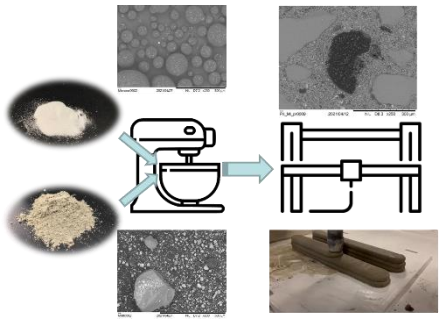
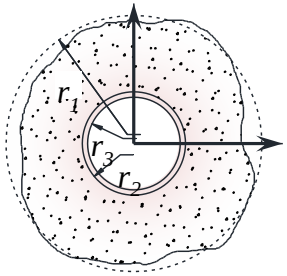
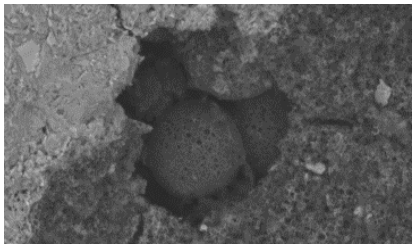
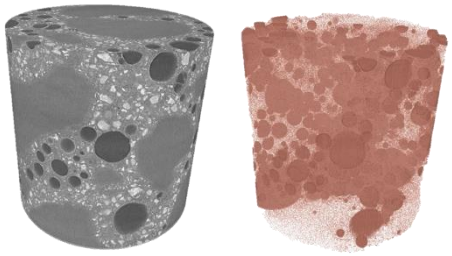
Ultra-Lightweight 3D Printable Cementitious Composites









Peyman Zandifaez, PhD Student; **Reese Sorgenfrei**, PhD Student
Hongyu 'Nick' Zhou, Ph.D., Associate Professor

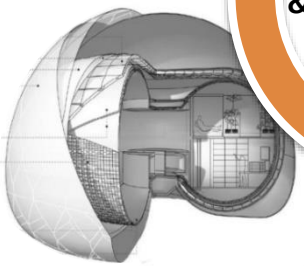
Department of Civil and Environmental Engineering
University of Tennessee, Knoxville

