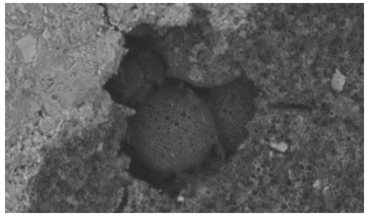
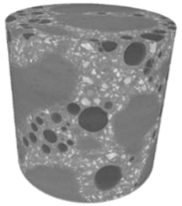
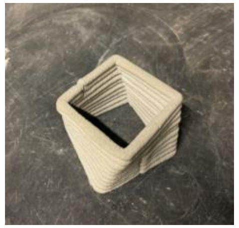
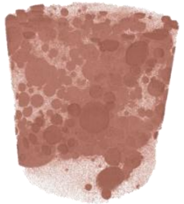
Developing 3D printable functional cementitious composite


Adam Brooks, Ph.D. Candidate
Hongyu 'Nick' Zhou, Ph.D., Assistant Professor
Department of Civil and Environmental Engineering
University of Tennessee Knoxville

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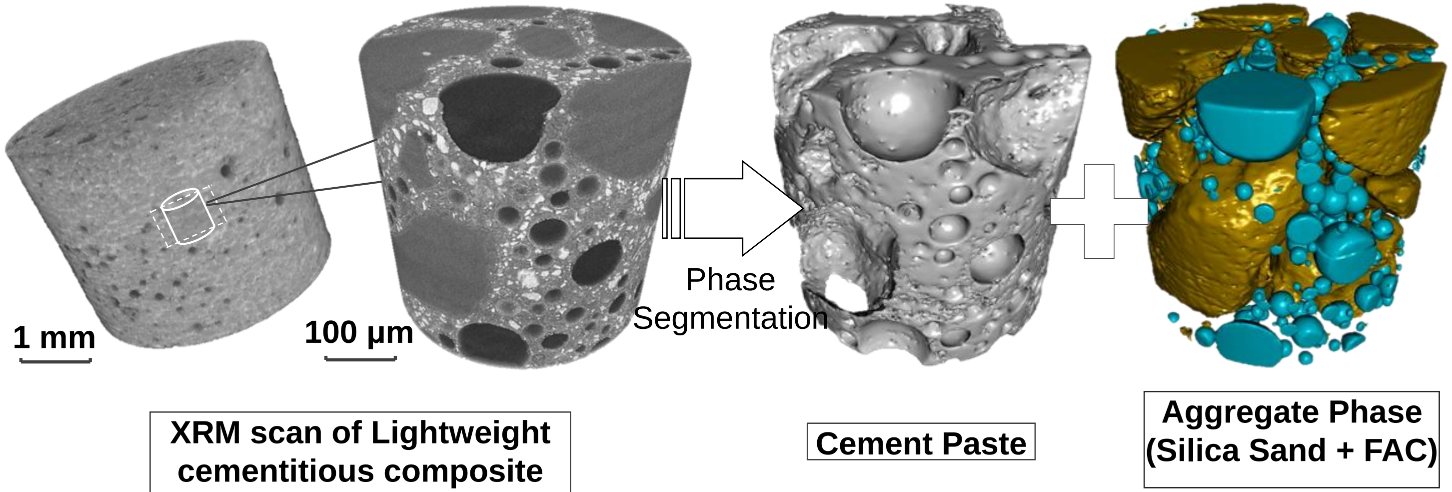
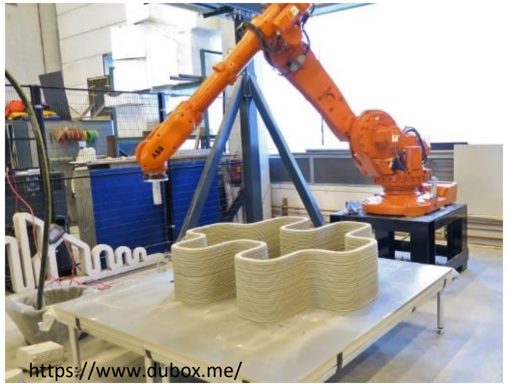
Outline

- Introduction
- Printing capacity and testing methods
- Cast materials
- Phase change material properties
- Printability
- Mechanical and thermal performance
- Scale model and simulation
- Conclusions

Introduction

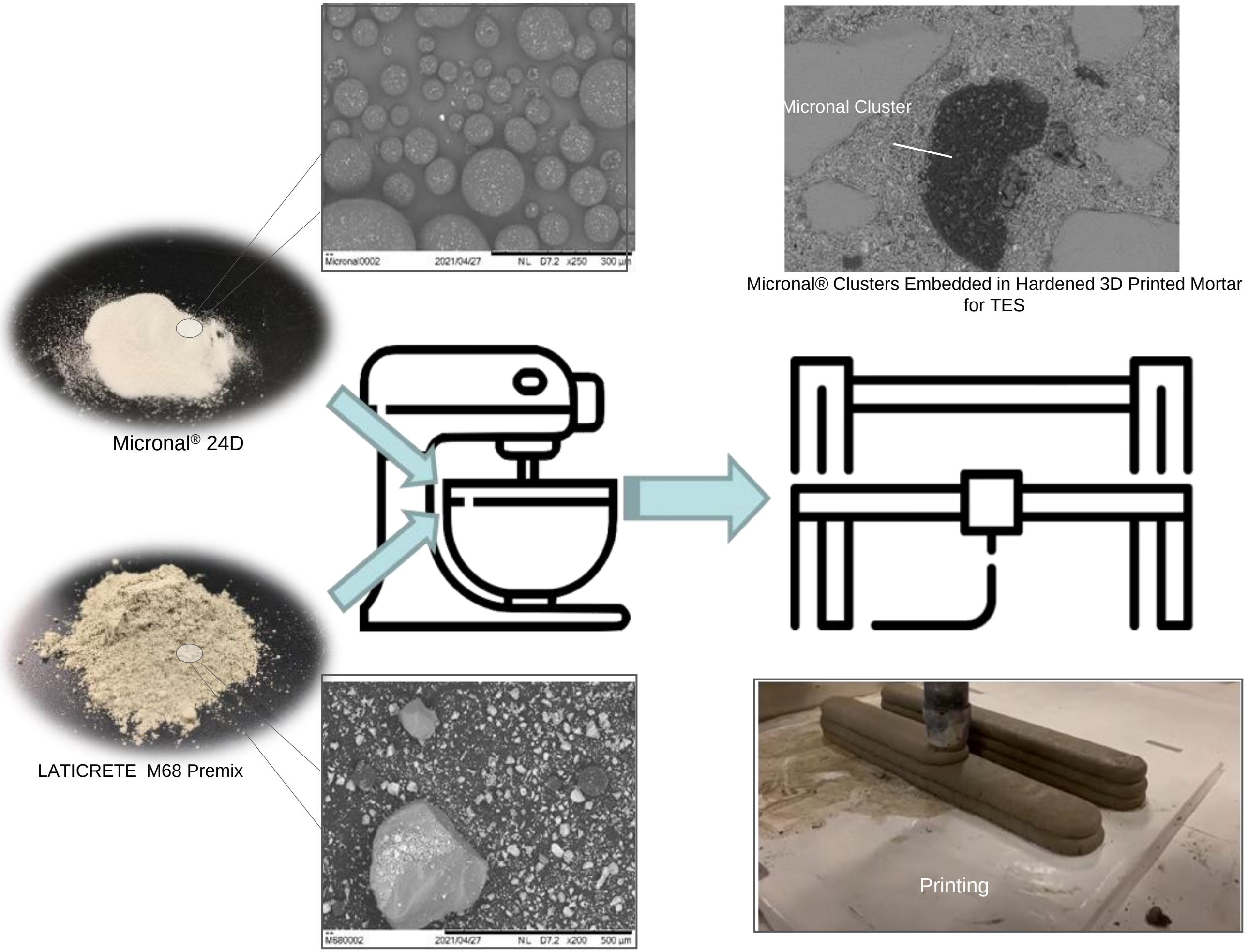
- Functional additives in concrete have continued to gain traction over the last decade
- Focused on low thermal conductivities, self-sensing, self-healing, and thermally responsive materials (i.e. Phase change materials)
- While their use in concrete has been well documented the transition of that existing research has yet to fully transition to 3D concrete printing



