Thermal Strains in Concrete Pavements – Measurements and Field Implementation

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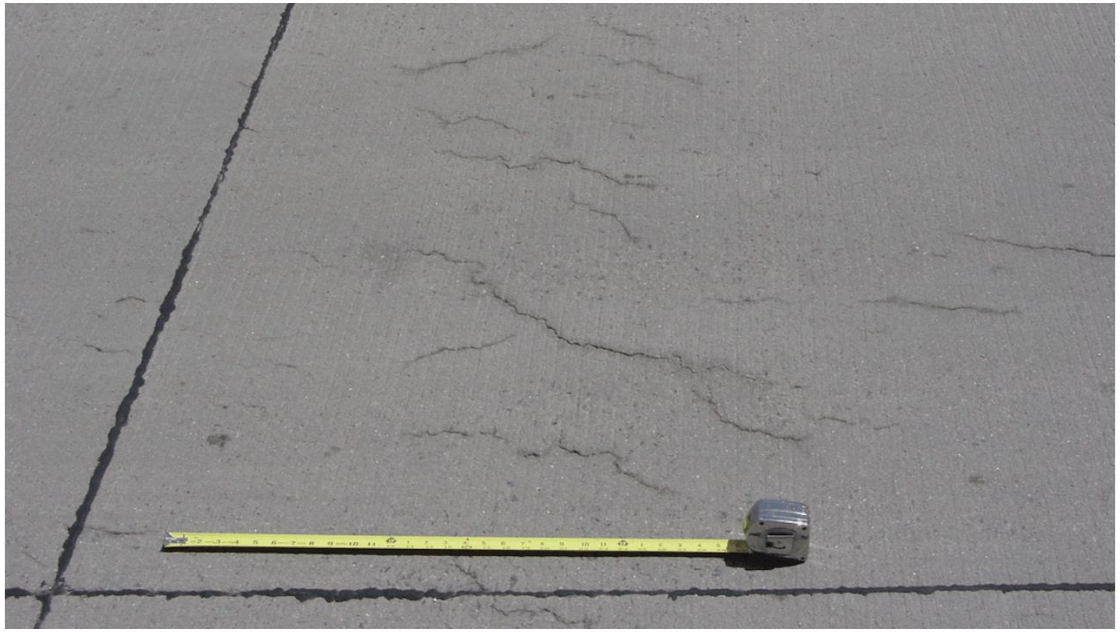

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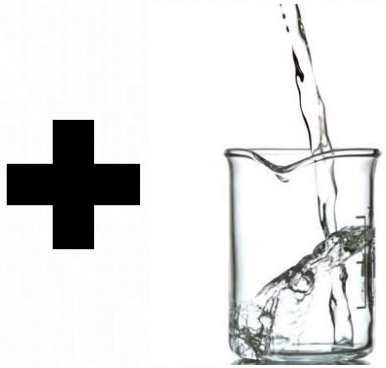
Introduction

Ordinary Portland Cement

Water

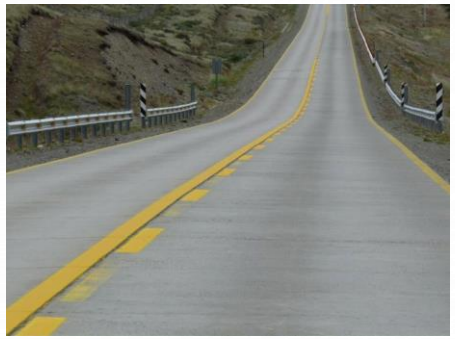


Aggregate

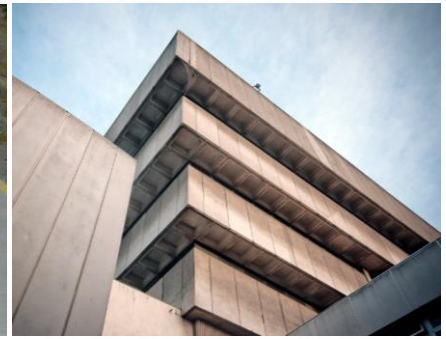
Dams

Bridges

Roadways



Buildings



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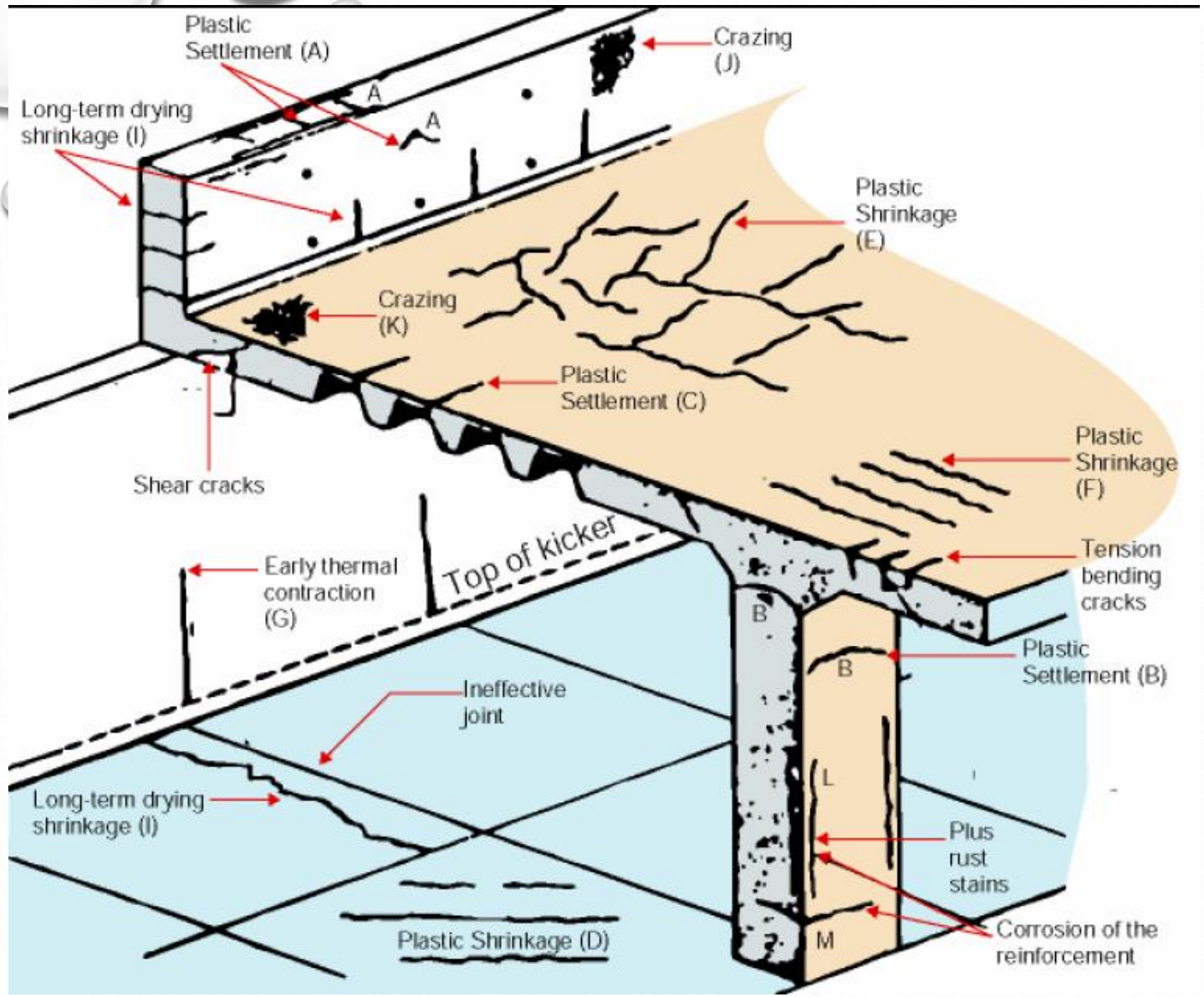
Types of Cracking

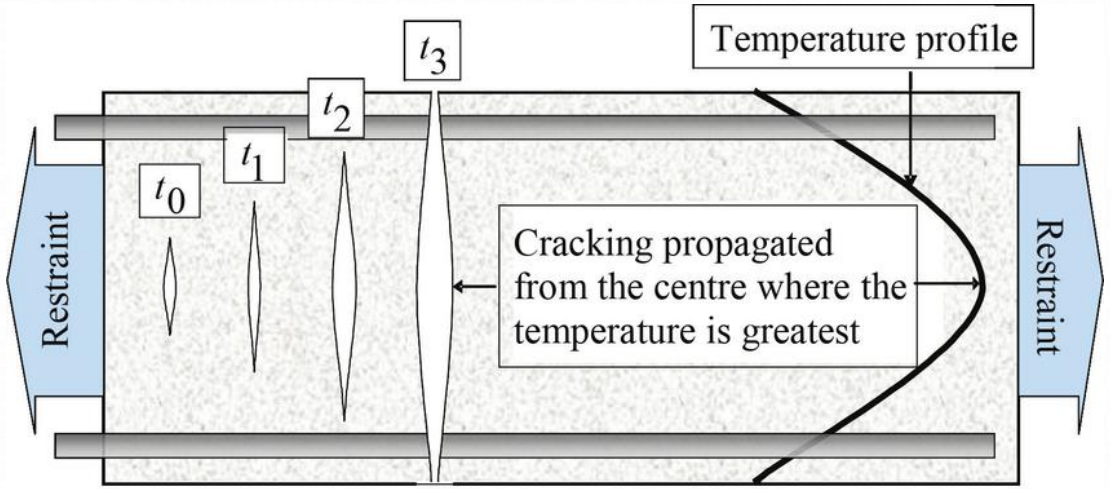


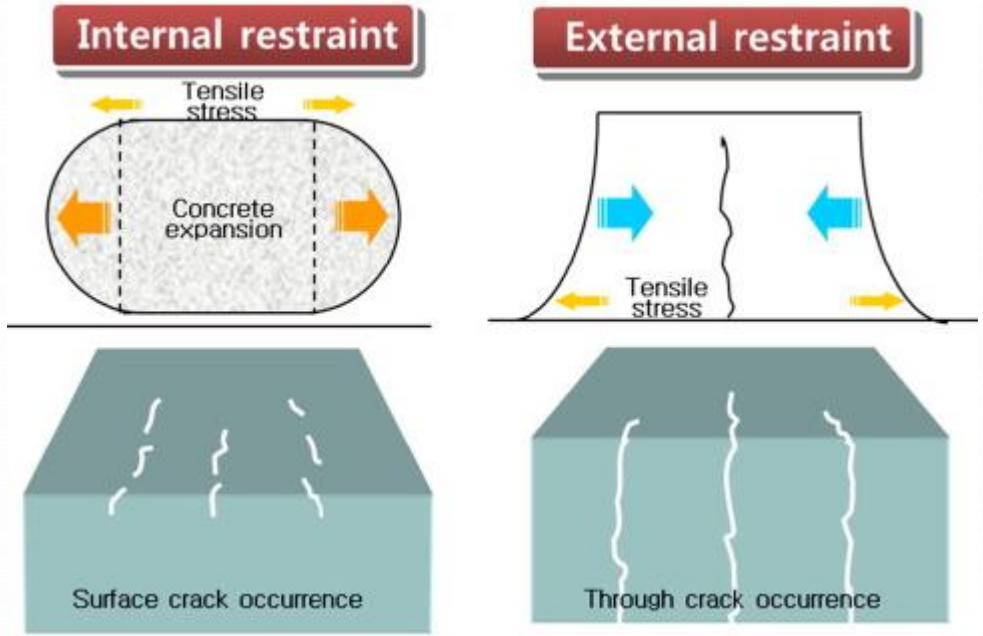
Thermal cracking

- Hydration of cement is an exothermic process it generates heat
- As the concrete cools it contracts and in extreme conditions may contract in three days as much due to cooling as it could in a year due to drying conditions
- A temperature differential of 35° F within 1 ft is usually considered enough to cause cracking
- However, within 24-hours of placement, concrete temperatures can reach anywhere from 20° to 50° F hotter than ambient temperatures