ACI Spring Convention, San Francisco
April, 2023

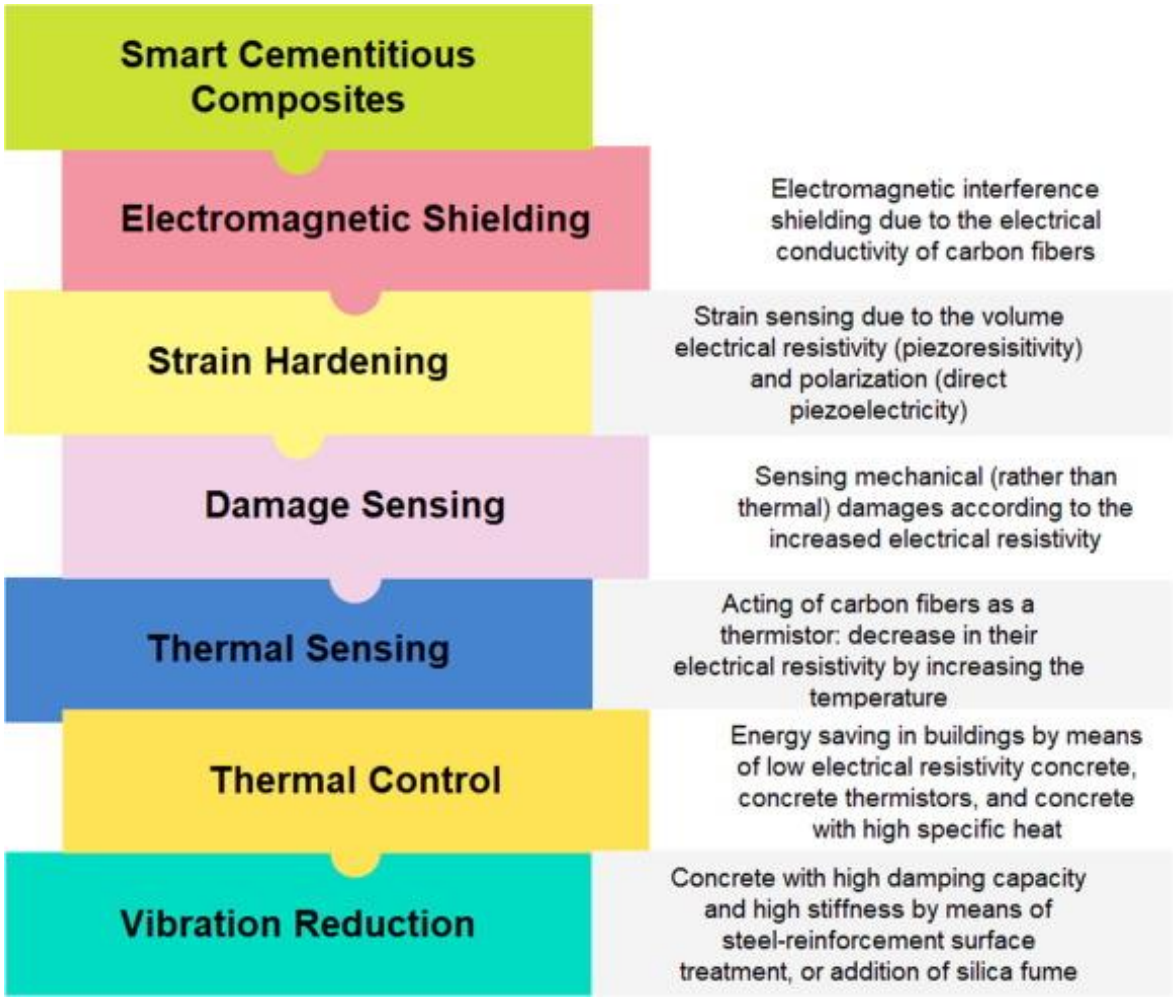
Tunable Building Materials

Architectural & Functional Demands

Digital Construction

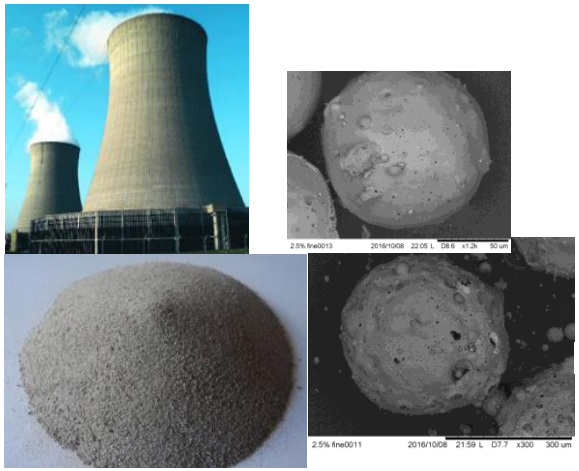


Functional Cementitious Composites

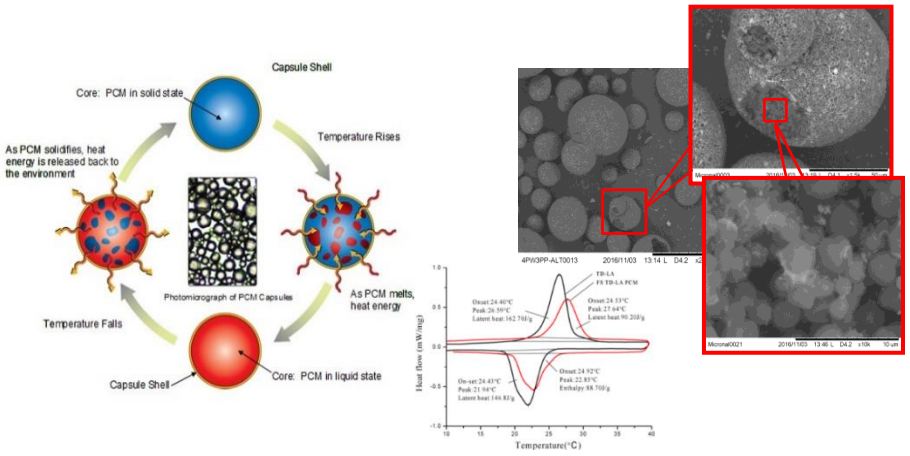


Hamidi F, and Aslani F. (2019), *Construction and Building Materials, 218(10): 582-609*.

