization.
5) PCMs energy storage technology contributes to the versatility and sustainability of green concrete and low carbon technology.