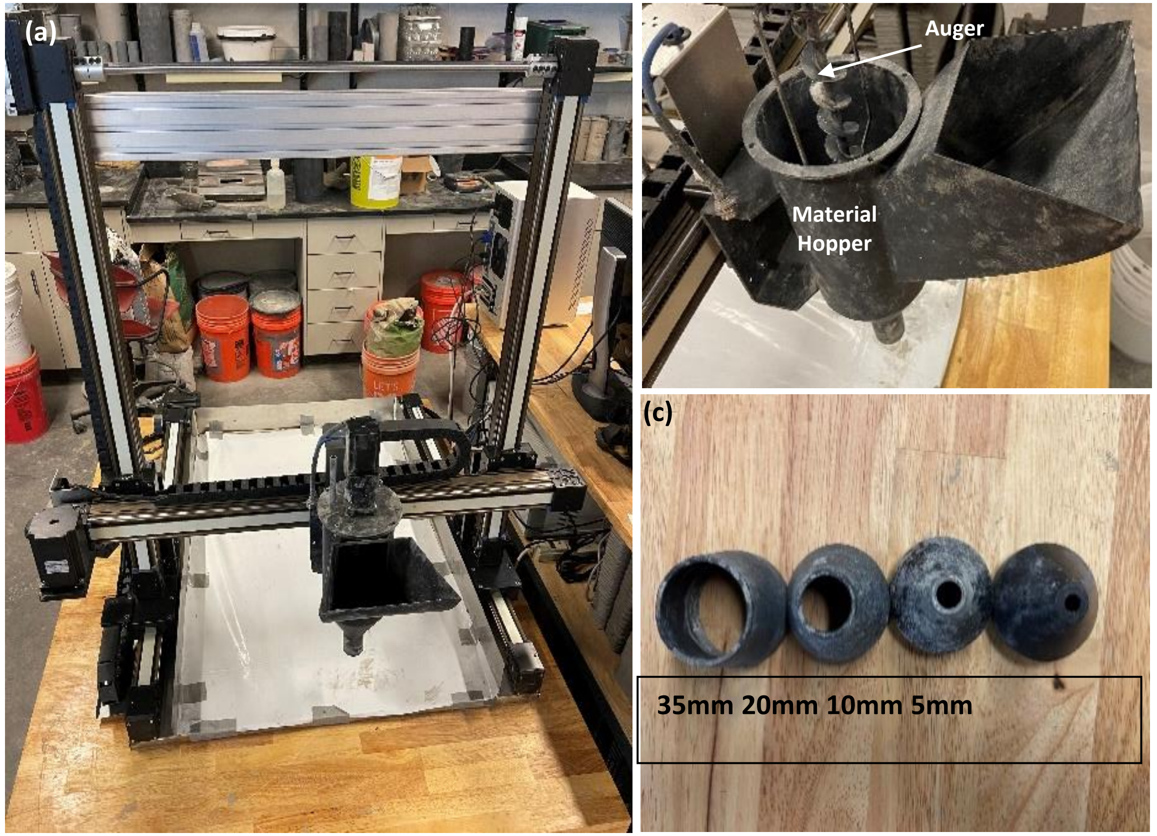


- Most existing research on 3D printed materials is conducted on maximizing the hydration kinetics, rheology, and structuration rate of the printed material
- This focus has created a large staging ground of information to allow further expansion into the use of functional additives in 3D concrete printing

Tabletop 3D concrete printer

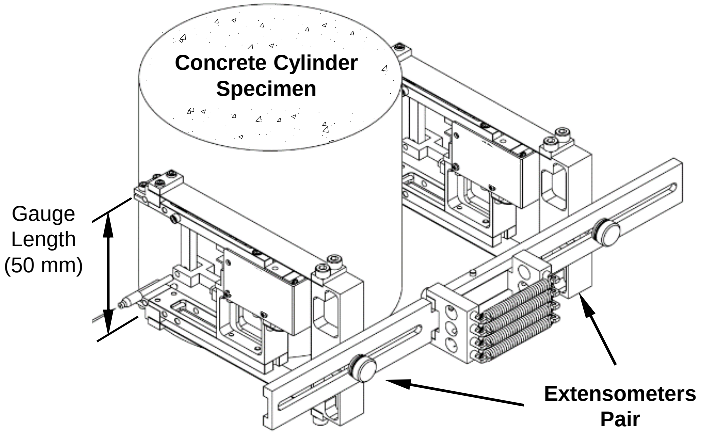


Micronal® Clusters Embedded in Hardened 3D Printed Mortar for TES

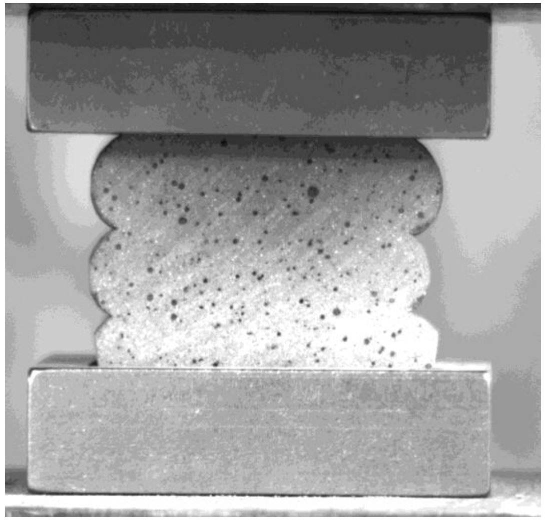


Mechanical test set up

Elastic Modulus test set up

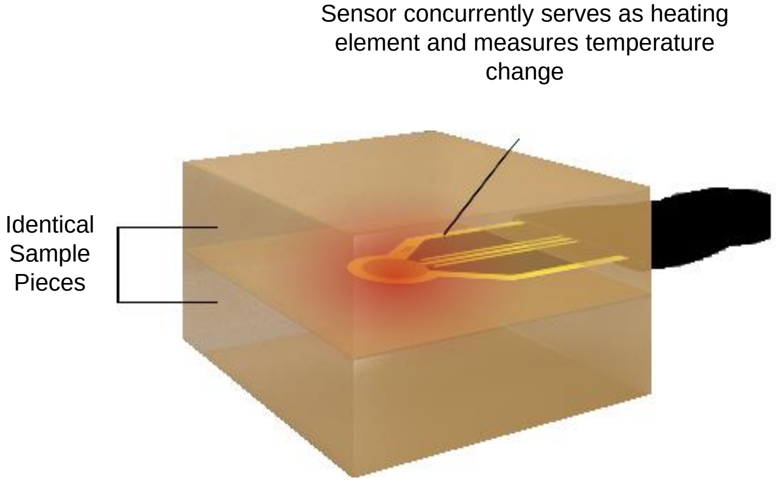


Compressive test set up

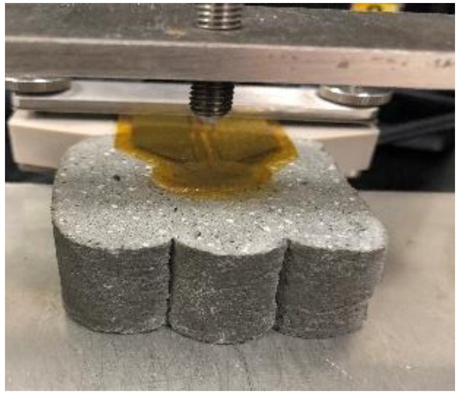


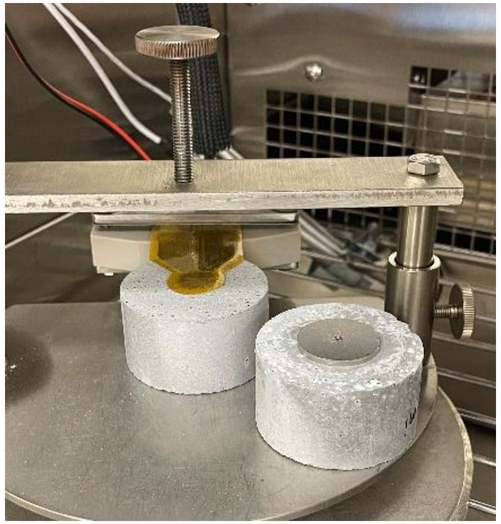
Thermal test set up

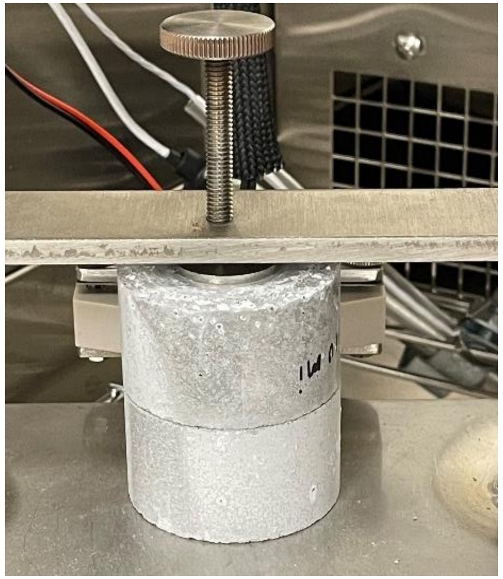
Tabletop Environmental Chamber used to condition samples