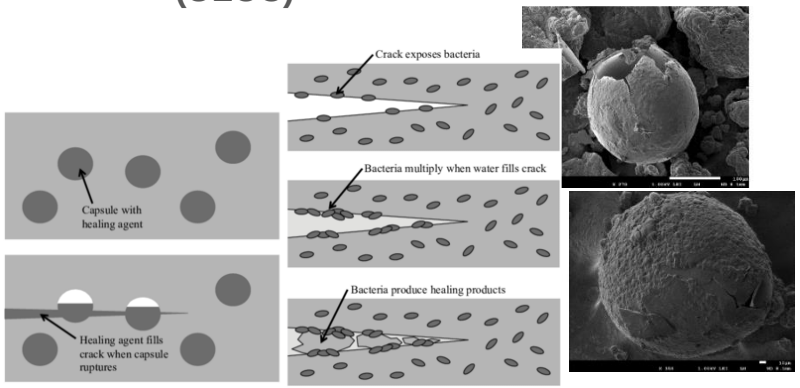
Functional Cementitious Composites for 3DP



Ultra-lightweight Cementitious Composite (ULCC)

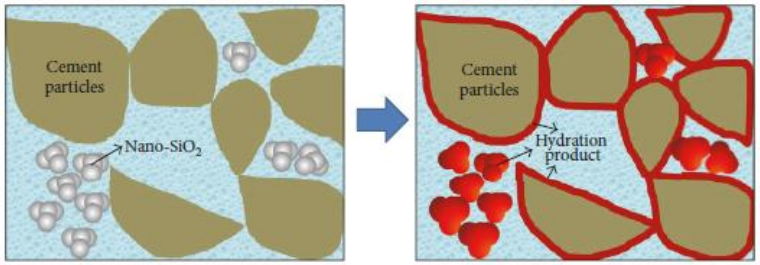


Thermal Energy Storage



Self-healing

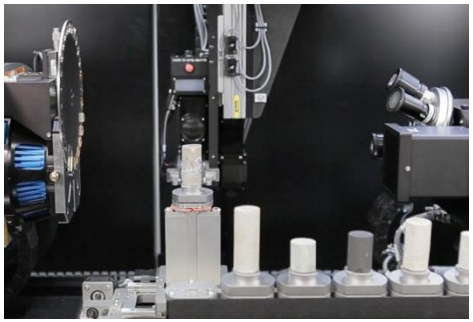
(VC Li et al., 2012)