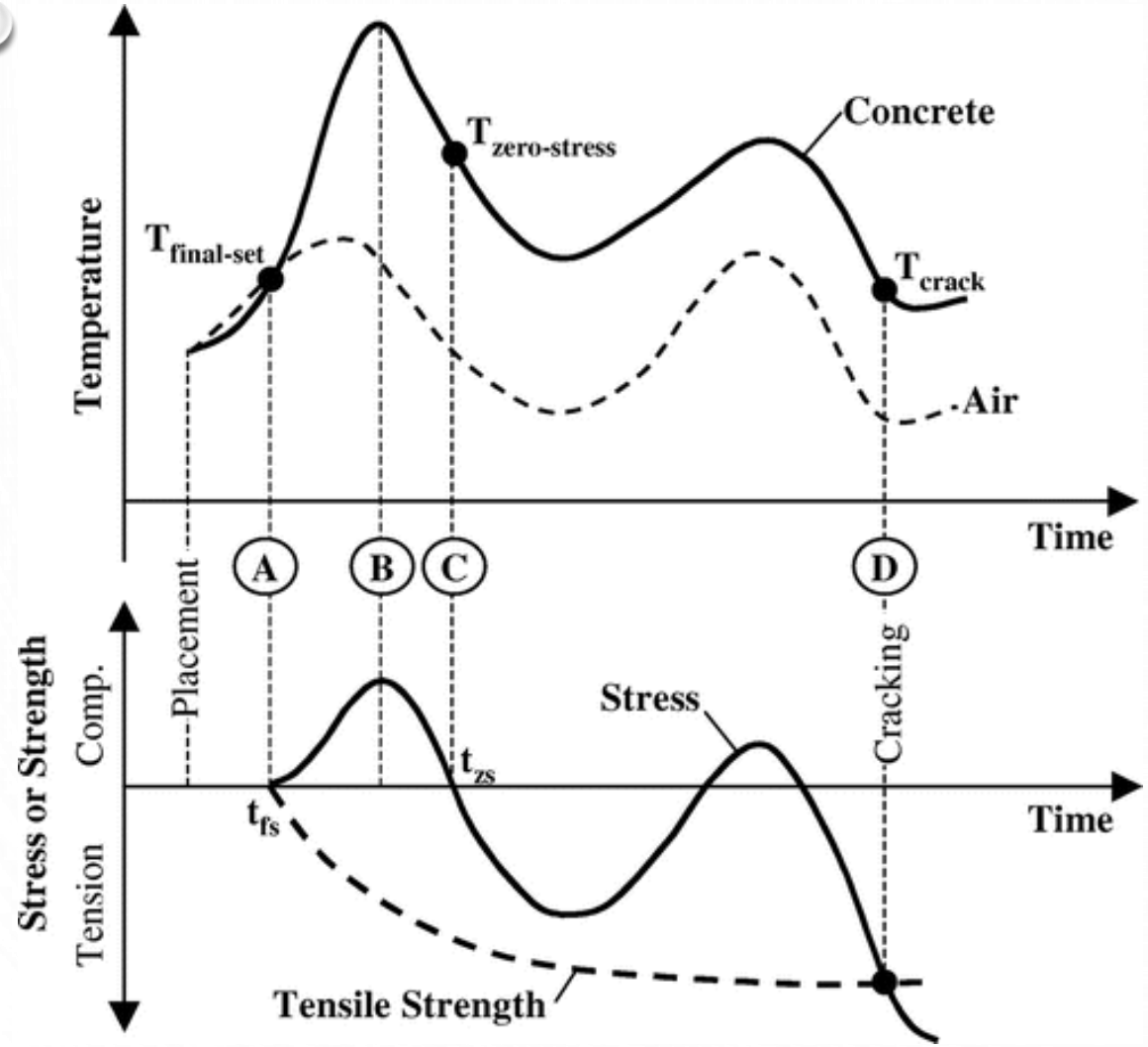
Motivation

Thermal Related Damage



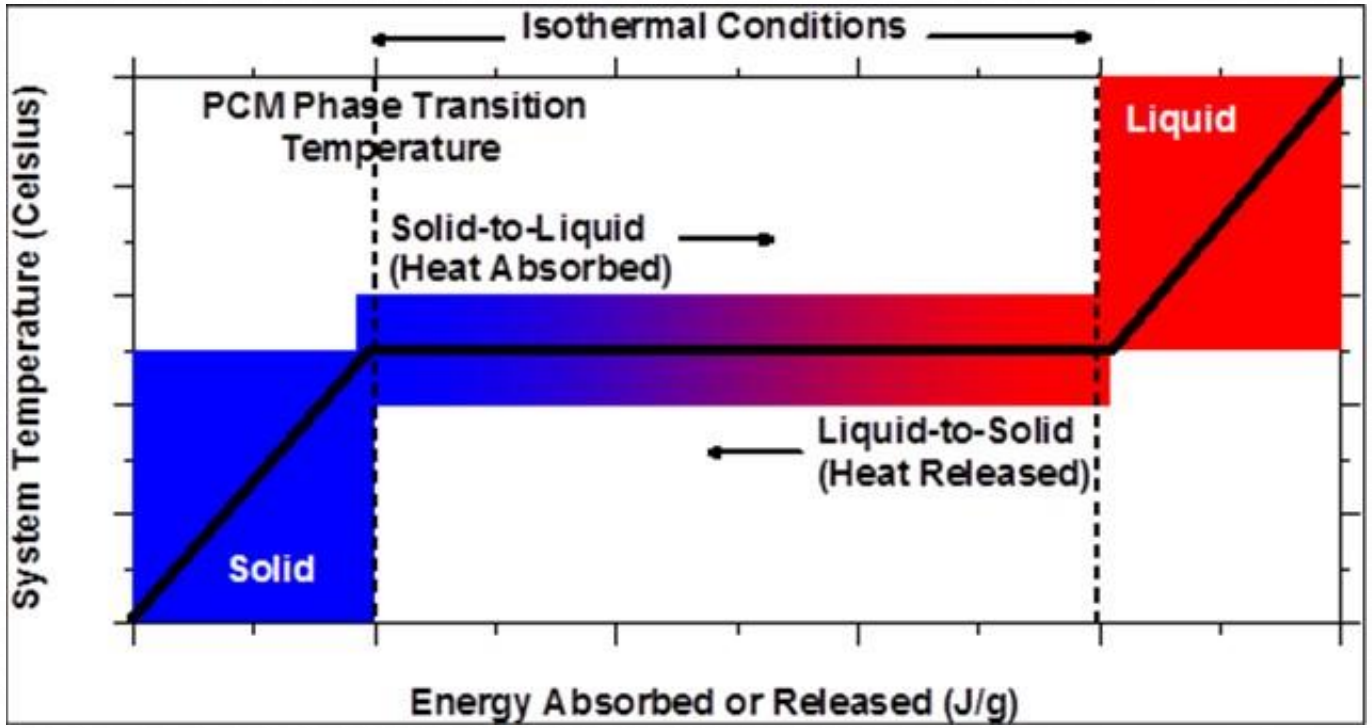


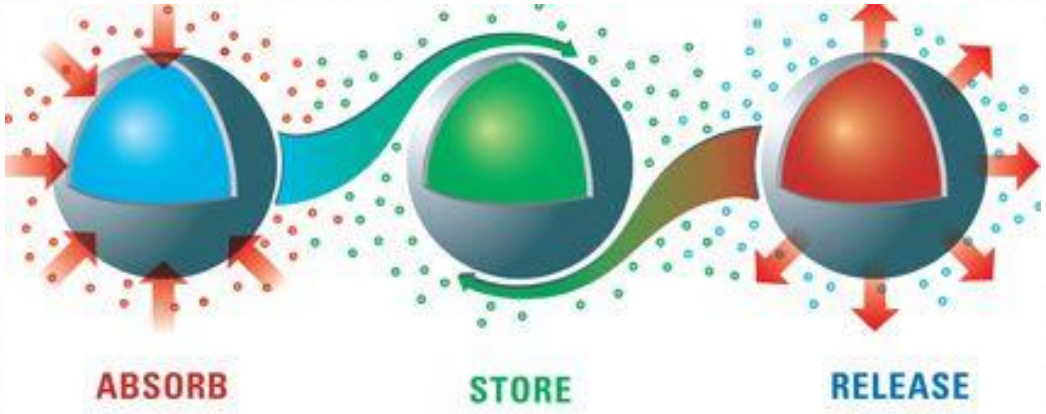
Early age cracking in infrastructure



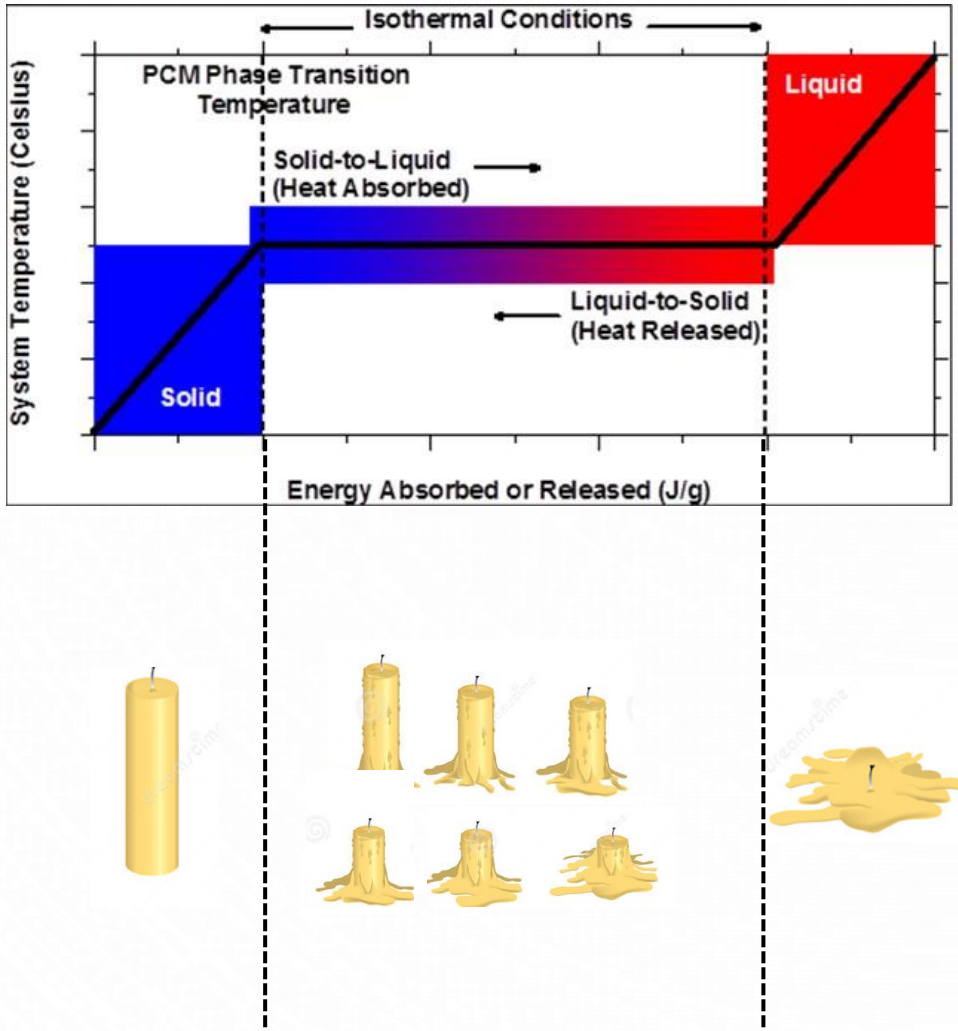
One Active Mitigation Strategy - PCMs

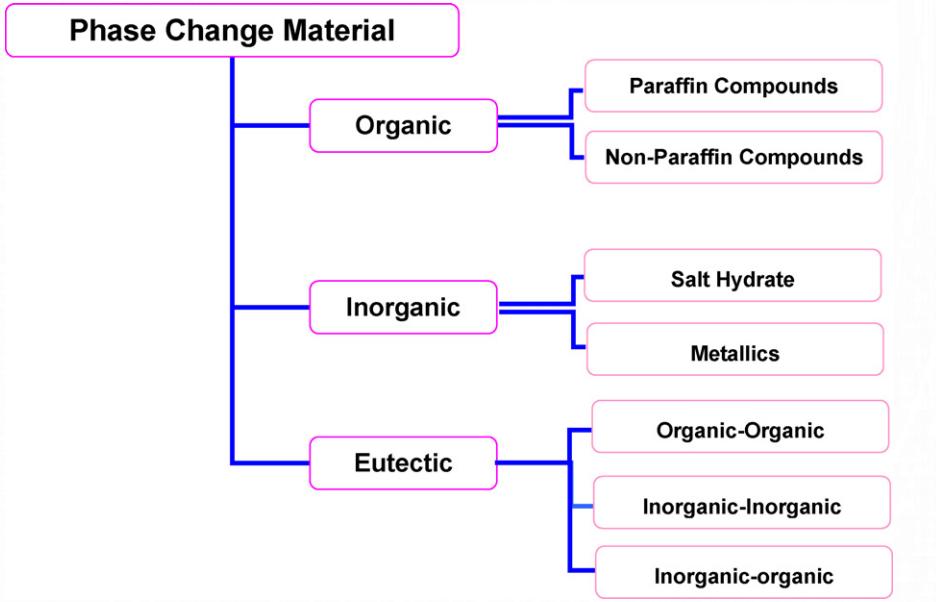
- **Phase change materials (PCM)** are combined sensible-and-latent heat materials that can be used to store and dissipate energy in the form of heat