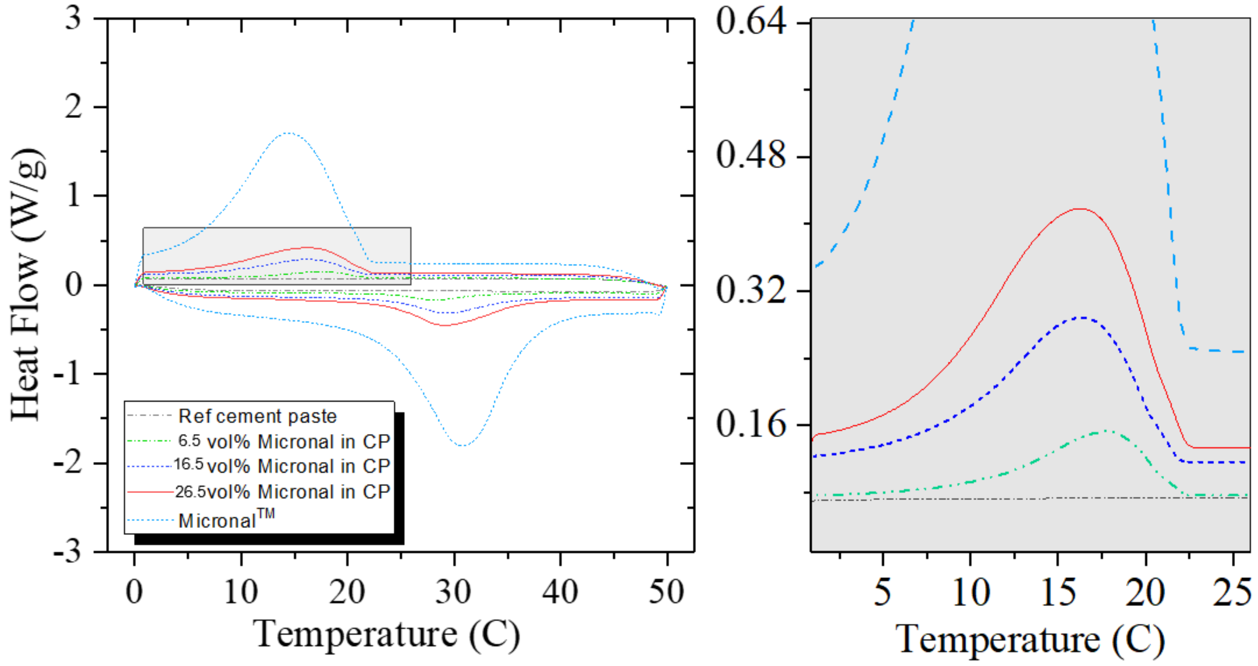
- Uses a Kapton supported spiraled nickel sensor
- Wheatstone bridge circuit
- Iterative process to solve both thermal conductivity and diffusivity





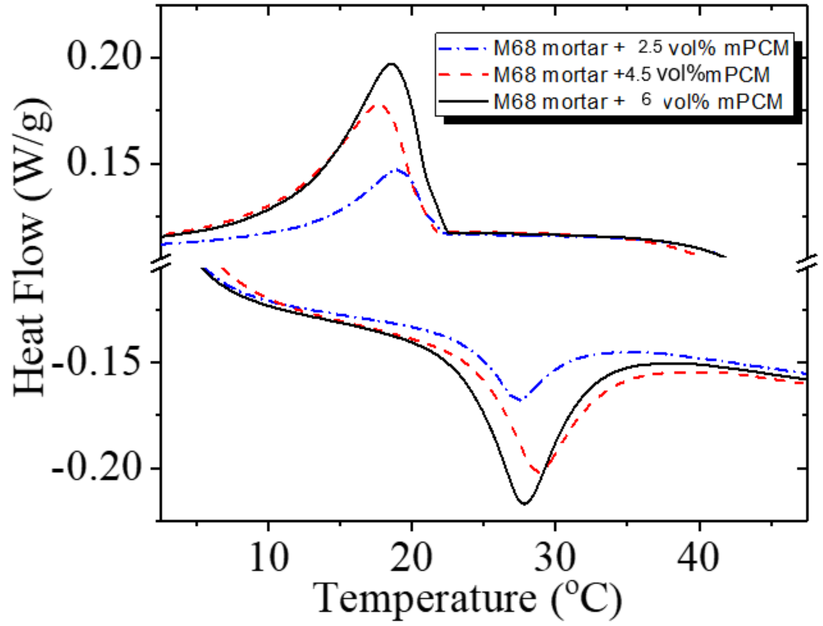


Energy Storage capacity of MEPCM and LWCC with MEPCM



Material	w/c	Volume % of mPCM	Heat of Fusion, ΔH_m	Phase Change Temp, T_m	Phase Change Temp, T_s
			kJ/kg	°C	°C
Cement Paste + 6.5 vol% mPCM	0.3	6.5	2.989	20.16	22.39
Cement Paste +16.5vol% mPCM		16.5	7.207	20.09	22.40
Cement Paste +26.5vol% mPCM		26.5	12.831	20.07	22.39
M68 Mortar + 2.5 vol% mPCM	0.35*	2.5	0.909	21.08	22.29
M68 Mortar + 4.5 vol% mPCM		4.5	1.678	21.07	22.01
M68 Mortar + 6 vol% mPCM		6	2.307	21.08	22.29

- the latent heat of cement paste containing Micronal® mPCM was tested roughly proportional to the weight presentation of the PCM within the composite materials system
- for cement paste containing 0, 6.5, 16.5, and 26.5 vol% of Micronal® microcapsules, which responds approximately the volume loadings of mPCM in the paste phase (excluding the fine aggregates and fillers)

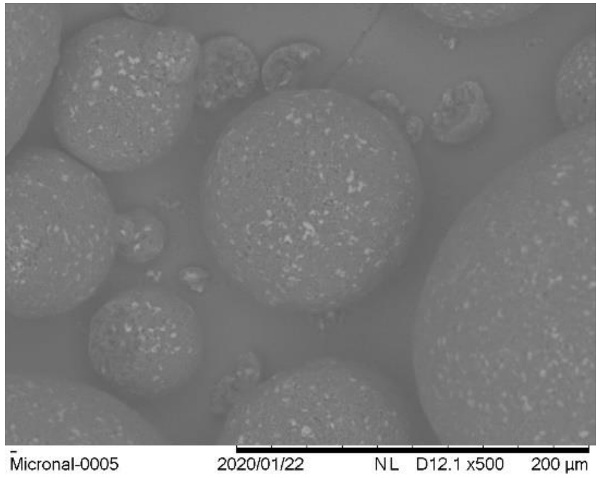


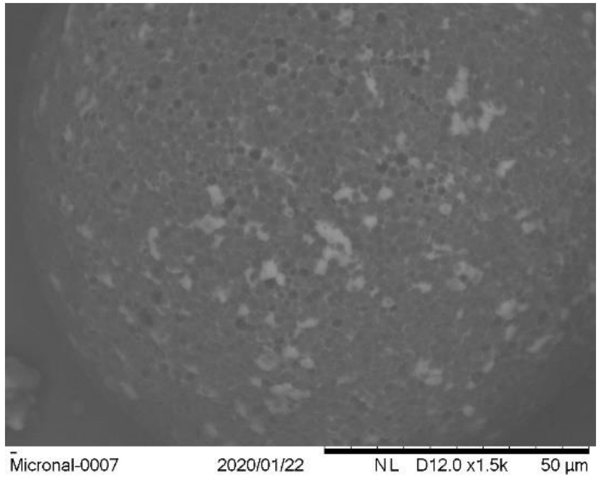
Properties of the mPCM

Material	Shell type	Mean Particle Size	Density	Heat of Fusion, ΔH_m		Phase Change Temp, T_m	Phase Change Temp, T_s
		μm	kg/m³	kJ/kg	kJ/L		
Micronal® 24D	Nonhazardous Polymers and synthetic	5-300 μm (agglomeration of 2-3 μm microcapsules)	1.005	90.31	90.74	22.3°C	21.1°C