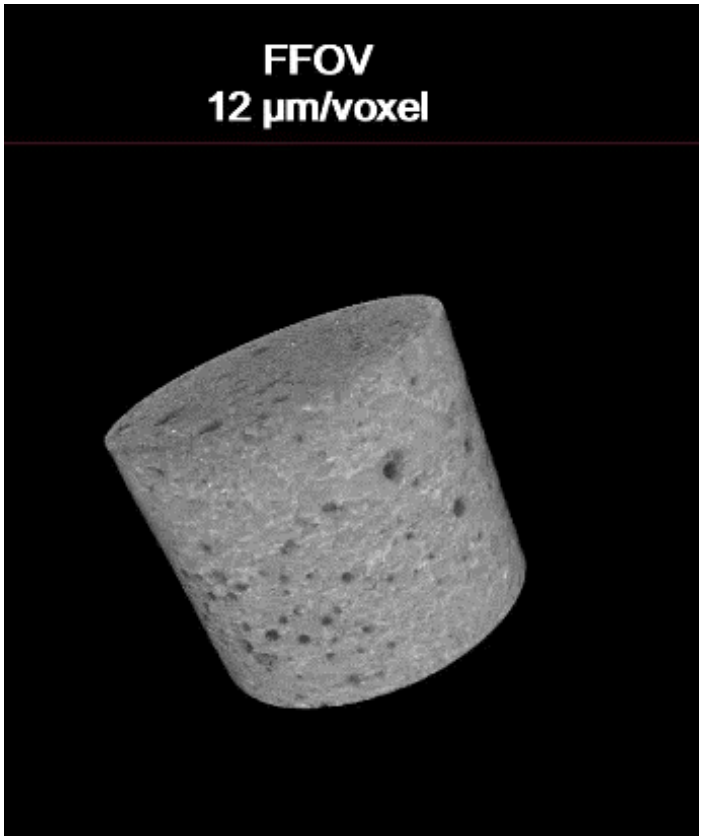


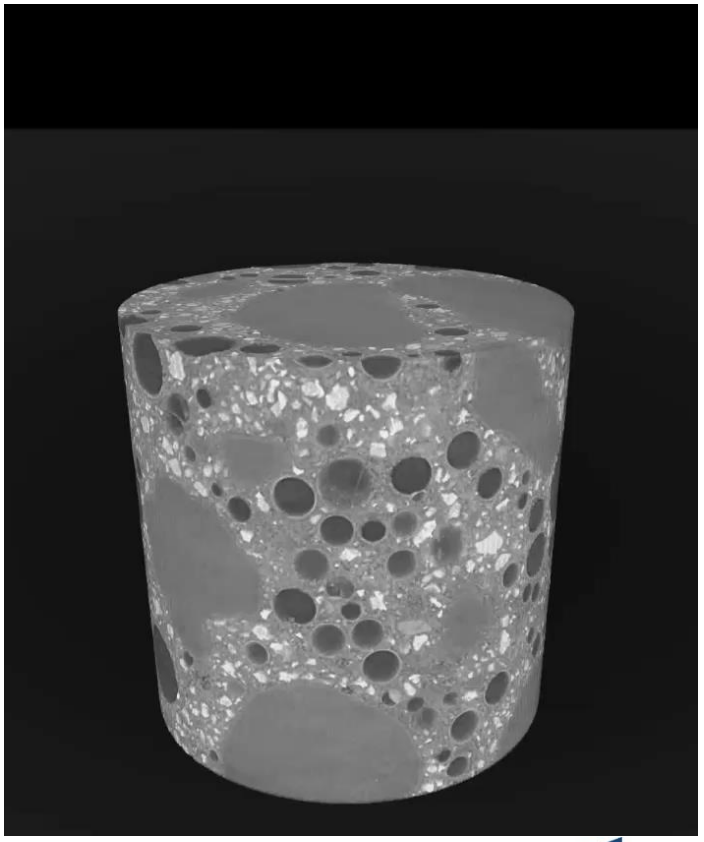
Hydration Control

(Gu et al. Adv. in mater. Eng., 2017, 3823621)

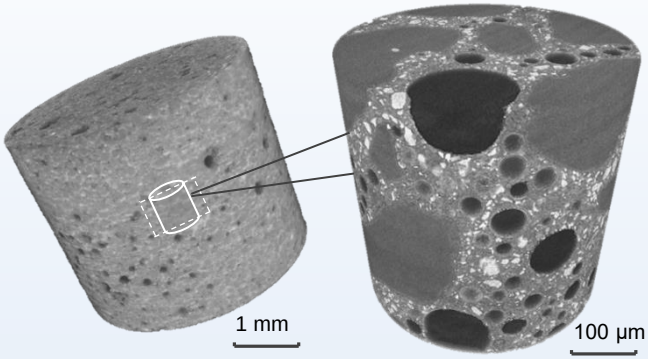
Functional Cementitious Composites





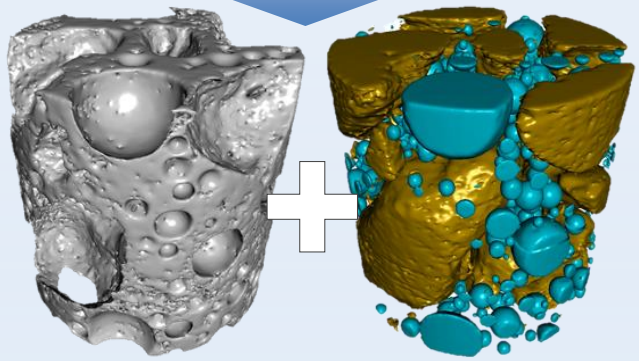


Micro-/Nano-Sized Hollow/ Core-Shell Inclusions in Cementitious Matrix



XRM scan of cementitious composite containing FAC CPS

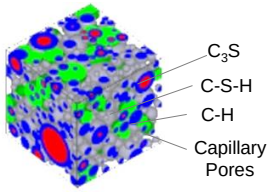
Phase Segmentation



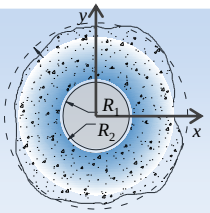
Cement Paste (Grey)