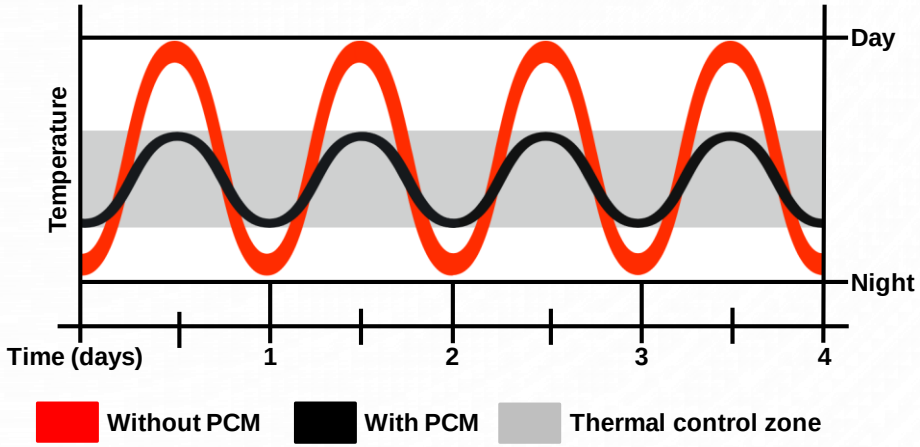




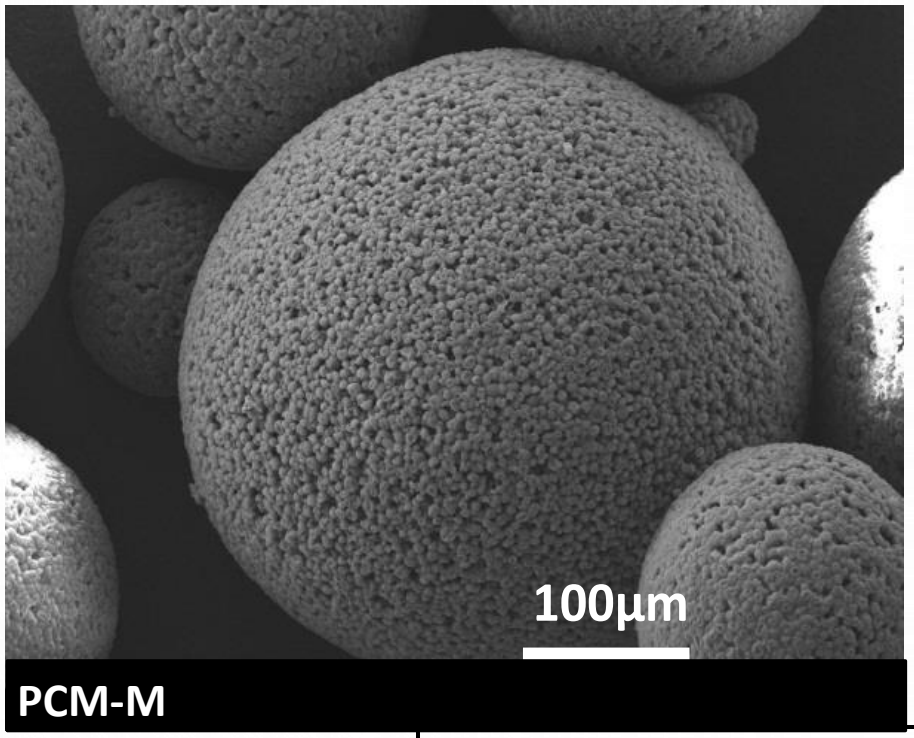
Background

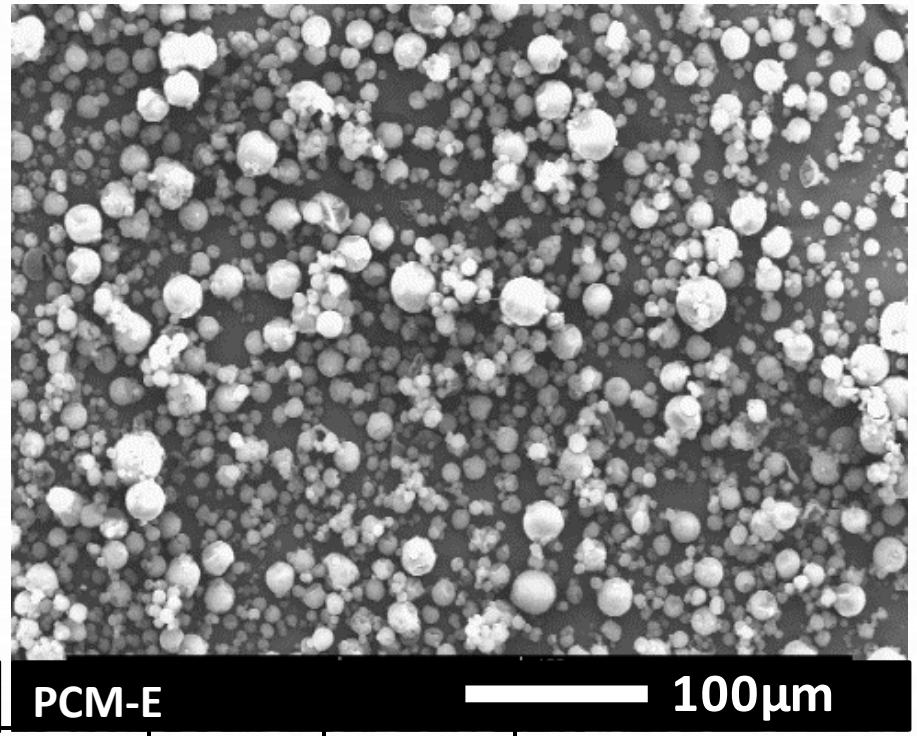

Isothermal Conditions
PCM Phase Transition Temperature
Liquid
Solid-to-Liquid (Heat Absorbed)
Liquid-to-Solid (Heat Released)
Solid
System Temperature (Celsius)
Energy Absorbed or Released (J/g)


Phase Change Material
Organic
Paraffin Compounds
Non-Paraffin Compounds
Inorganic
Salt Hydrate
Metallics
Eutectic
Organic-Organic
Inorganic-Inorganic
Inorganic-organic


Day
Temperature
Night
Time (days)
1
2
3
4
Without PCM
With PCM
Thermal control zone

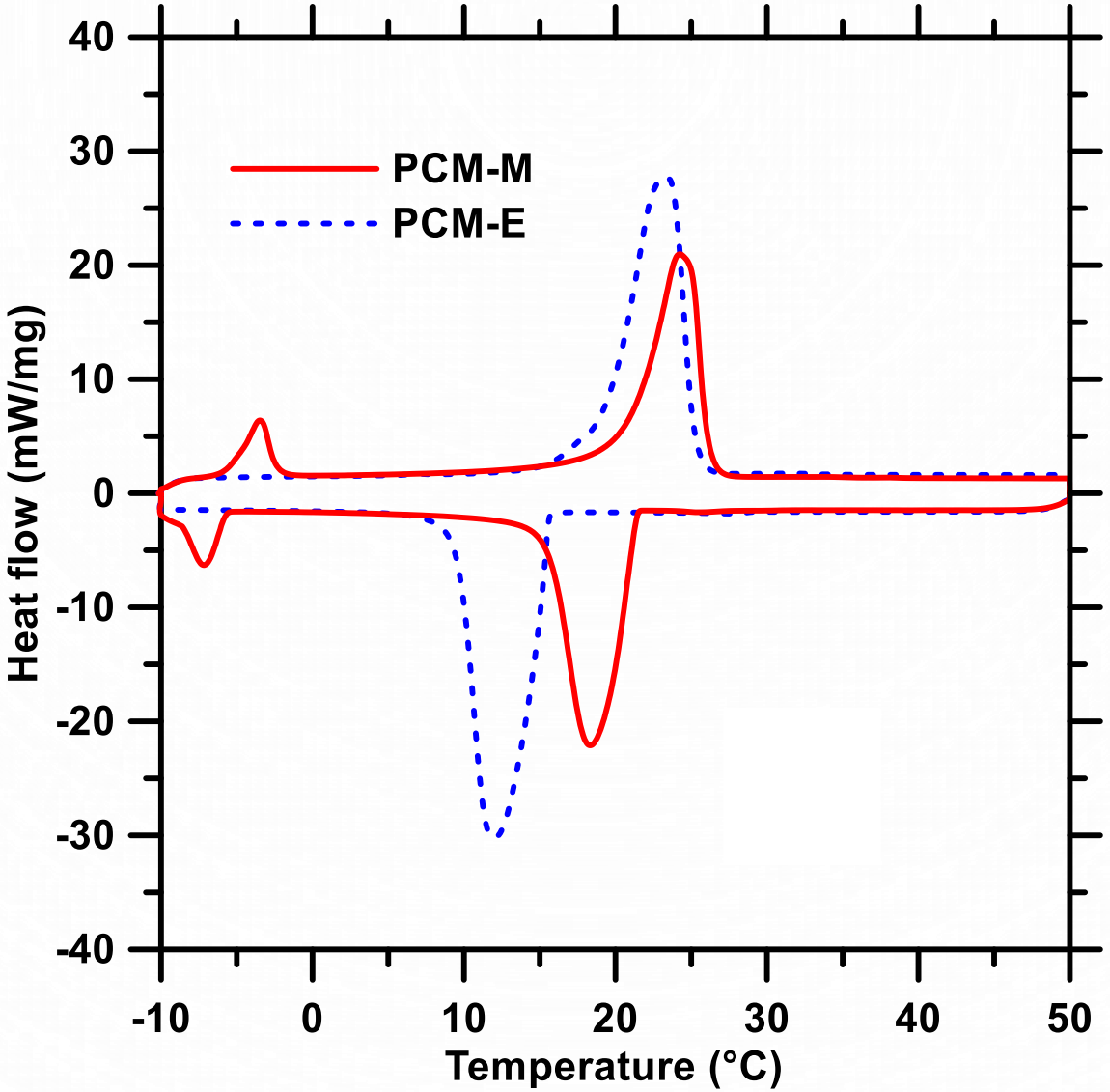
Microencapsulated PCM Type



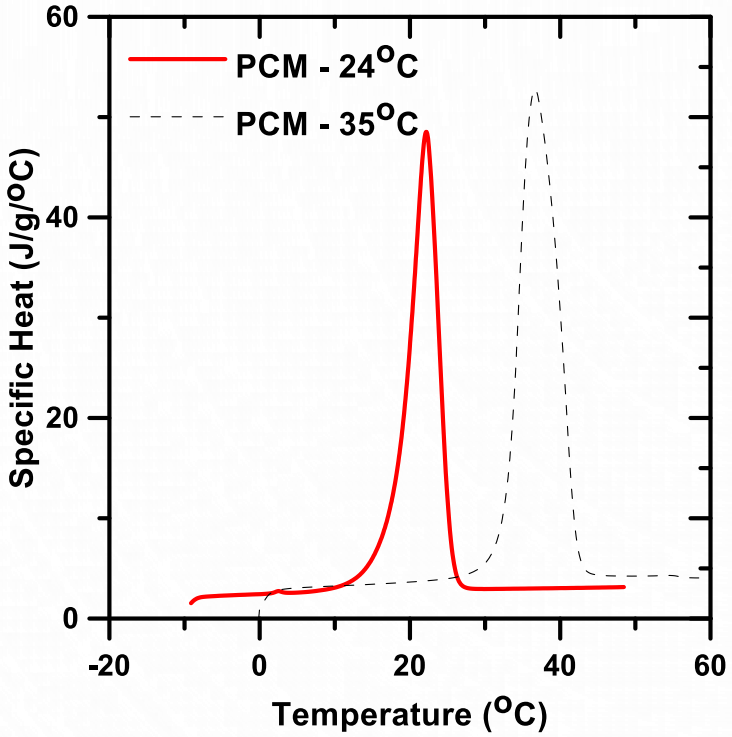


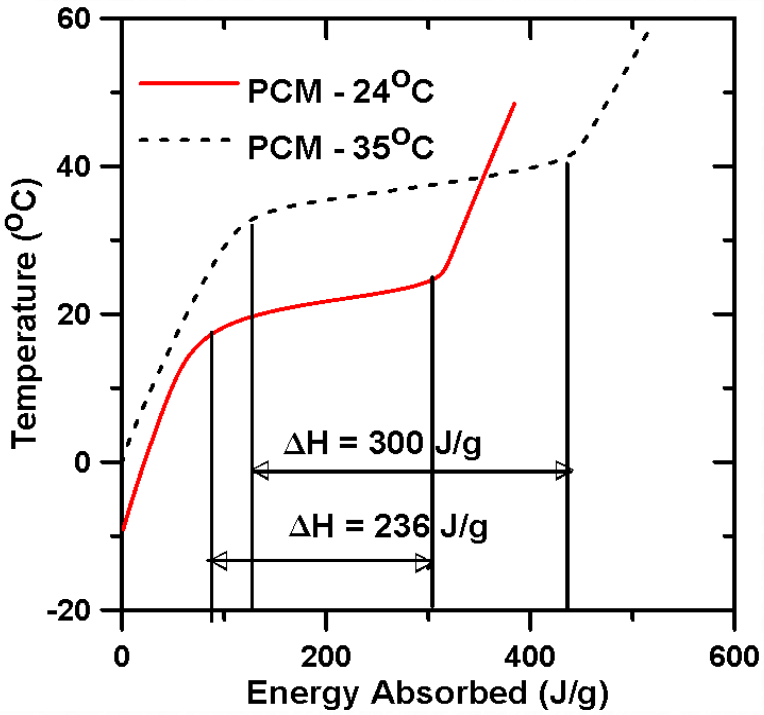
Chemical Composition	PCM-M	PCM-E
Paraffin wax (%)	69.50	90.22
Polymeric capsule (%)	20.70	7.67
Residue (%)	9.80	2.10
Core-to-shell ratio (mass-based)	3.4	11.8