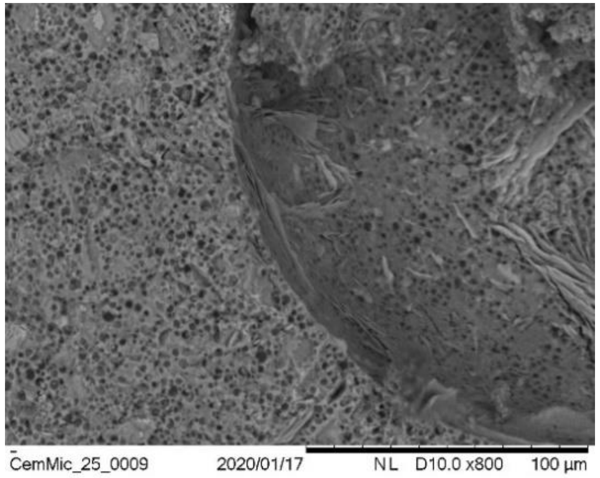
Microscopy analysis of MEPCM

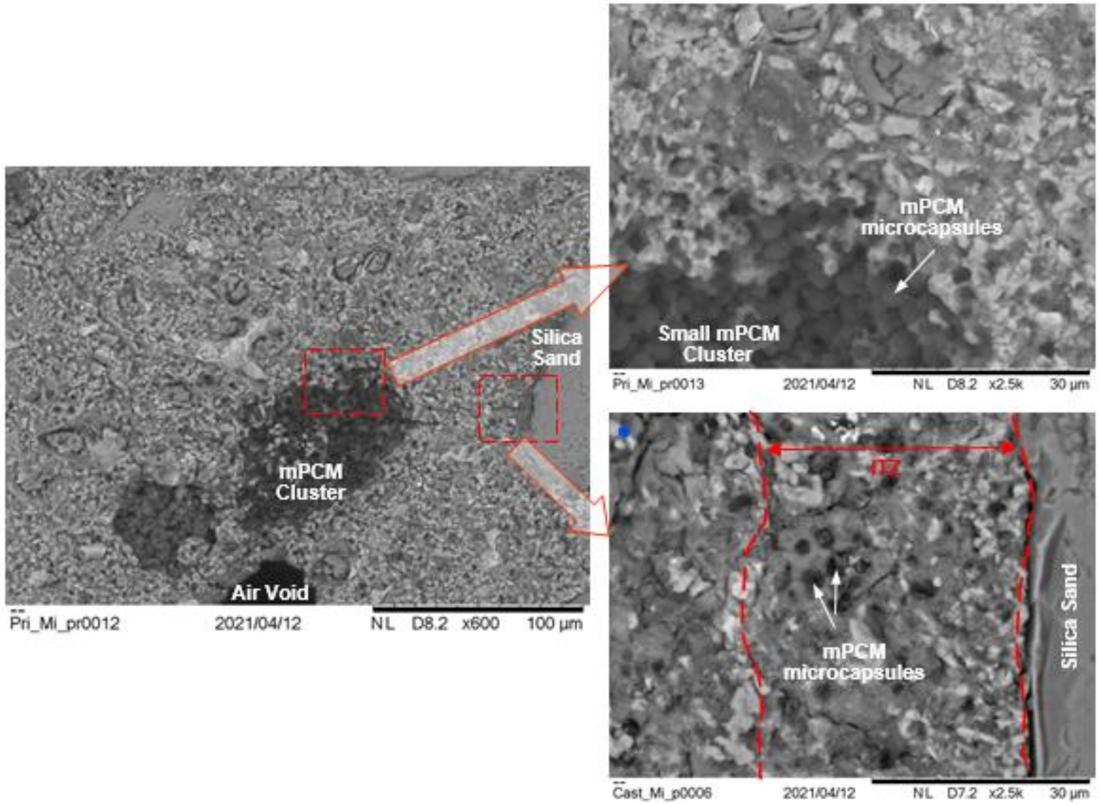
Raw Material





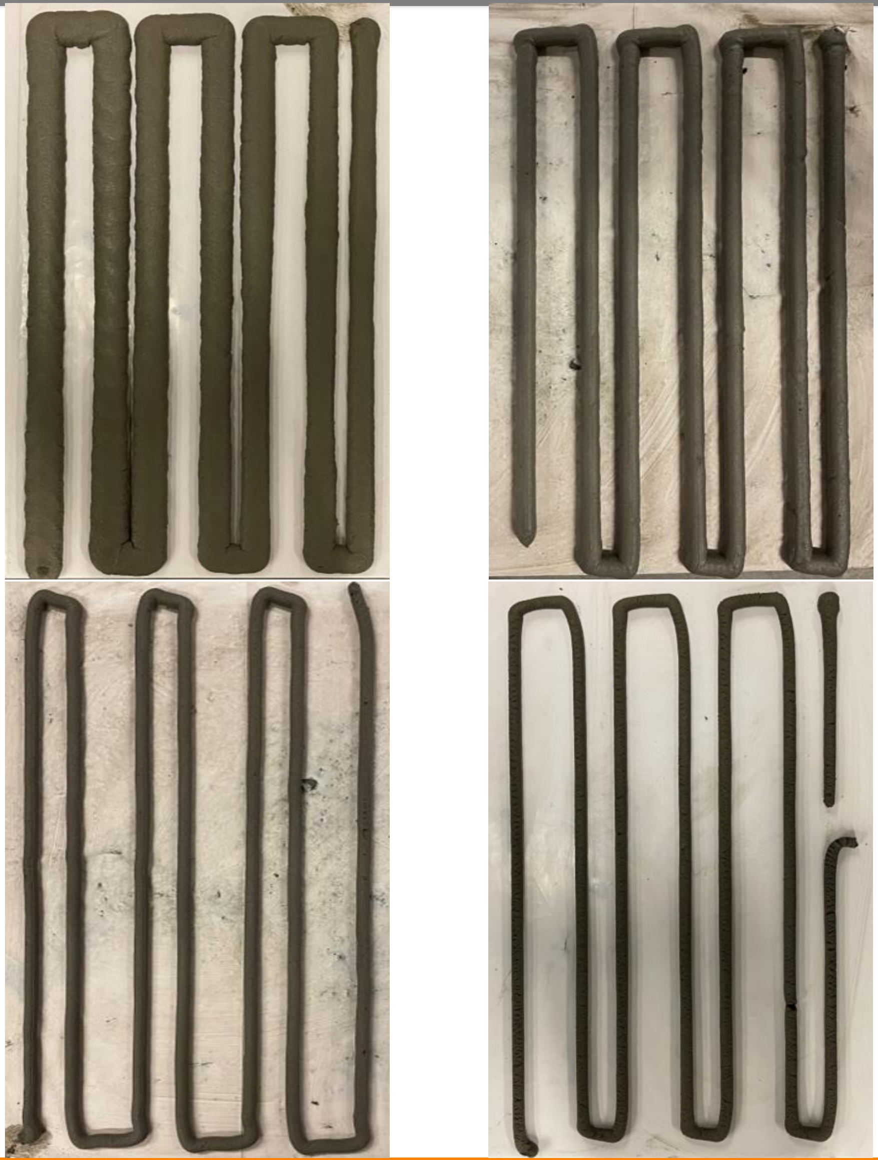
Cement Mortar





- It is noted that during mixing (and printing), the binder for the conglomerated Micronal® particles dissolves and the PCM microcapsules (2-3µm in size) uniformly distributed within the cementitious matrix

Extrudability testing

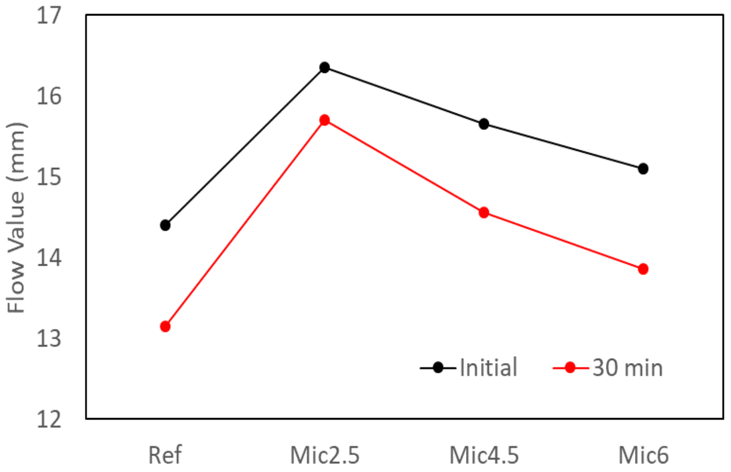


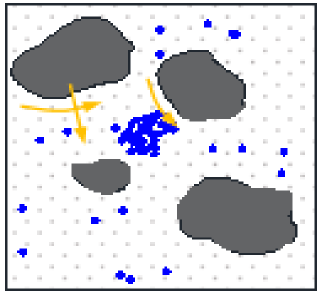
Extrudability of printing materials with different contents of PCM.