Inclusion Phase: Silica Sand (Yellow) + FAC CSP (Blue)

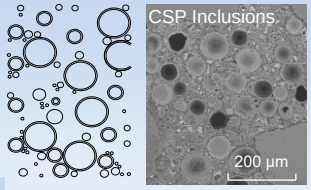
Microstructure of Cement Paste
< 1µm



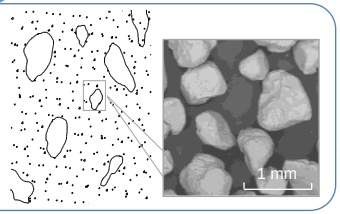
A Single Core-Shell Particulate (CSP) Functional Additive
1 – 100µm



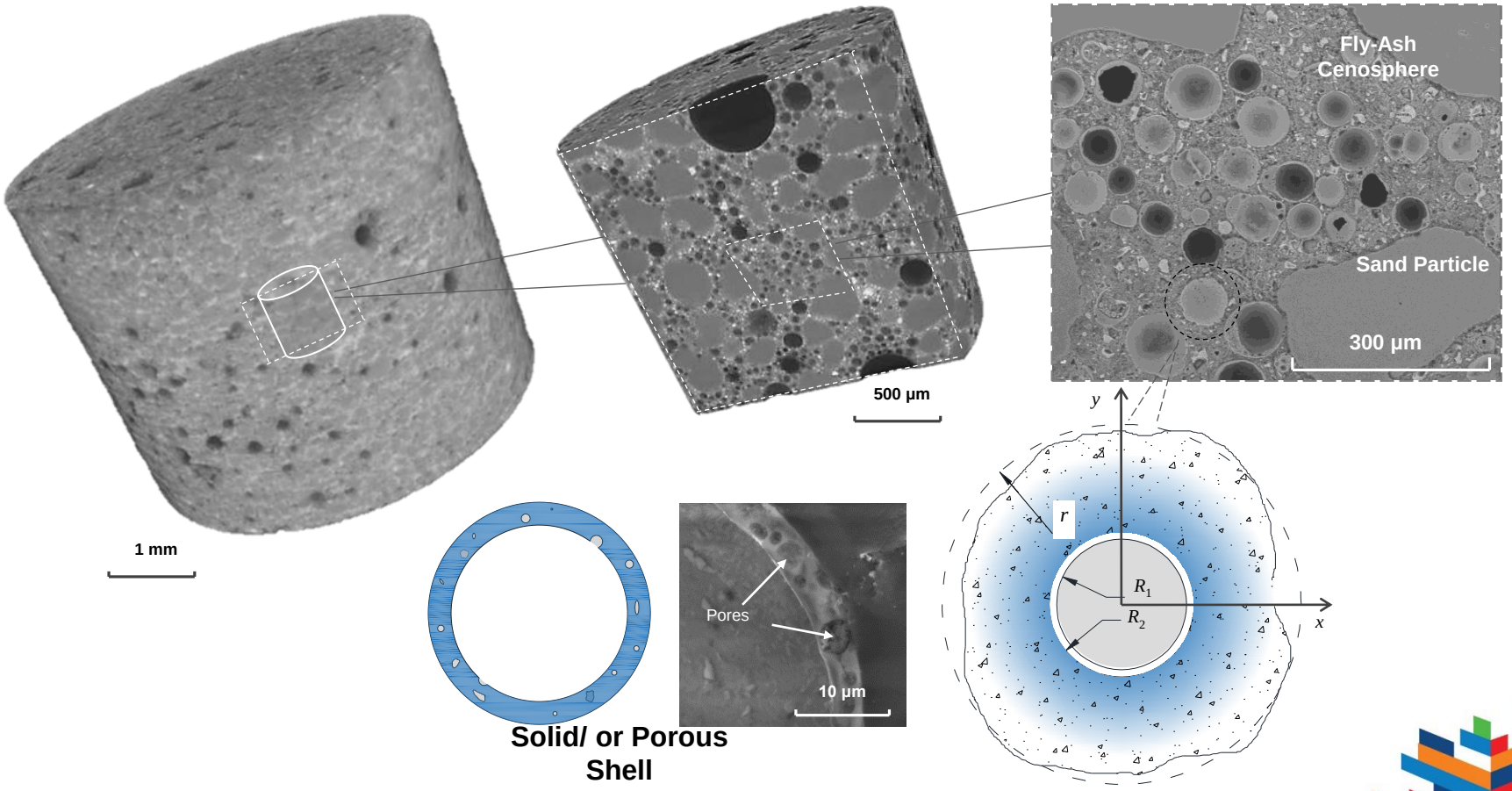
Cementitious Composite Containing Multiple CSP Inclusions
100µm – 1mm