Thermal Energy Storage



Characterization of Phase Change Materials

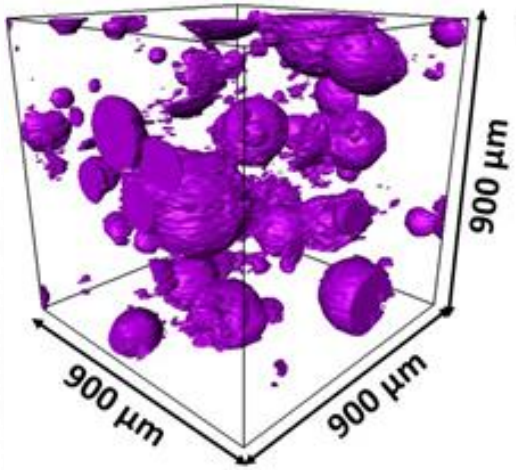


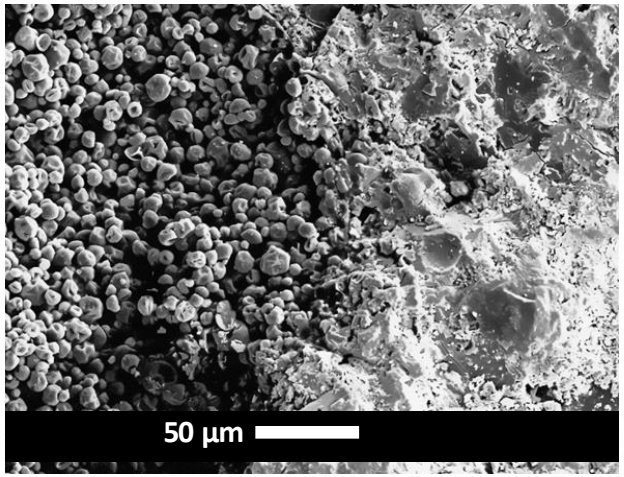


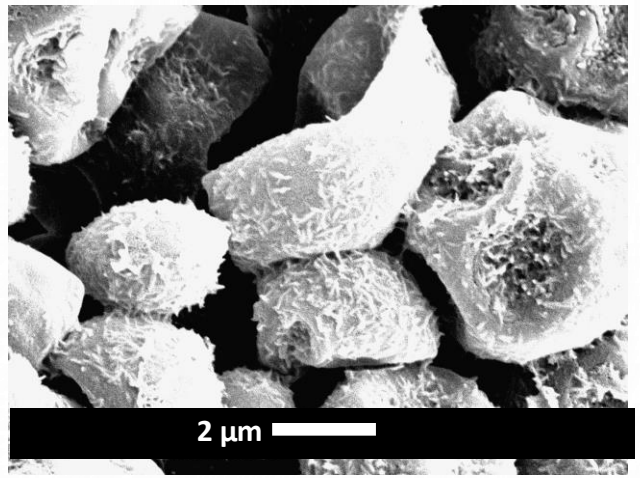
- PCMs absorb and release heat, which scales as a function of their dosage and enthalpy of phase change.
- During the phase transition, the PCM stores latent heat energy, helping to maintain a constant system temperature

Matrix Dispersion

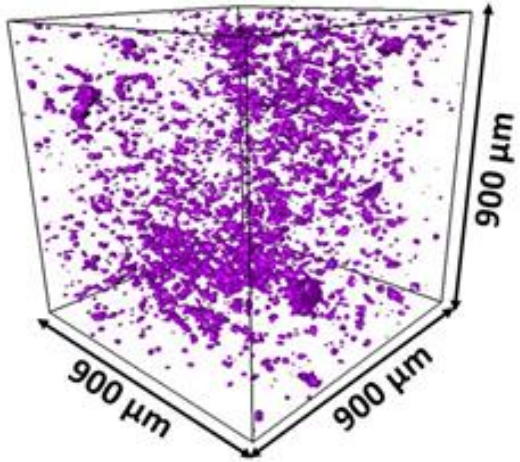
10% PCM-M by vol.

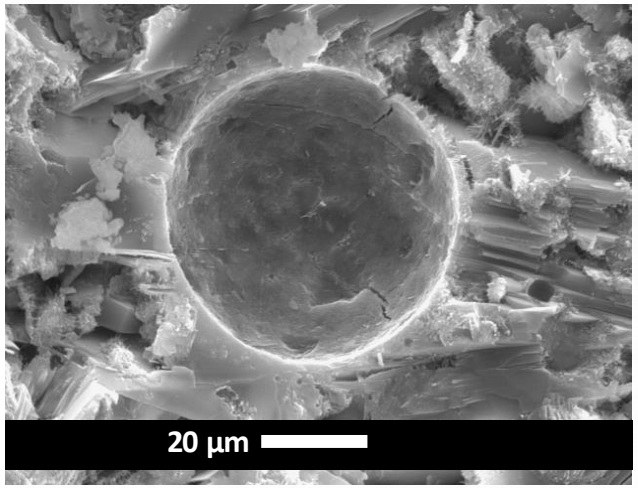


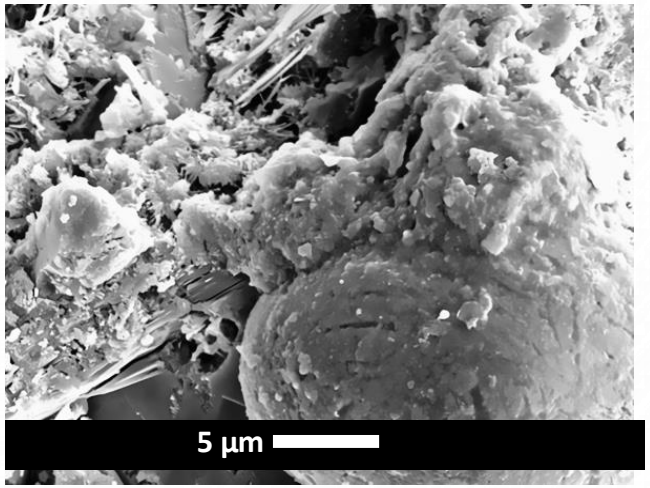




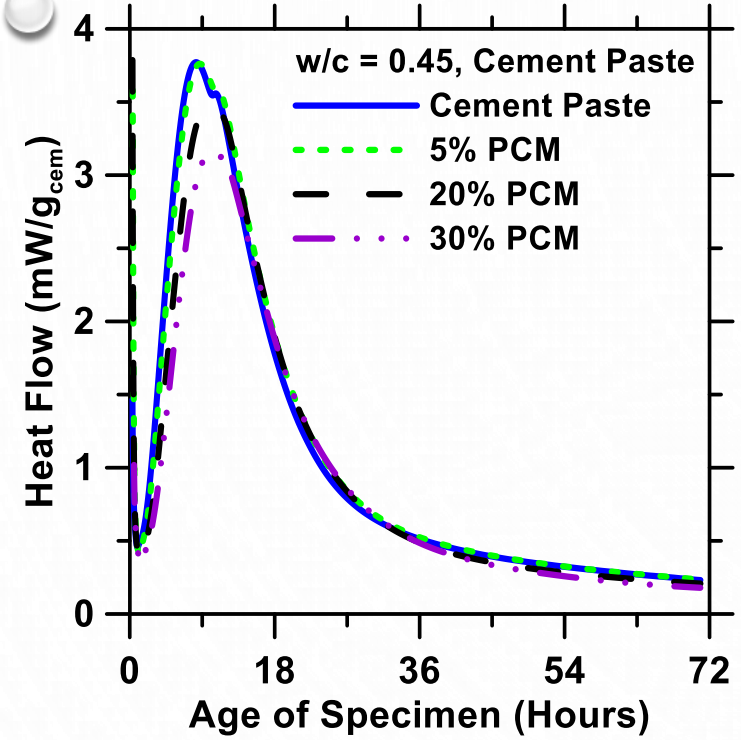
10% PCM-E by vol.