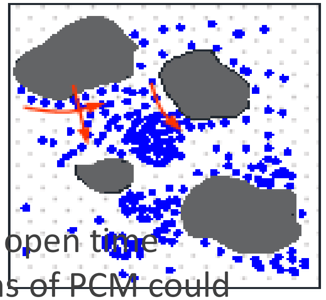
Mixture	Extrusion rate (Low = 0.57 rps)			Extrusion rate (Moderate = 1 rps)			Extrusion rate (High = 1.7 rps)		
	Print head velocity (mm/s unit)			Print head velocity (mm/s unit)			Print head velocity (mm/s unit)		
	45	65	90	45	65	90	45	65	90
Ref	O	E	E	O	E	E	O	O	O
Mic2.5	O	E	E	O	E	E	O	O	O
Mic4.5	E	U	U	O	E	E	O	O	E
Mic6	E	B	U	E	E	U	O	E	E

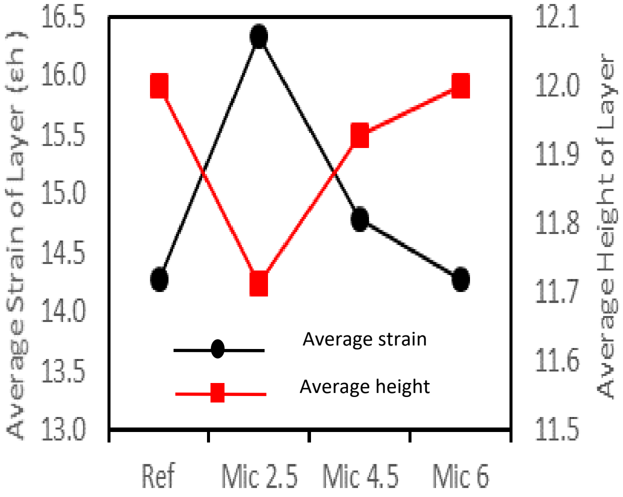
- Results showed that the printing parameters had a significant impact on the extrudability of the mixtures as the mPCM volume loading varied
- Inclusion of higher contents of mPCM required higher extrusion rate and print head velocity, which can be explained by the lower flowability of the mixtures with the addition of > 2.5 vol% mPCM
- Ref and Mic2.5 required lower extrusion rates to achieve the desirable extrudability. Wheatstone bridge circuit
- The addition of 6 vol% mPCM reduced the flowability while increasing the buildability (green strength and yield strength) of the mixture, which necessitated the higher extrusion rate

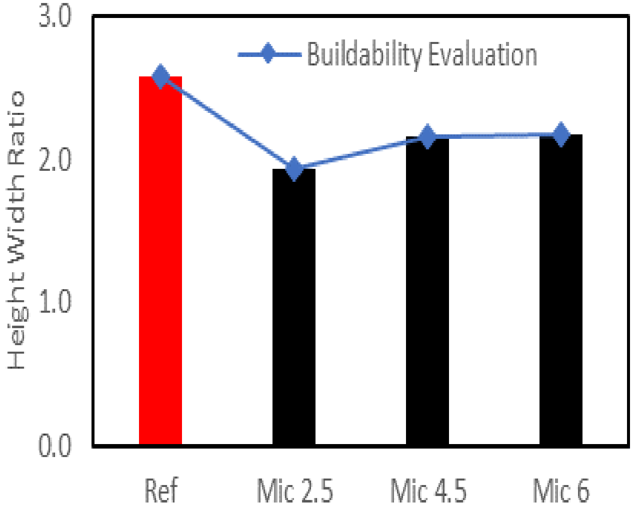
Printability testing



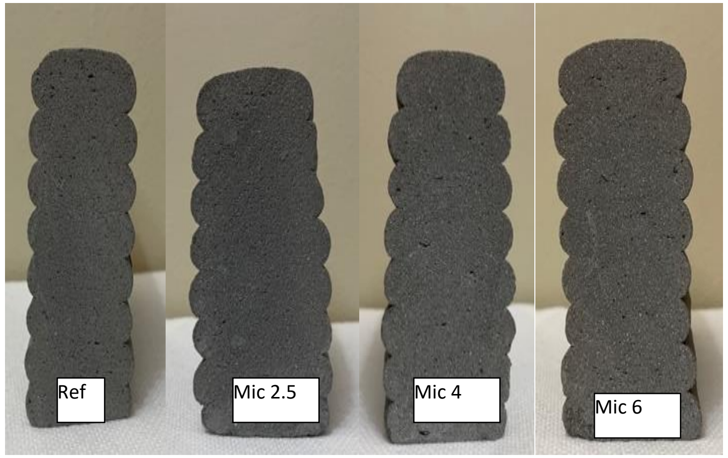








- Reduction in workability after 30 minutes of open time
- Increased workability at lower concentrations of PCM could be due to the spherical shape of mPCM particles, which may act as a rolling lubricate to facilitate the slide of solid components such as fine aggregates in the mixture
- the addition of 2.5 vol% mPCM increased the average strain of layers decreased the height width ration
- the higher loading volumes of mPCM increased the buildability and the printed mixture retained its shape



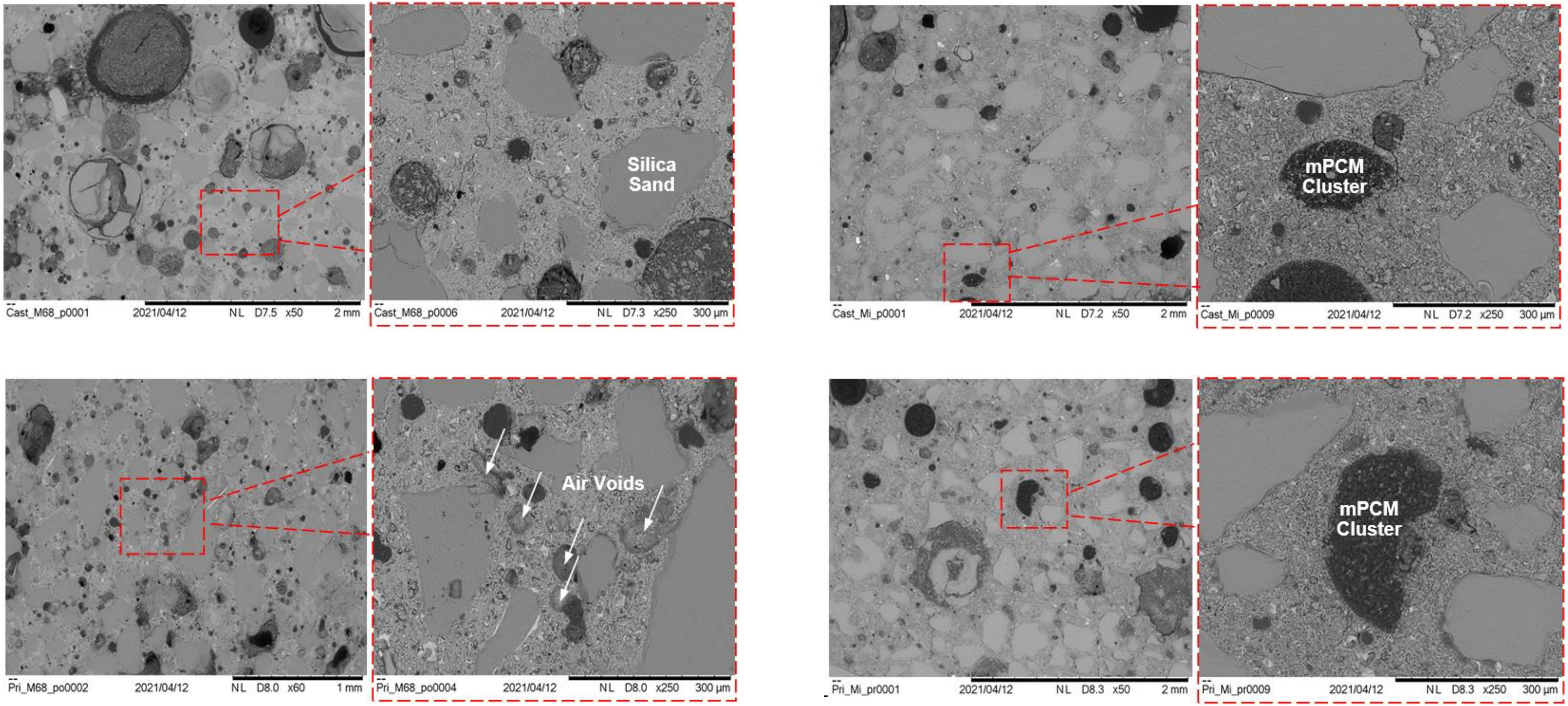
Microscopy analysis of cast and printed samples