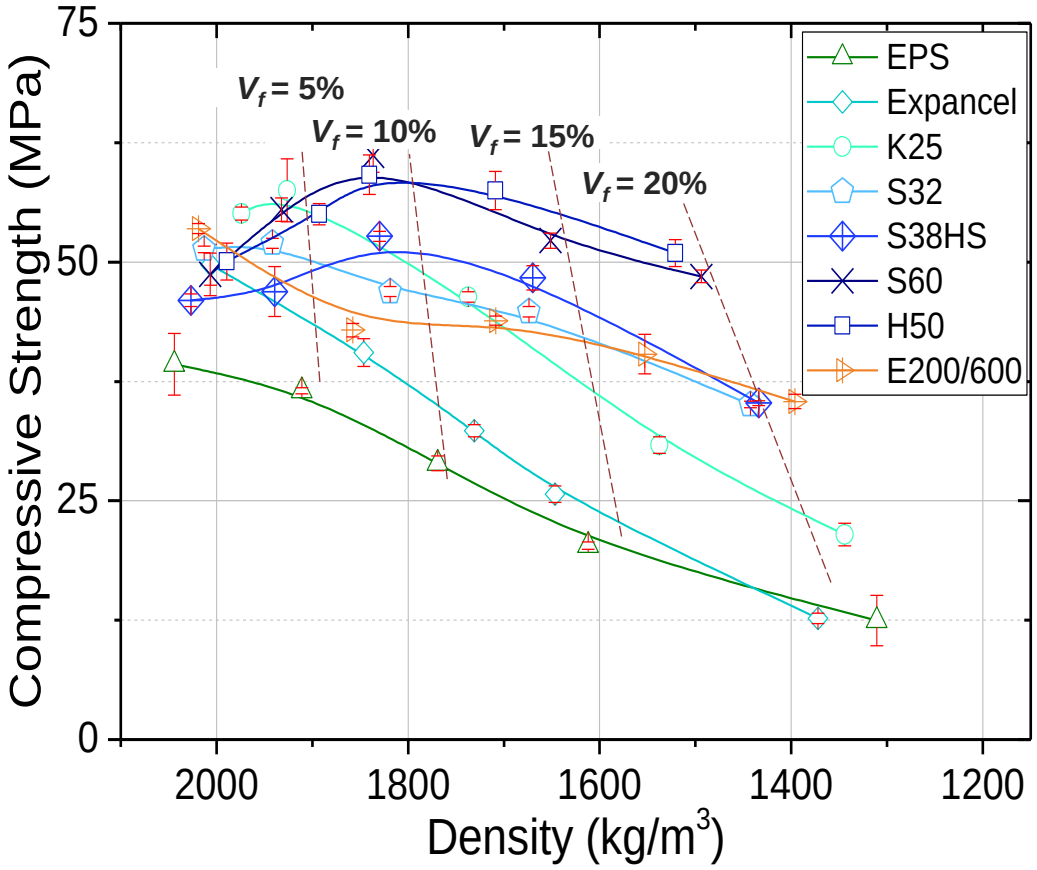
Fine and Coarse Aggregates
> 1mm



(ii) Synthetic Foam



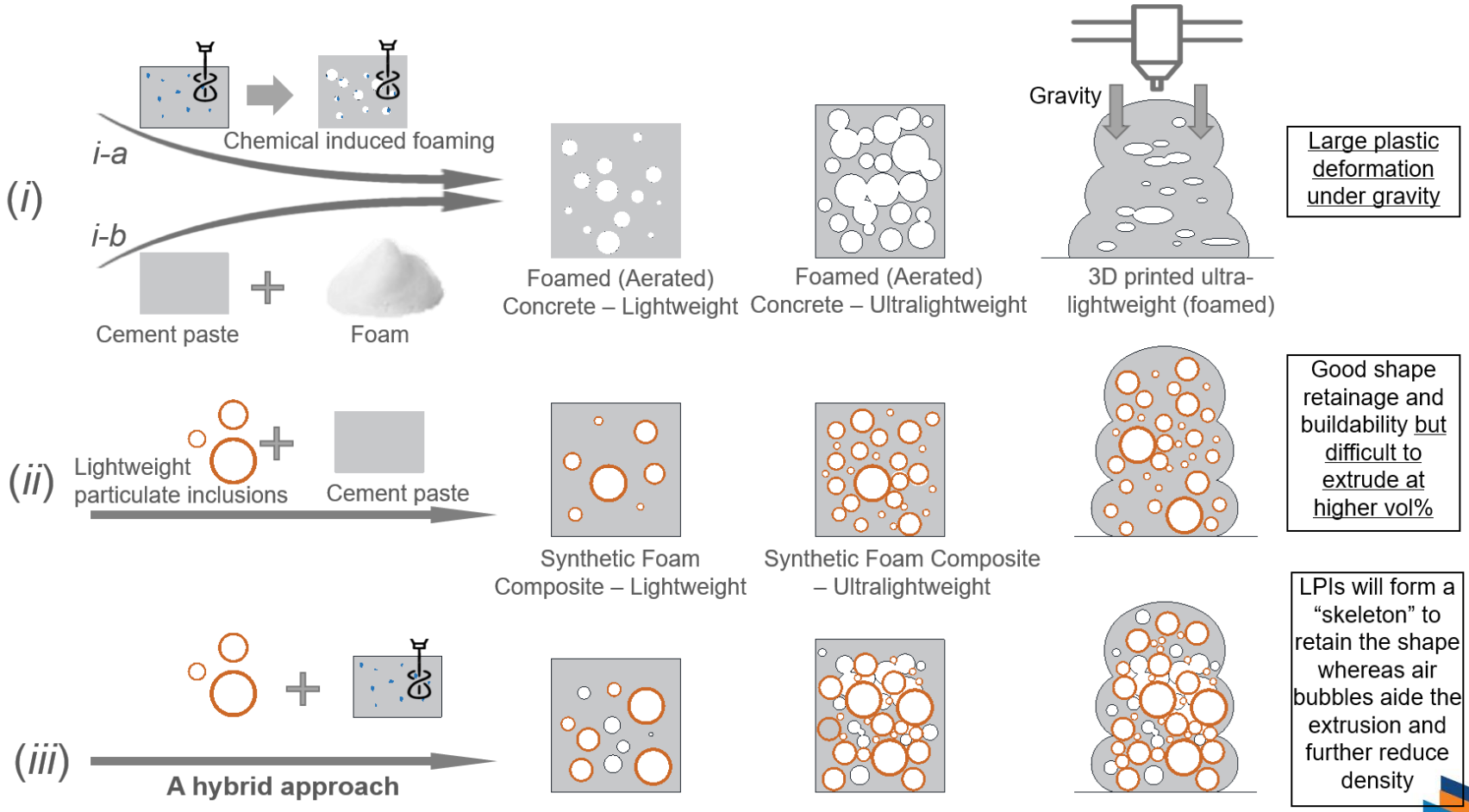
Solid/ or Porous Shell



- **The mechanical properties of ULCC 'synthetic foam' depend highly on the particle size and shell properties of the inclusion phase (micro-fillers).**
- **There seems to be an "size effect": Smaller particle are likely to yield higher stiffness (Young's modulus) and strength.**
- ***What exactly is dictating the material properties?***

Brooks, A.L.*, **Zhou, H.**, and Hanna, D.* (2018), Comparative study of the mechanical and thermal properties of lightweight cementitious composites. *Construction and Building Materials*, 159: 316-328.