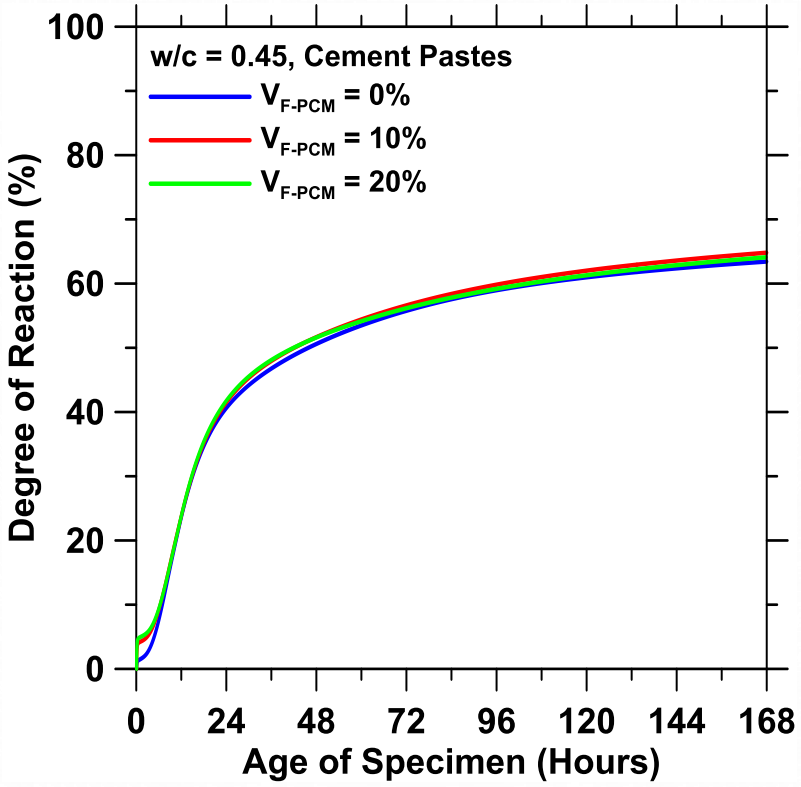


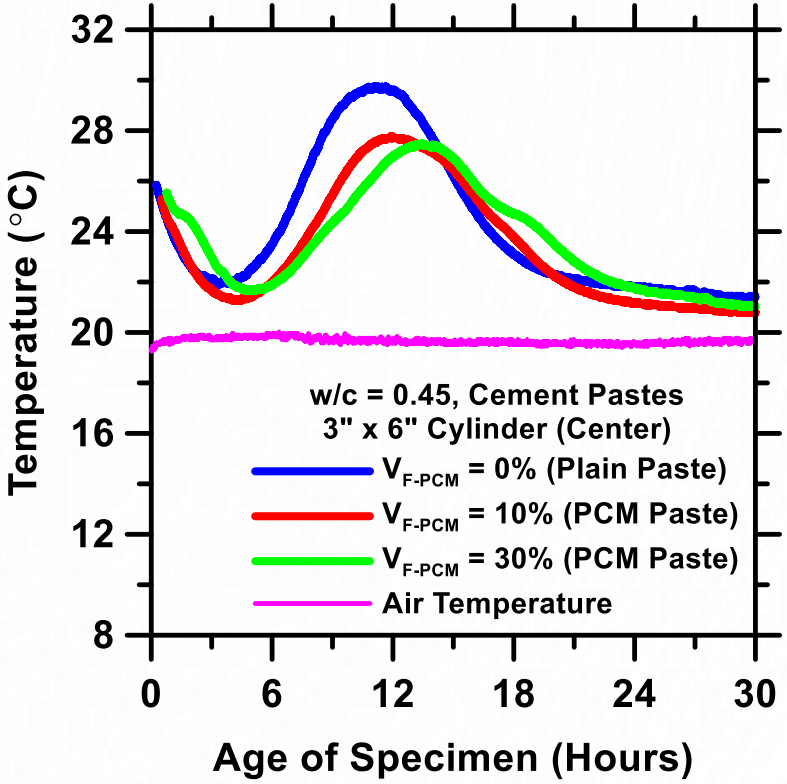




Heat of hydration and temperature development

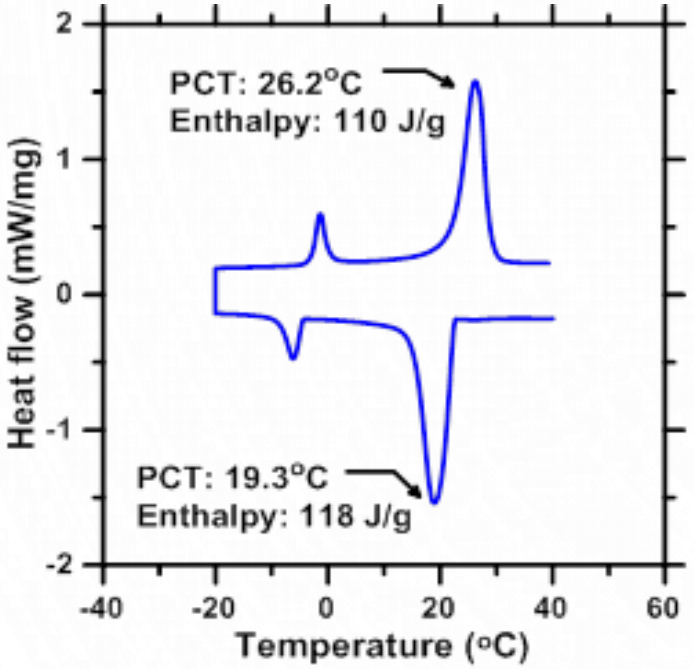


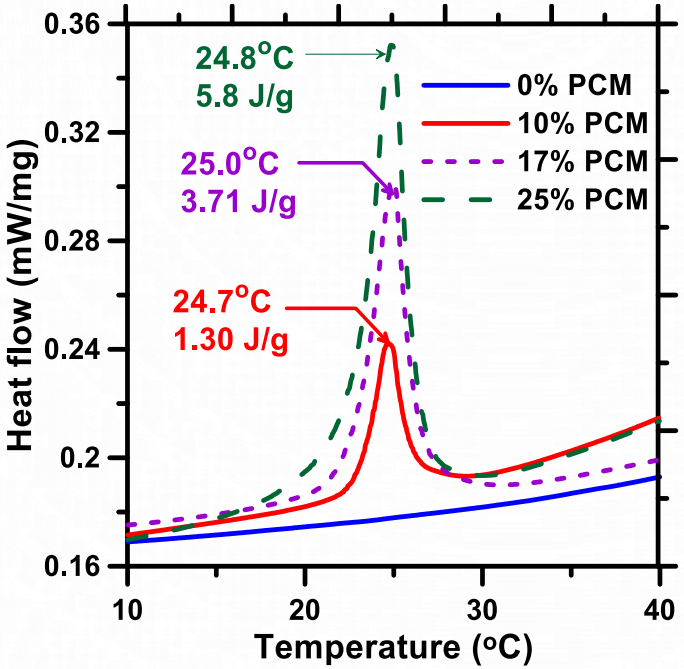




- Lower heat development – both isothermal and semi-adiabatic temperature rise
- Delaying time to peak temperature

Thermal Performance – heat flow

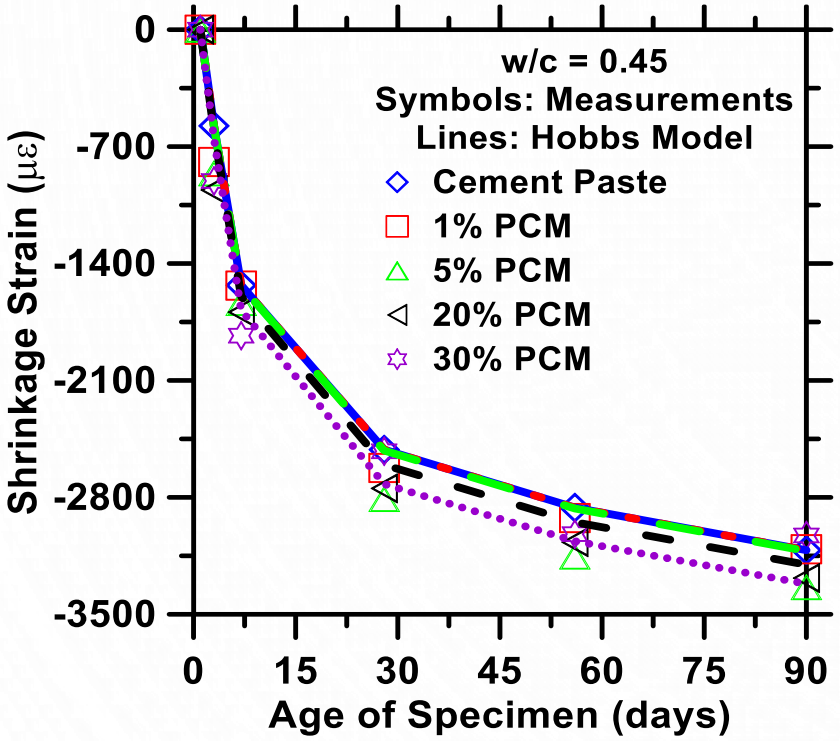




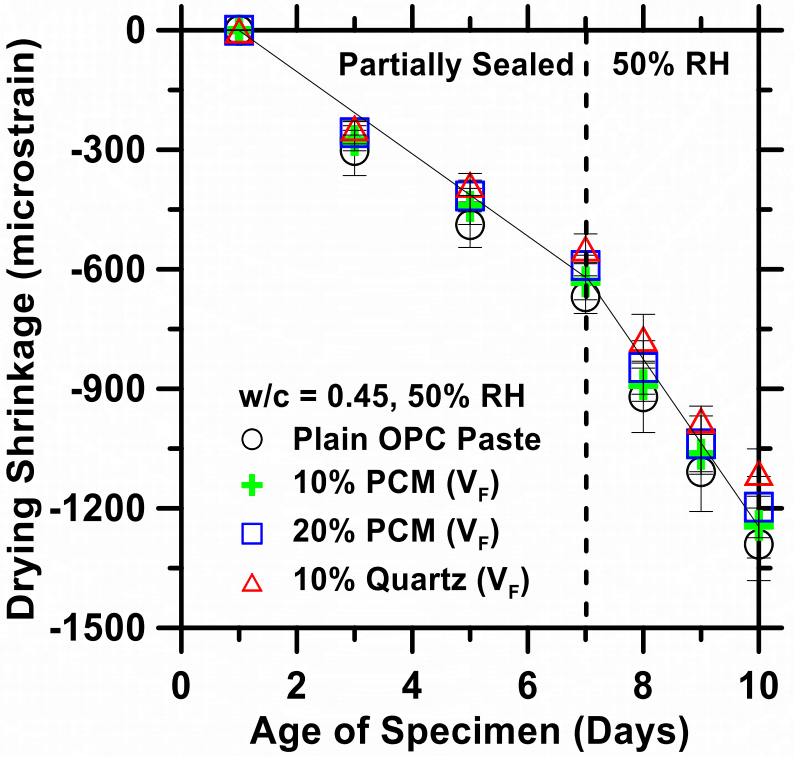
- The enthalpy of phase change determined as the area under the heat flow curve during the time the phase transition is active
- Onset temperature (T_{onset}) corresponding to melting is 21.9°C and the completion temperature ($T_{completion}$) is 29°C, with the endothermic peak noted at 26.2°C.