Reference

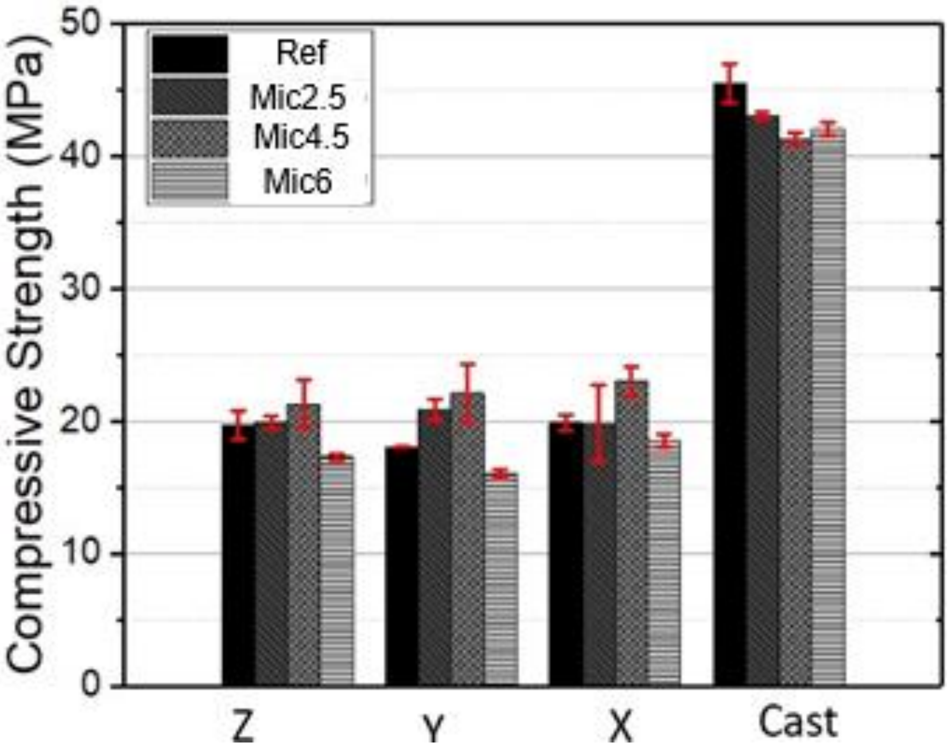
6% micronal

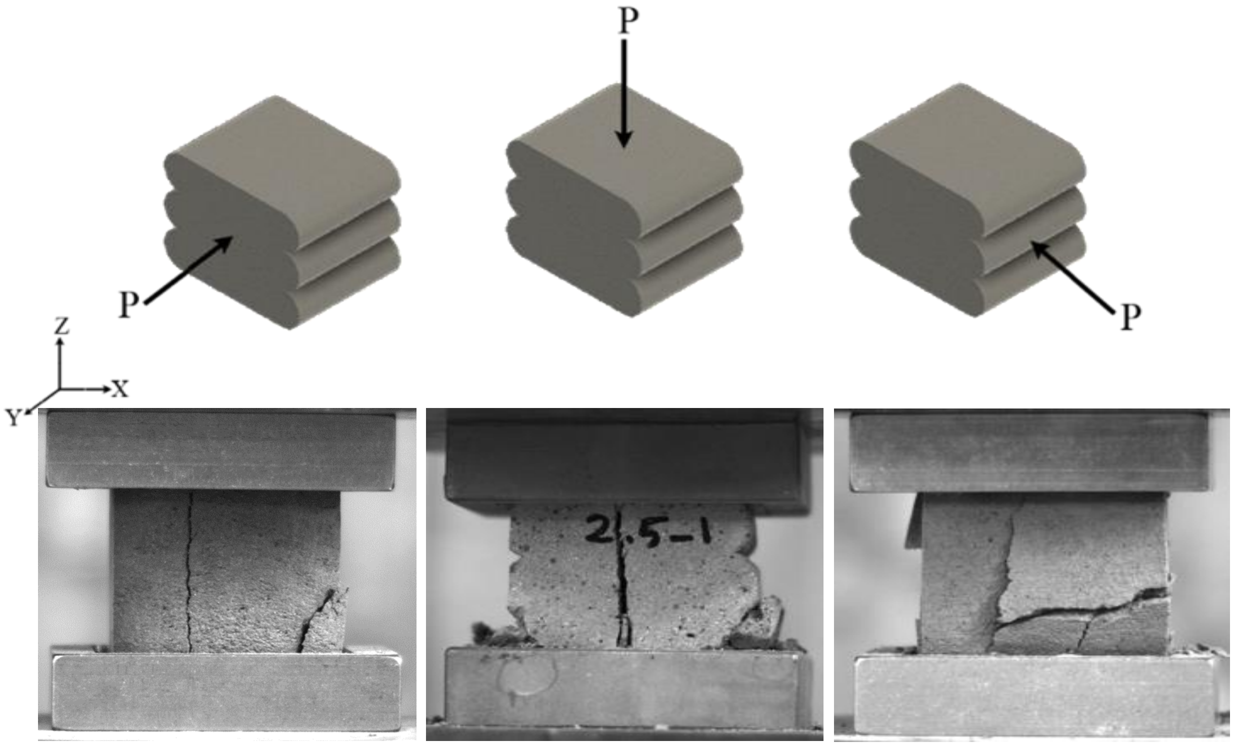
Cast

printed



Mechanical performance



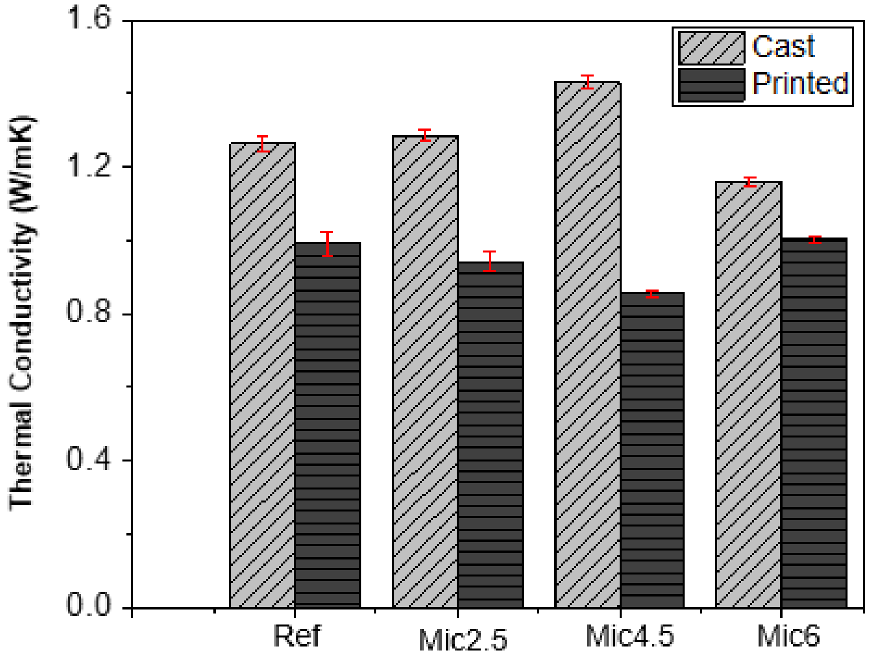


- elastic modulus is affected by both the physical properties of the added mPCM and their volume fractions
- shell properties (stiffness), shell thickness, and the particle size of the micro-inclusion all have an impact on the elastic properties
- an increase in the compressive strength in comparison with the printed reference when the vol% of mPCM is below 4.5%