Thermal Performance – thermal/shrinkage strains

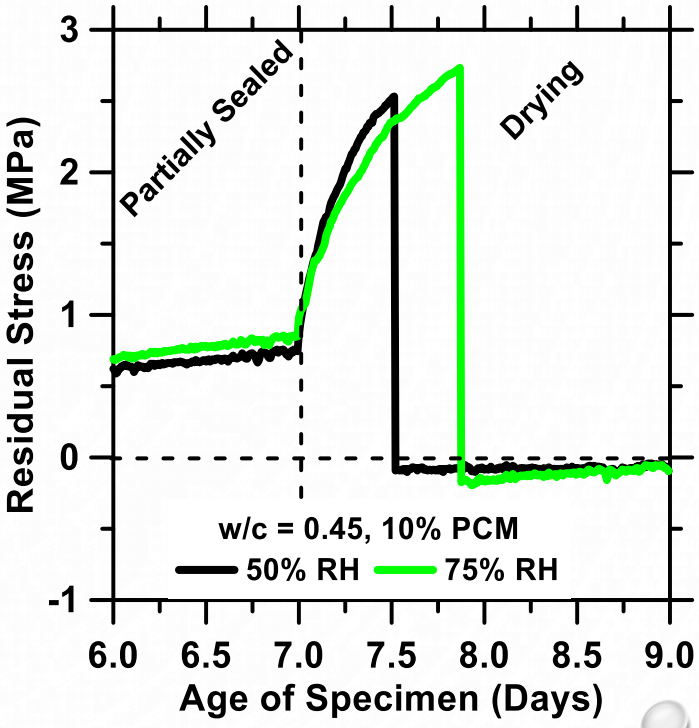
Free shrinkage



Partially sealed

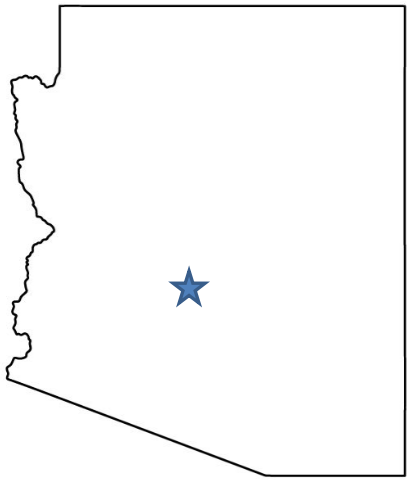


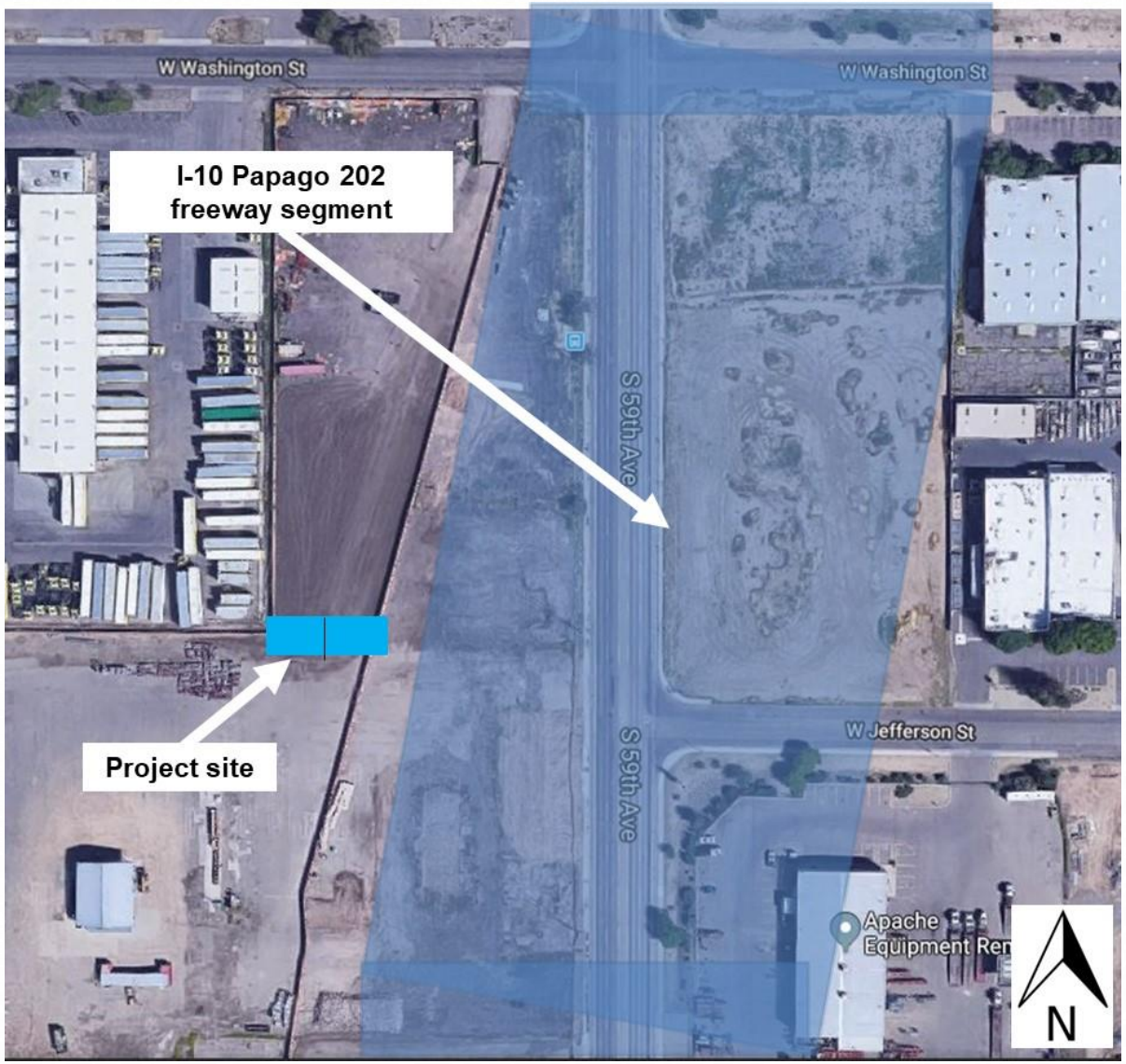
Residual stress



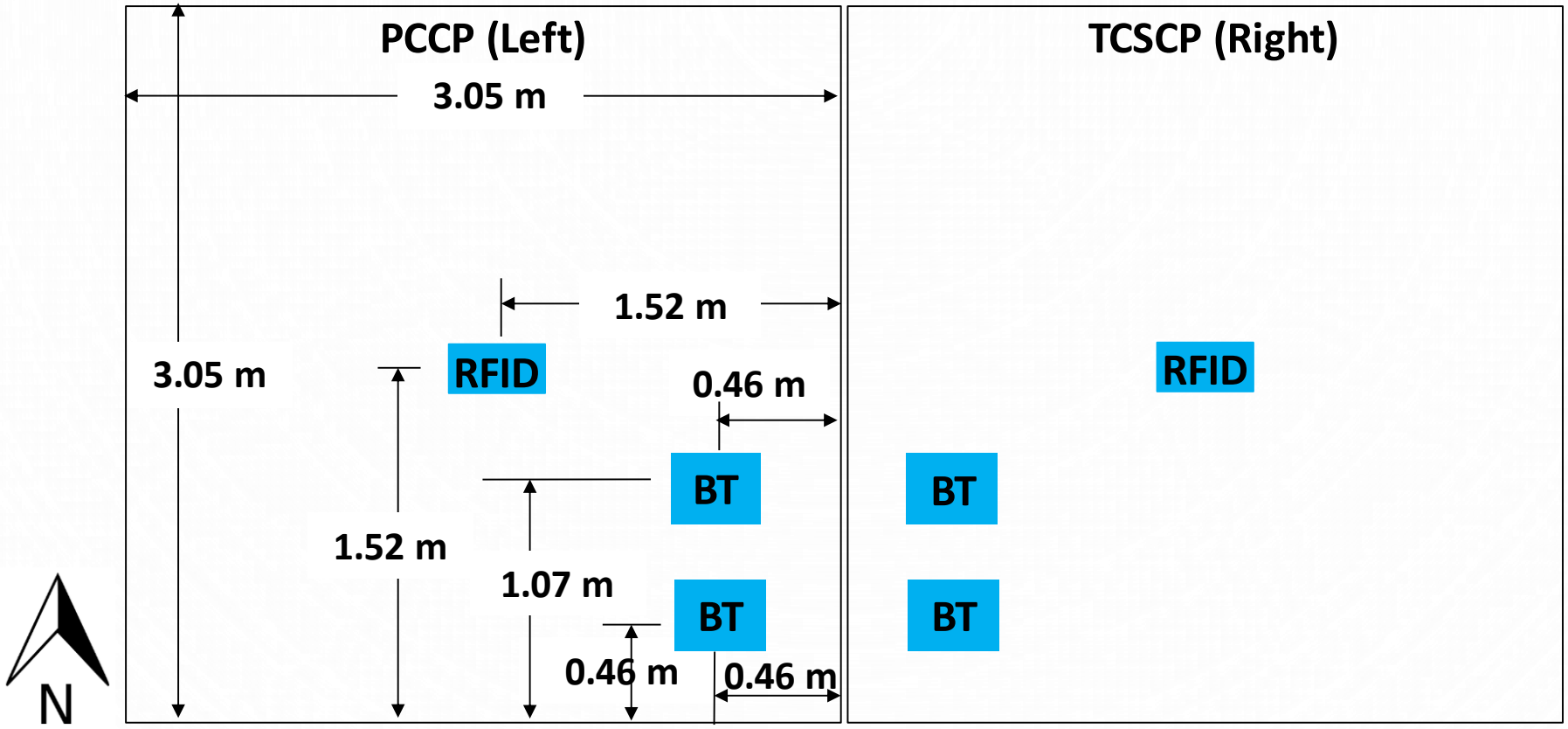
- No adverse influence on free strains; Delay in the age of cracking
- All the cementitious mixtures fail at tensile stresses substantially (around 50%) lower than the tensile strength of the material around 7 days

Project Location

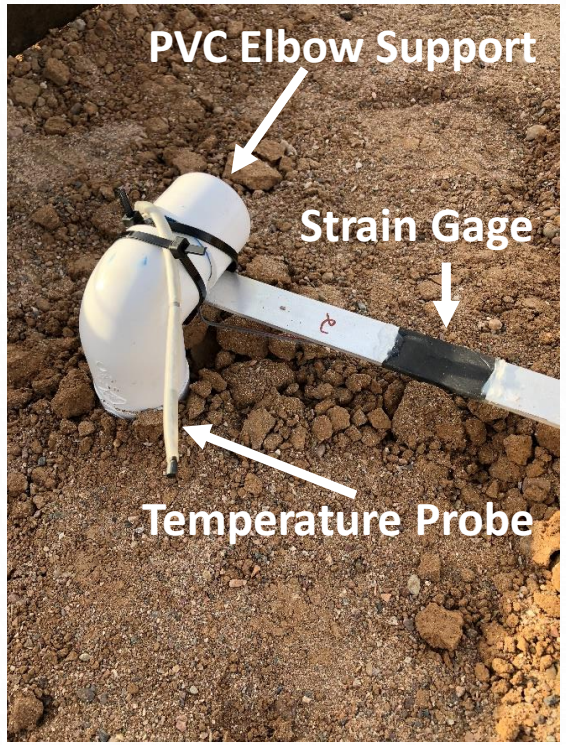


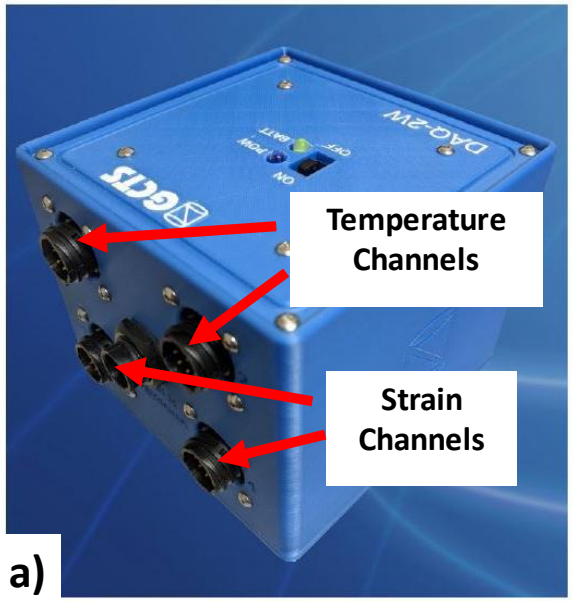


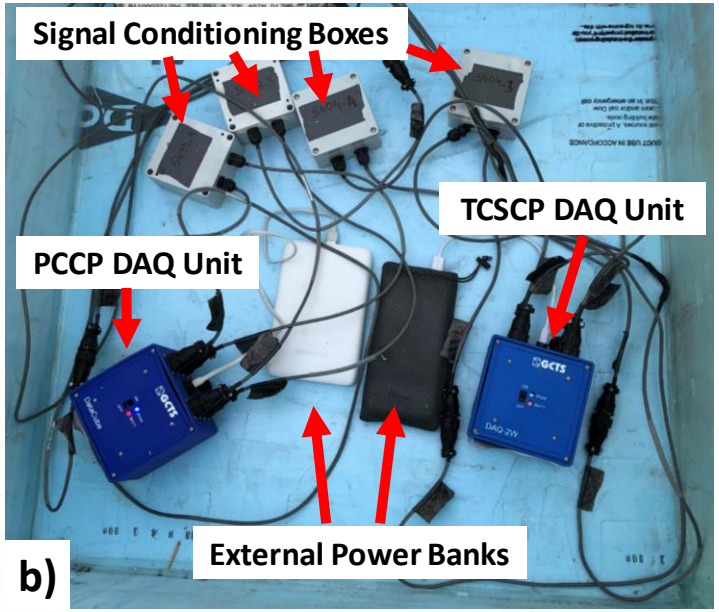
Sensor Locations



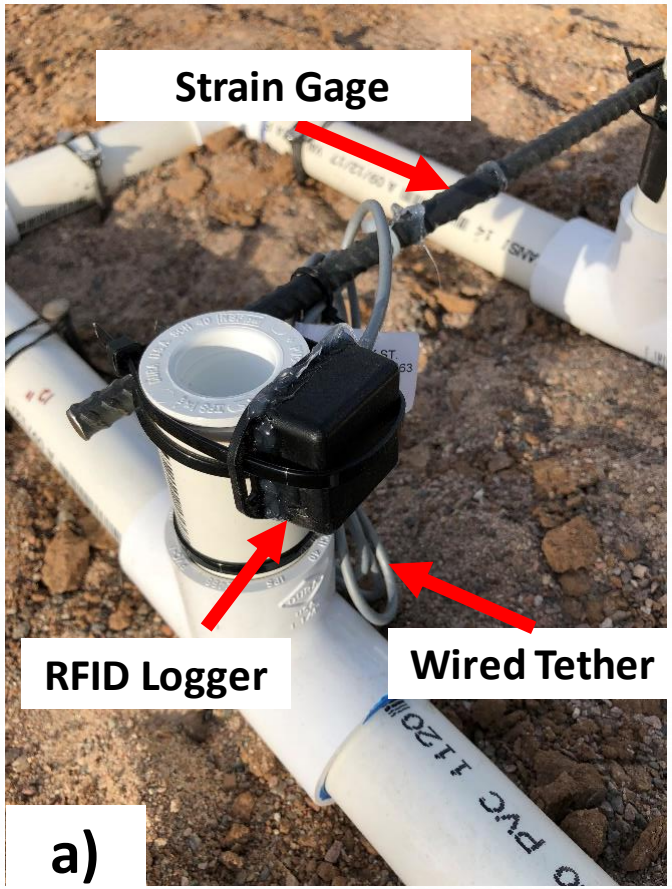
Bluetooth Monitoring System

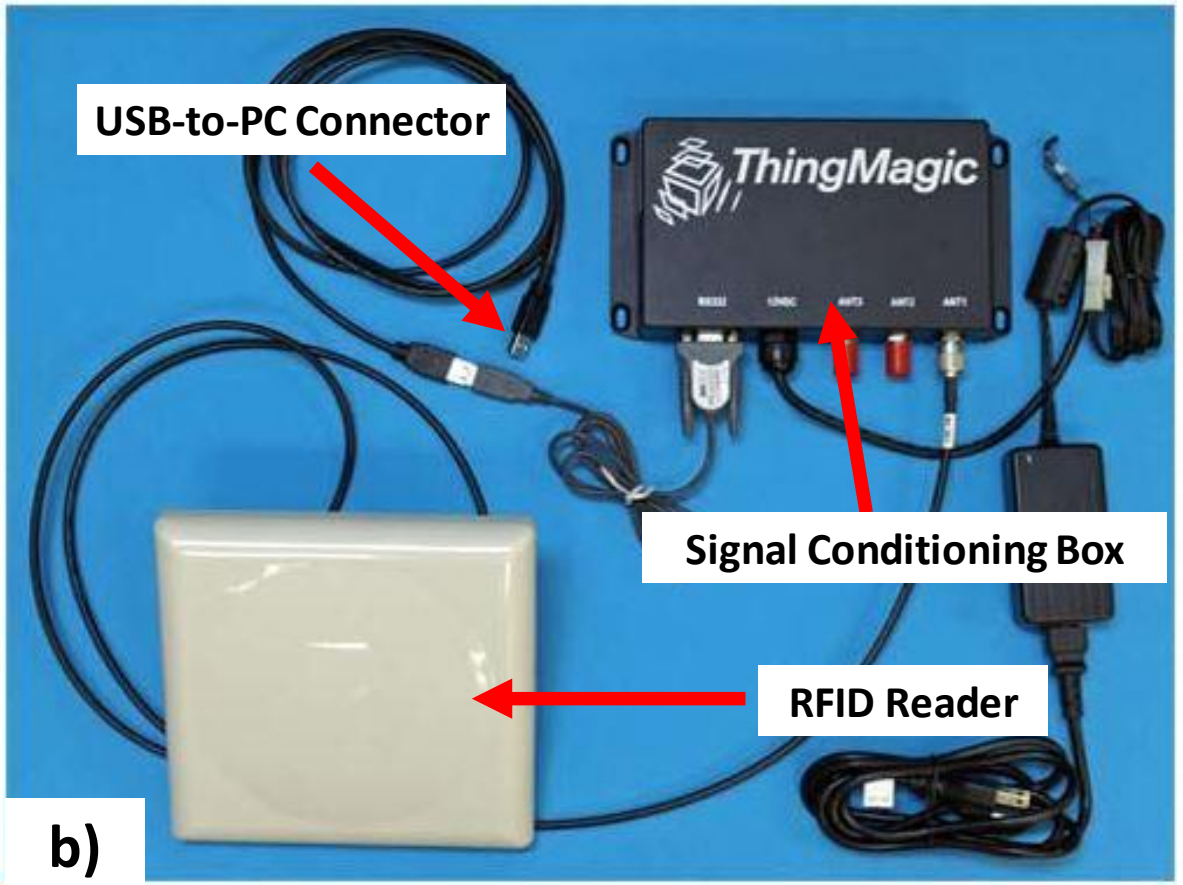




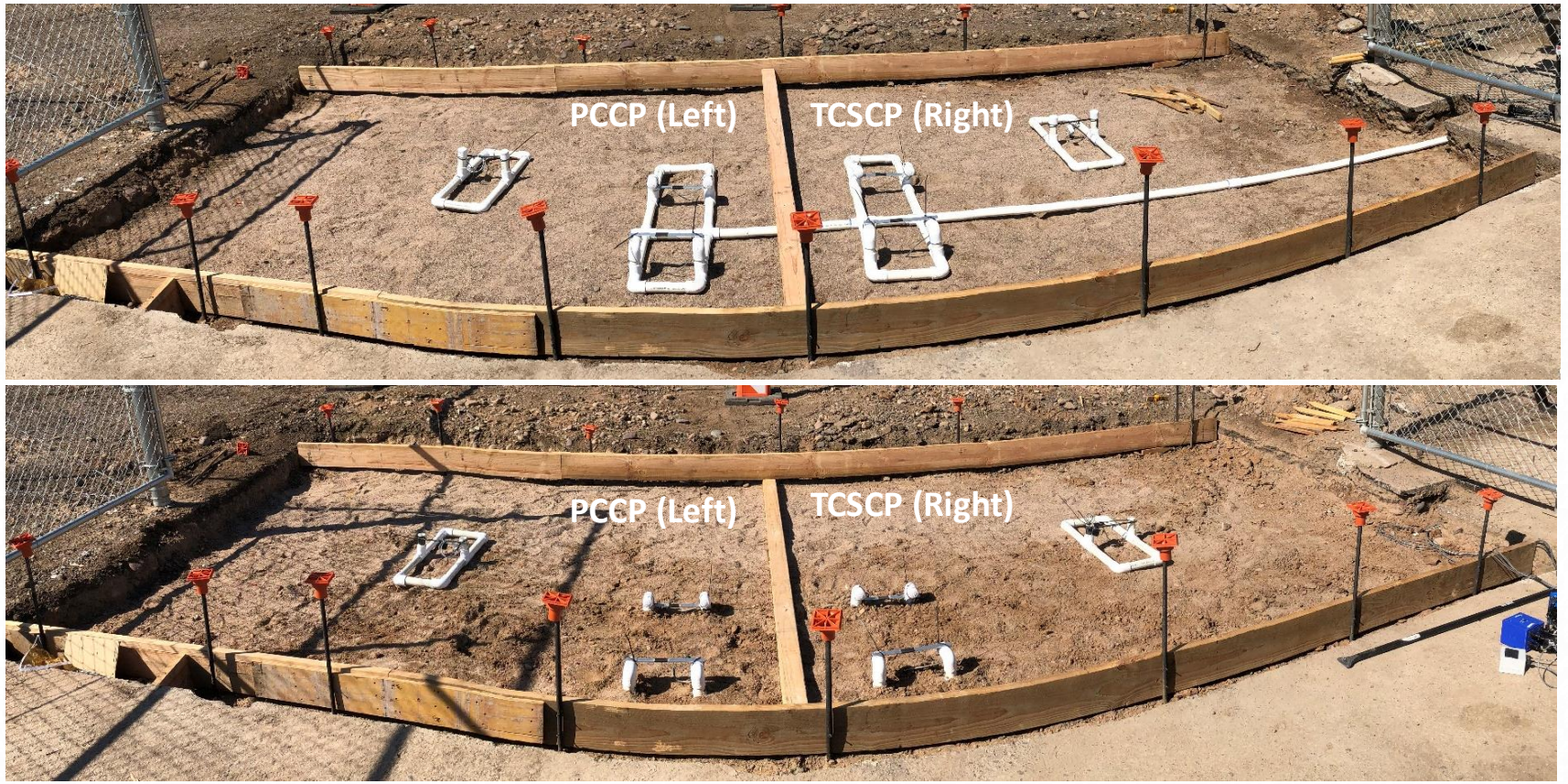


RFID Monitoring System

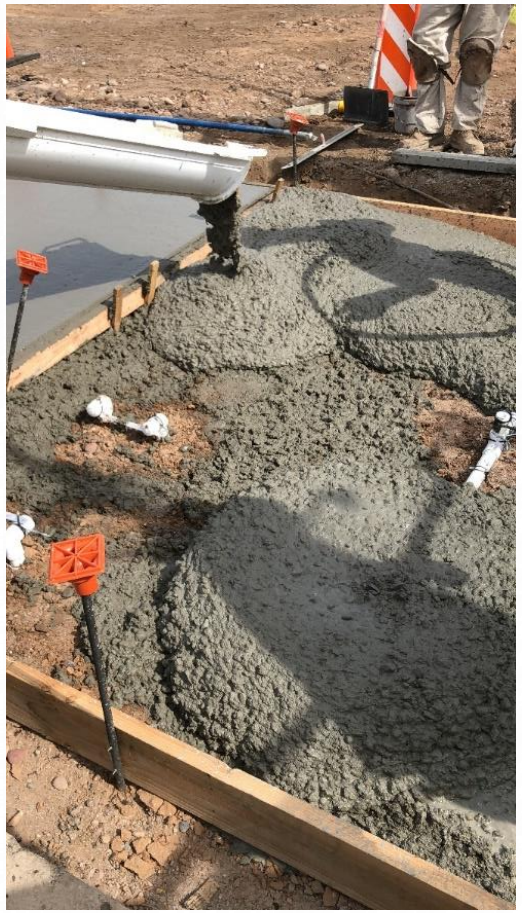




Sensor Locations

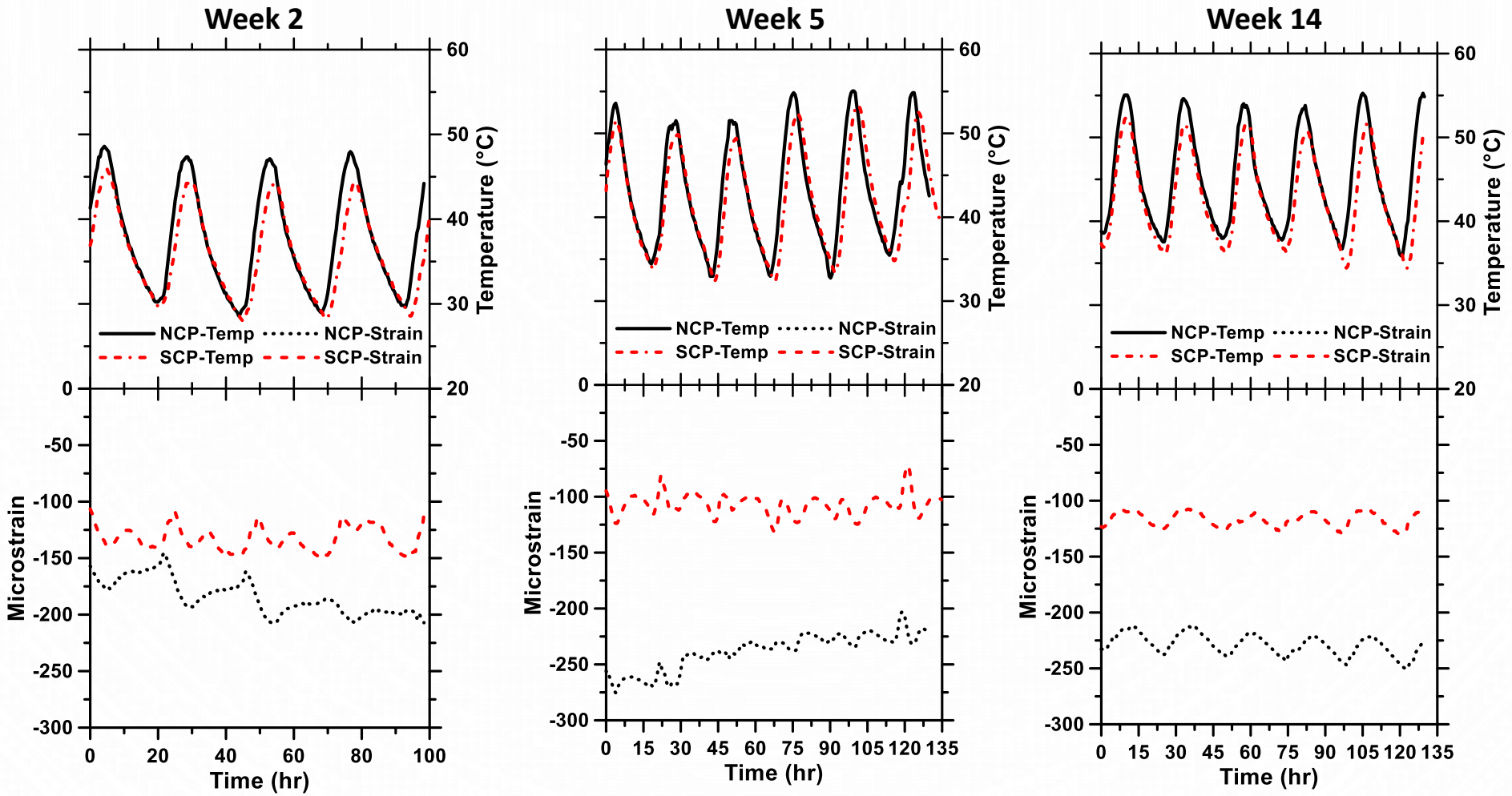


PCM Dispersion

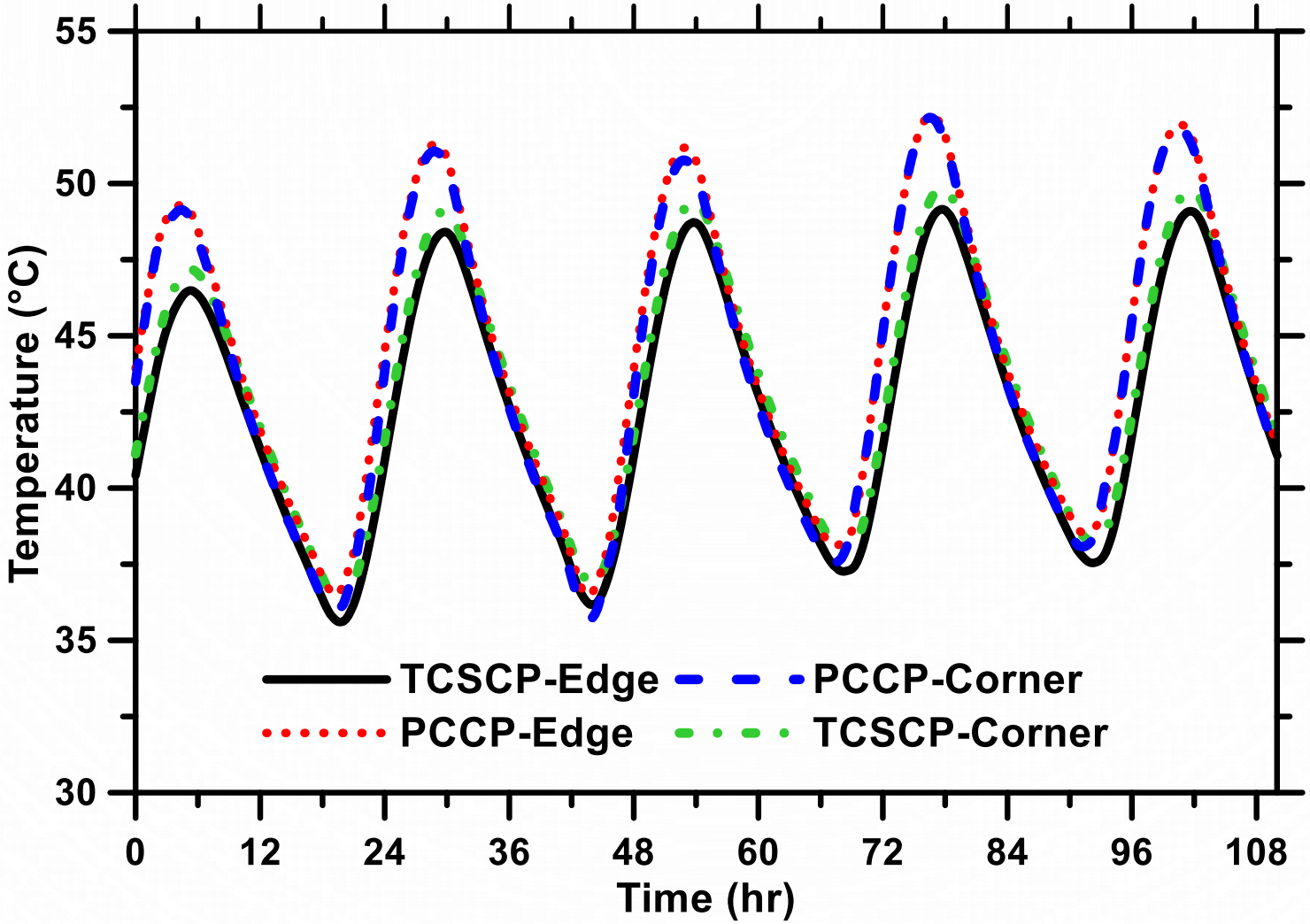


Final PCCP and TCSCP Sections

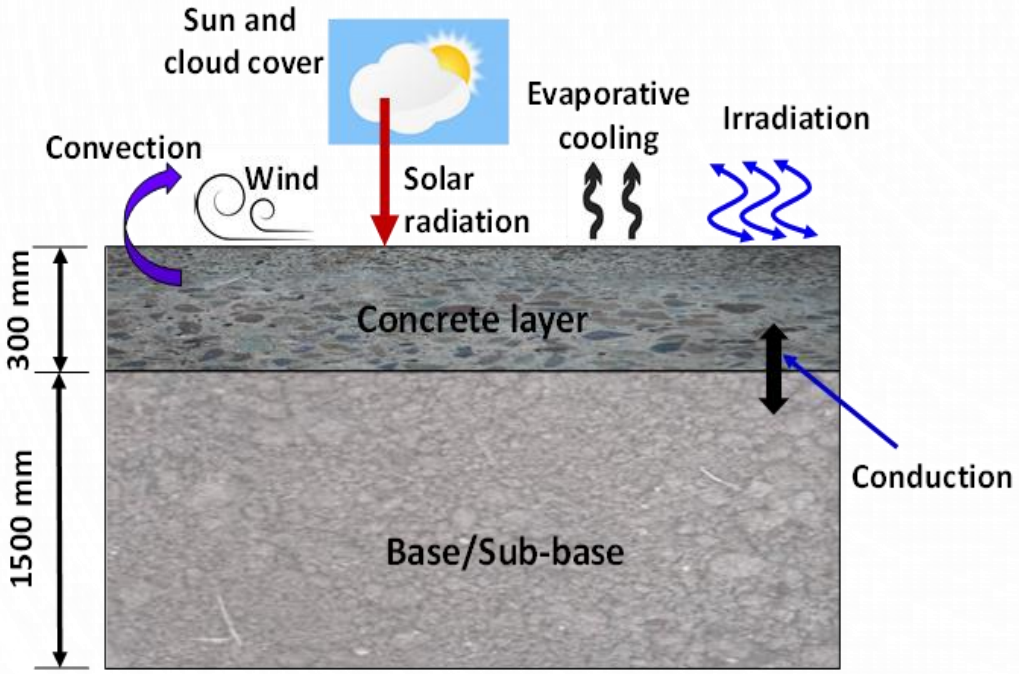
RFID Temperature and Strain Development



Temperature Development



Numerical Modeling



$$-k_{comp}\frac{\partial T(0,t)}{\partial x} = h_0(T(0,t)-T_0) + \varepsilon\sigma(T_0^4 - T(0,t)^4) - \beta_s q_s$$

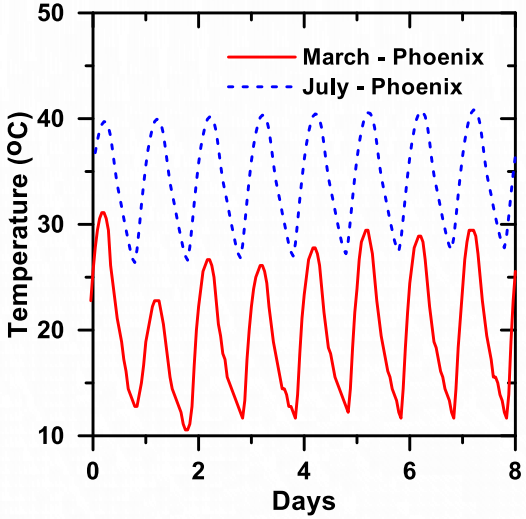
Convective heat transfer | Radiative heat transfer | Solar absorption

$$T(x,-L) = T_g$$

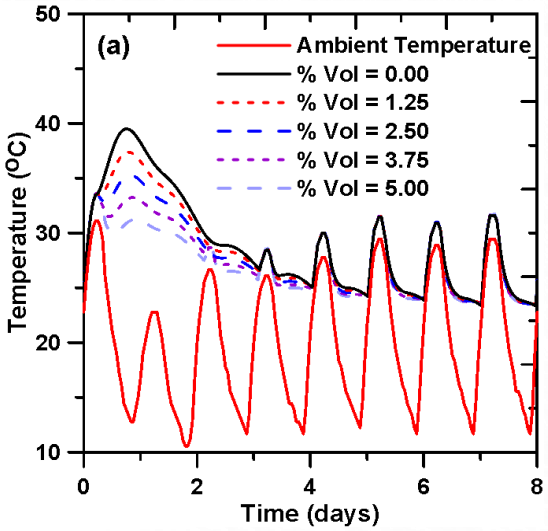
$$k_{comp}\frac{\partial T(L,t)}{\partial x} = k_{soil}\frac{\partial T_{soil}(L,t)}{\partial x}$$

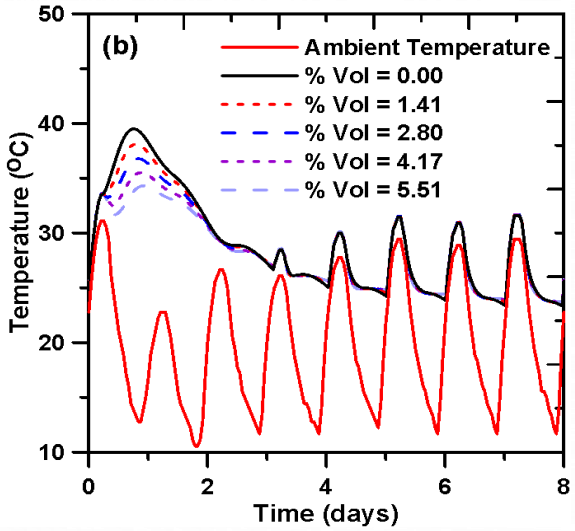
50 layers each were considered for the concrete pavement as well as the base/sub-base, which translated into layer thicknesses of 6 mm and 30 mm respectively for these components

Temperature profile