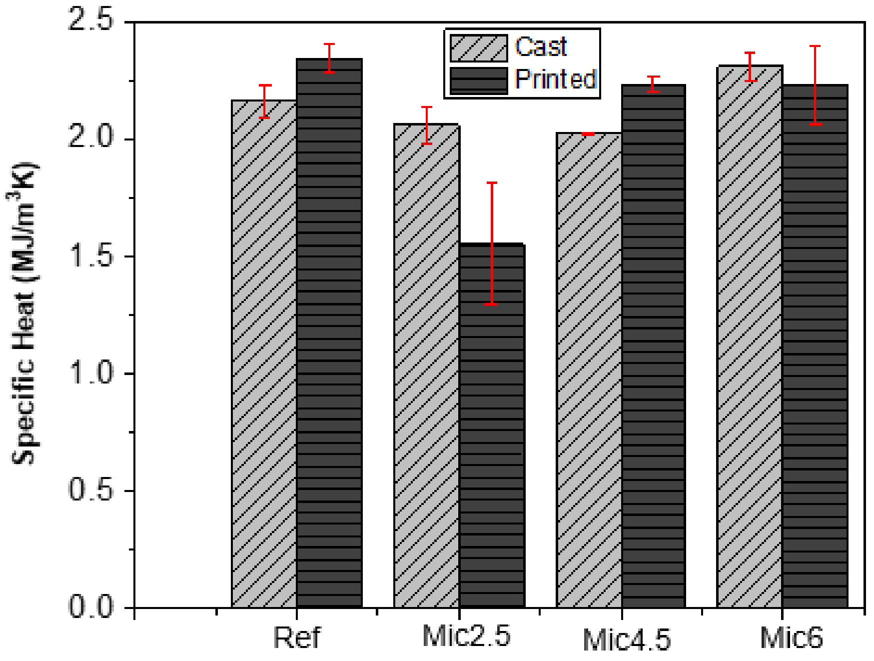
Density, mechanical, and thermal properties of the tested mixture groups

Mix ID	mPCM Volume Fraction v_f (%)*	Density* (cast) (kg/m³)	Density* (printed) (kg/m³)	Elastic Modulus (cast) (GPa)	Compressive Strength (cast) (MPa)	Compressive Strength (Printed x)	Compressive Strength (Printed y)	Compressive Strength (Printed z)
Reference	0.0	1793±19	1753±45	22.0±0.7	45.5±1.47	19.9±0.559	18.0±0.042	19.7±1.06
Mic2.5	2.5	1764±3	1681±15	20.3±1.3	43.1±0.311	19.8±2.932	20.9±0.827	19.9±0.55
Mic4.5	4.5	1786±12	1715±48	16.6±1.2	41.3±0.527	23.0±1.119	22.1±2.201	21.3±1.812
Mic6	6	1791±8	1739±20	15.4±0.8	42.1±0.459	17.8±1.079	18.4±3.326	19.2±2.728

Thermal Performance



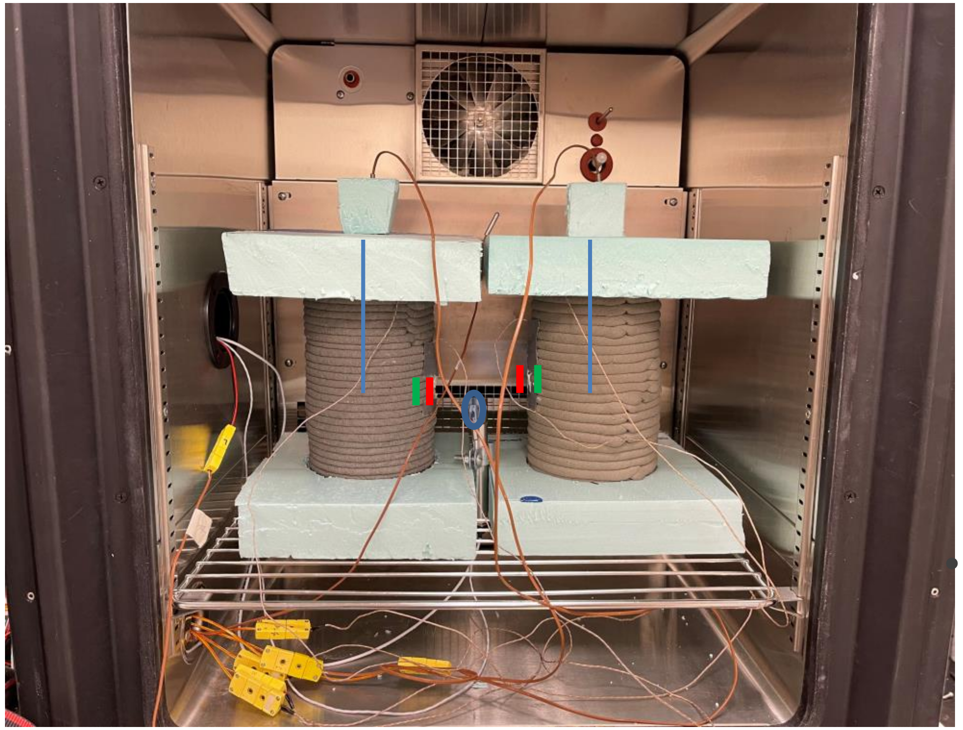
- thermal conductivity for cast samples agrees with the workability tests discussed earlier
- Printed samples showed an inconsistent trend when compared with the cast samples this is due to inconsistent compaction
- cast samples also do not show a clear trend with mPCM dosage which is likely due to the low thermal conductivity polymeric constituents added to the M68 mortar



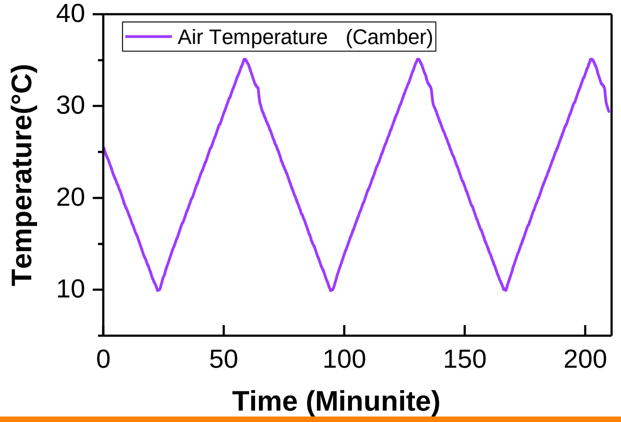
Thermal properties of the tested mixture groups

Mix ID	mPCM Volume Fraction v_c (%)*	Thermal Conductivity (Cast) W m^{-1}K^{-1}	Thermal Conductivity (Printed) W m^{-1}K^{-1}	Specific Heat Capacity (Cast) MJ/m^{3}K	Specific Heat Capacity (Printed) MJ/m^{3}K
Ref	0.0	1.2637±0.022	0.9915±0.032	2.163±0.069	2.342±0.059
Mic2.5	2.5	1.1833±0.0165	0.9417±0.027	2.06±0.082	1.553±0.257
Mic4.5	4.5	1.2857±0.0176	0.8556±0.0078	2.023±0.004	2.233±0.034
Mic6	6	1.1613±0.0122	1.002±0.011	2.309±0.064	2.229±0.163

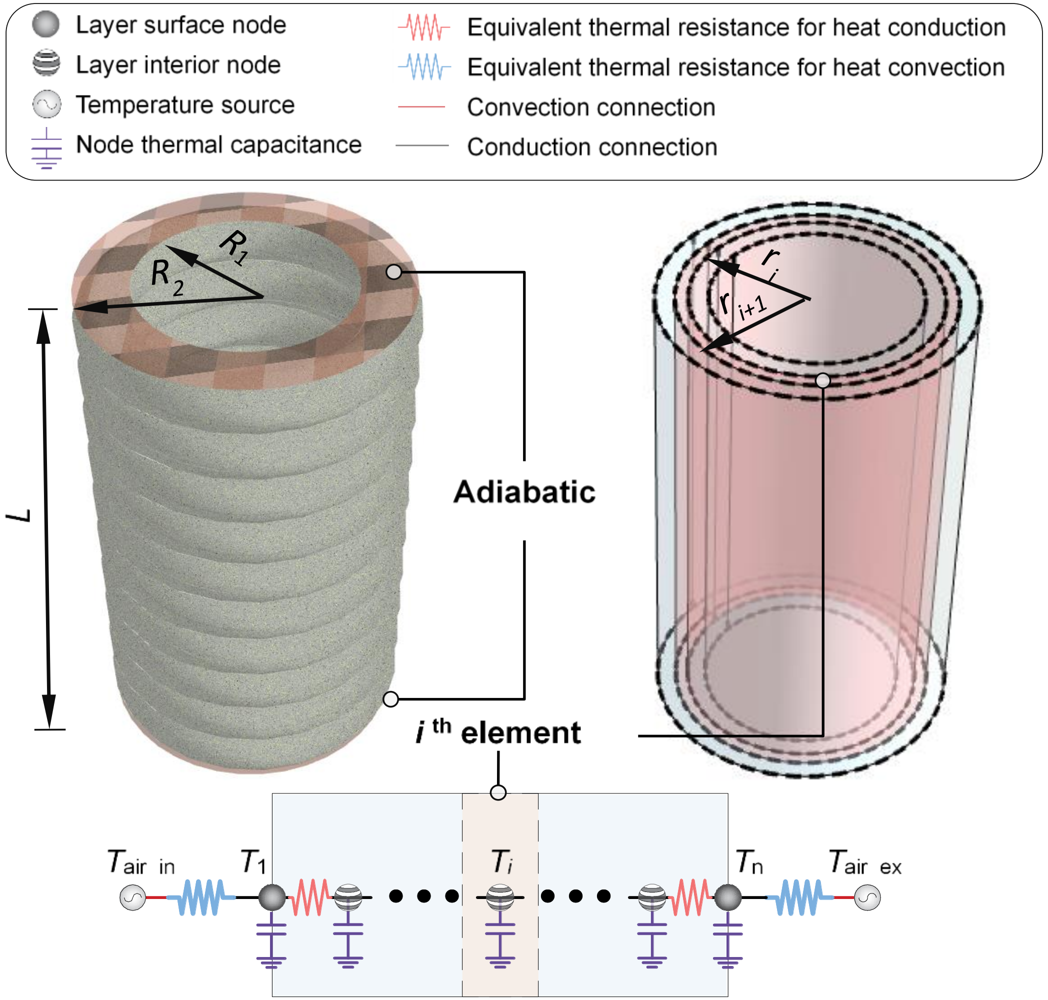
Thermal Cylinder Cyclical Test



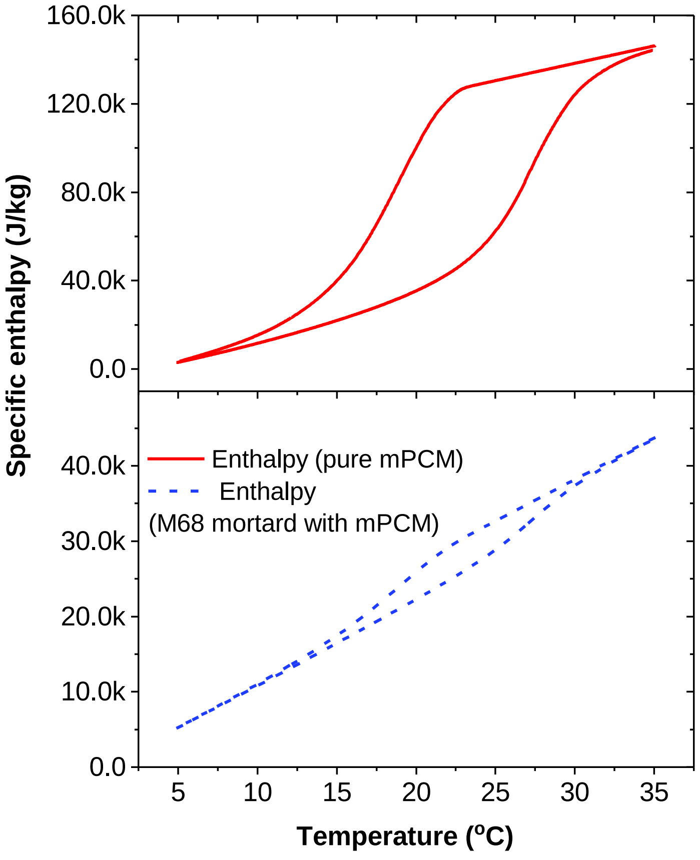
Air Temp Sensors
Inside Surface TC
Outside Surface TC

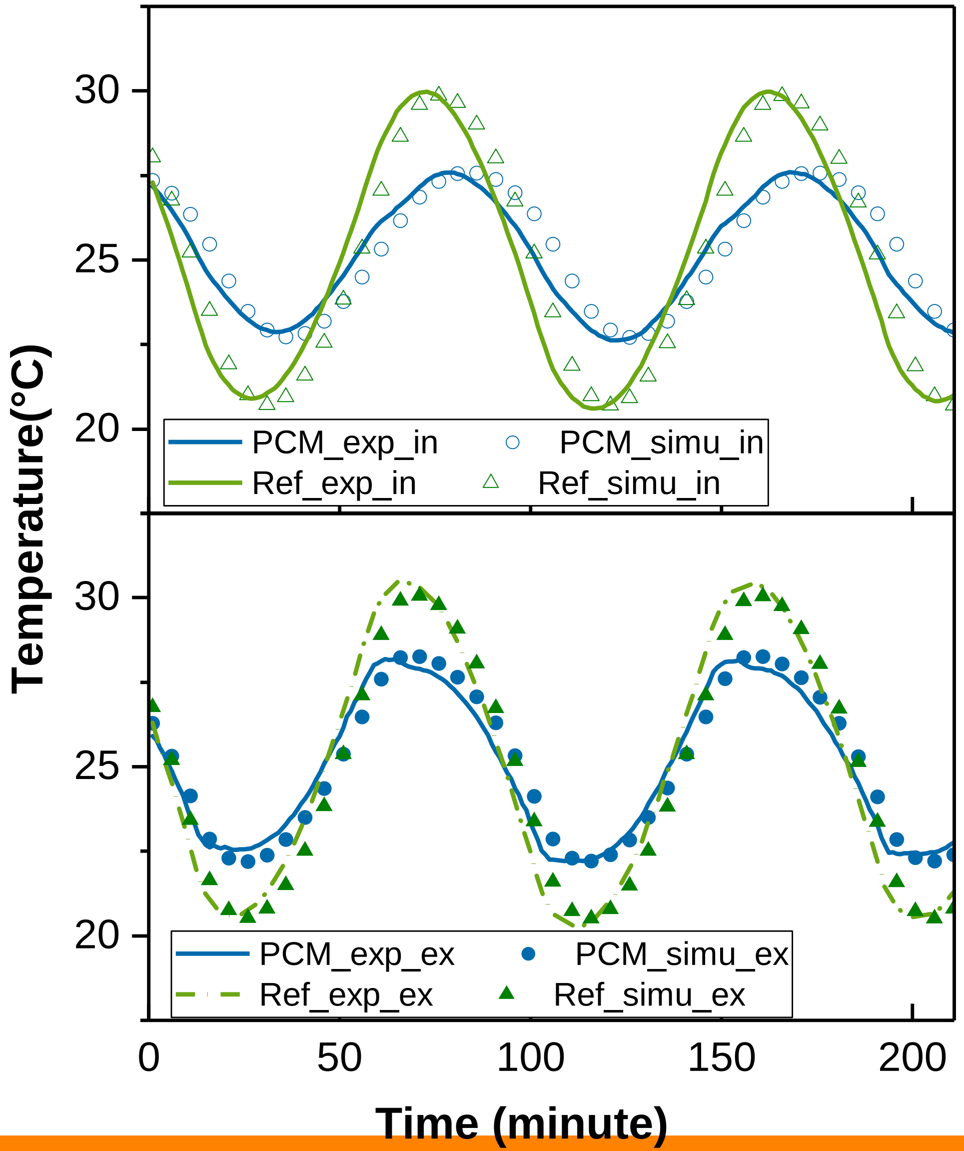


- 6-hour periodic cycles were used to represent a 24-hr diurnal cycle based on the 21mm thickness resulting in a ½ scale wall
- Due to insulation on the top and bottom the heat transfer was deemed to be 1-D
- Iterative process to solve both thermal conductivity and diffusivity



Model results





- One curve model was used in the simulation under cyclic thermal load
- Simulations agree well with both the reference and the Micronal samples
- Mic6 mortar exhibited significantly smaller temperature fluctuations in temperature
  - nearly 50% reduction in temperature amplitude
- Wheatstone bridge circuit
- Iterative process to solve both thermal conductivity and diffusivity

Conclusions

- The mPCM affected the printability of the cementitious ink material in different ways depending on the volumetric loading level. The results showed that the lower volume loading of the Micronal® mPCM (2.5%) increased the flowability as compared to the Ref mixture. However, as the dosage increased, a decrease of flowability was observed.
- The mechanical properties are greatly affected by the filler particle properties including the size, shell thickness, and crushing strength of the particles. The compressive strength of 3D printed cementitious composites containing <4.5 vol% mPCM slightly increases as compared to the Ref mixture.
- The elastic modulus is affected by both the inclusions physical properties and their volume percentage. The inclusion of polymer encapsulated mPCM resulted in a linear decrease in stiffness with increasing mPCM inclusion
- For cast samples the inclusion of mPCM at a low volume percentage can increase the thermal conductivity of the cementitious composite. For printed samples the variation of compaction states caused an erratic trend for the measured thermal conductivities
- Thermal cycling tests indicated that microencapsulated PCM materials are a potentially good candidate as an inclusion phase for 3D-printable cementitious composite materials to improve building’s thermal and energy performance.

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