- Maximum section temperatures when PCM replaces cement or sand by a certain volume



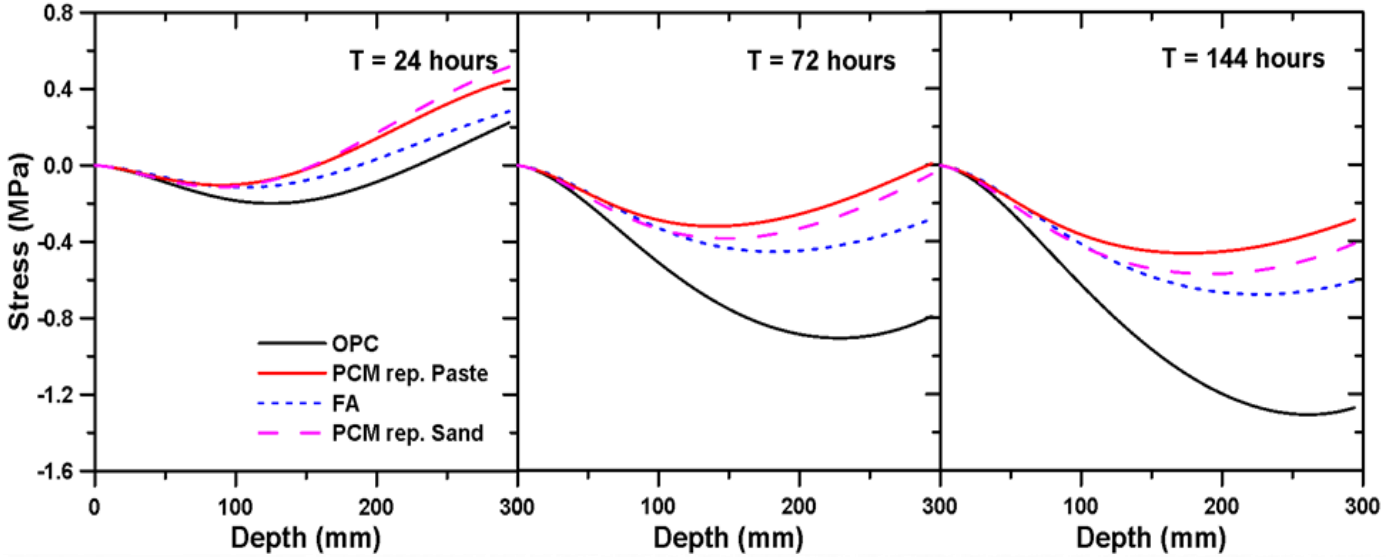


Stress development

$$\Delta T_{axial} = \frac{\sum_{z=0}^{h}\left[\left(T_{z,current} - T_{z,final-set}\right)\Delta z\right]}{h}$$

$$\varepsilon_{axial}(t) = \alpha_{comp}(t).\Delta T_{axial}(t)$$

$$\sigma_{axial}(t) = E(t).\varepsilon_{axial}(t)$$

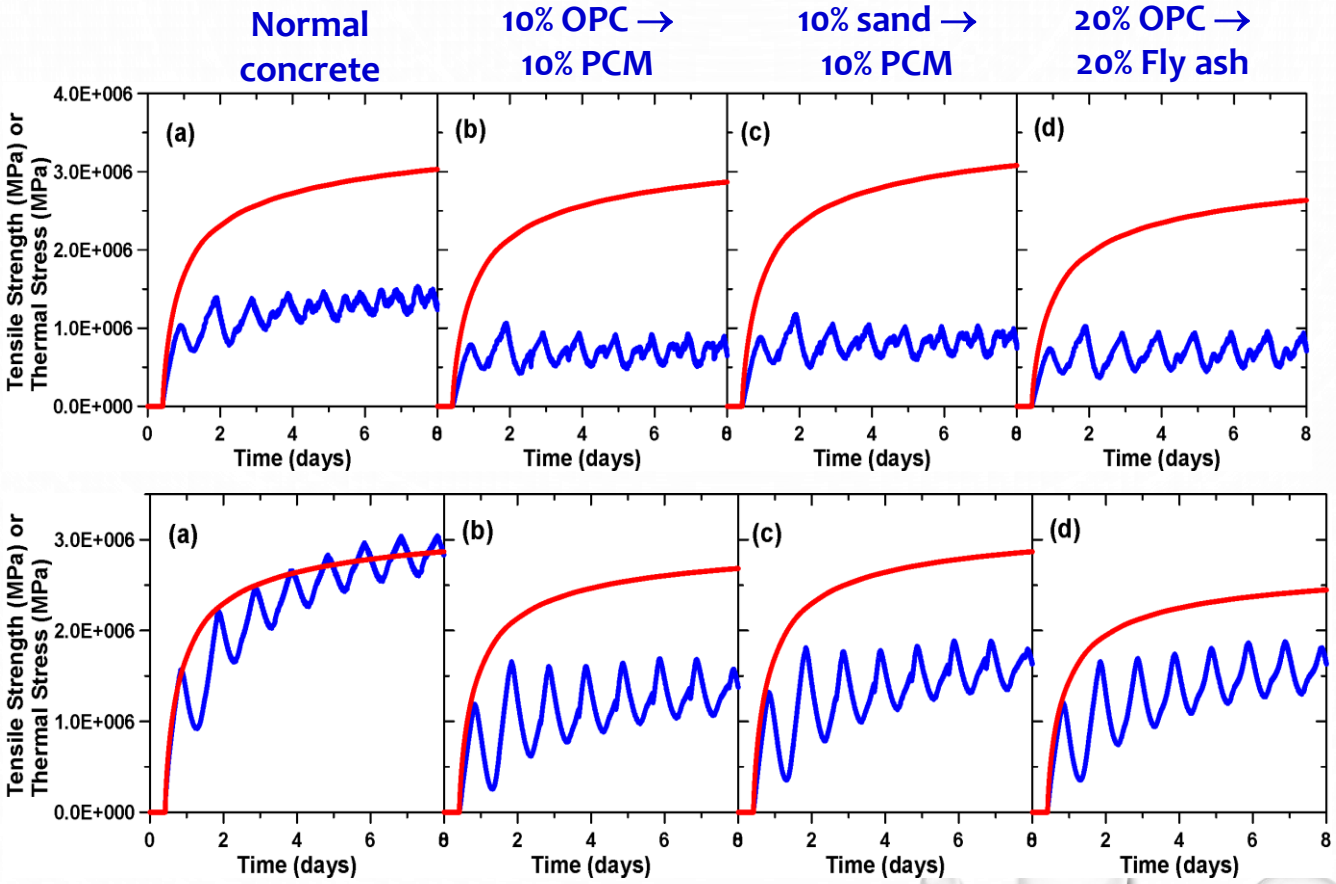


$$\Delta T_{curl} = \left(T_{top,current} - T_{bottom,current}\right) - \left(T_{top,final-set} - T_{bottom,final-set}\right)$$

$$\sigma_{curl} = \frac{\alpha_{comp}.\Delta T_{curl}.E}{2(1-\nu^2)}\left(C_{max} + \nu C_{min}\right)$$

Thermal stress and cracking potential

$$\sigma_{critical} = MAX_{tensile} \begin{cases} \varepsilon_{axial,top} \times R_F(top) \times E + \sigma_{curl,top} \\ \varepsilon_{axial,z} \times R_F(z) \times E \\ \varepsilon_{axial,bottom} \times R_F(bottom) \times E + \sigma_{curl,bottom} \\ 0 \end{cases}$$



Phoenix - March

Phoenix - July

Conclusions

- Laboratory and field studies on the use of phase change materials in concrete
- Thermal stress/strain mitigation and crack control
- RFID strain sensing for quality control and prediction
- Experiments, models, and field studies to establish the beneficial attributes of a novel technology

Acknowledgements

Presented at the ACI Fall 2023 Convention, November 1, 2023