Pathways to achieve lightweight/Ultra-lightweight cementitious composite for 3DP

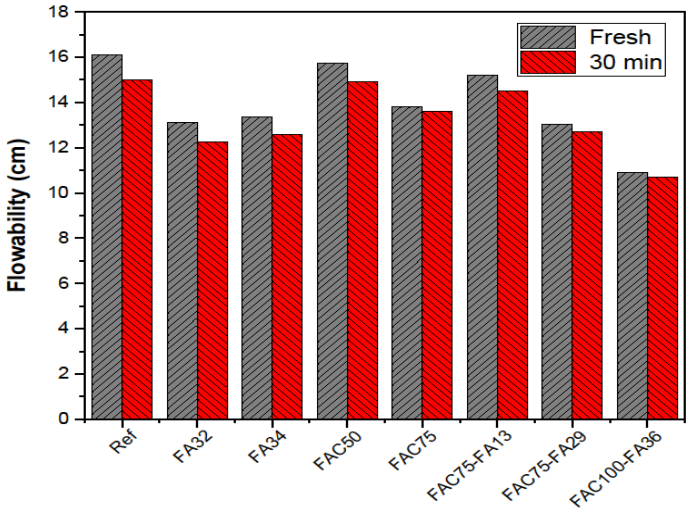


Experimental design

Mix ID	OPC	CSA	Sand	FAC	SP	CE	Foaming Agent	Water	Density
	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
Ref	981.1	9.9	991.0	0.0	1.7	1.4	0.00	306.4	2200
FA32	973.8	16.2	869.9	0.0	0.0	8.5	32.3	304.3	1310
FA34	968.2	16.1	864.9	0.0	0.0	8.5	33.9	306.6	1040
FAC50	977.4	9.9	493.7	169.5	6.5	1.4	0.0	305.3	1840
FAC75	974.0	9.8	246.0	253.4	11.0	1.4	0.0	304.2	1680
FAC75-FA13	1014.4	16.9	229.0	235.9	10.1	0.9	12.7	304.3	1160
FAC75-FA29	980.6	16.3	221.3	228.0	4.9	4.1	29.4	306.5	840
FAC100-FA36	950.2	15.8	0.0	293.8	0.0	8.3	36.4	313.9	470

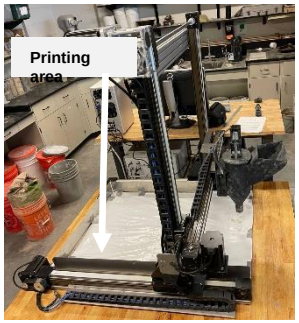
Printability

Flowability



Extrudability

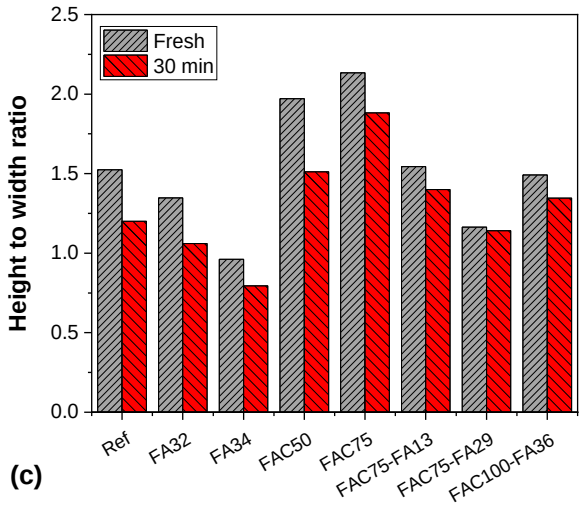
Mixture	Fresh	30 min	Fresh		30 min	
			Avg (cm)	Std (cm)	Avg (cm)	Std (cm)
Ref	E	E	1.60	0.10	1.23	0.18
FA32	E	E	1.62	0.03	1.49	0.04
FA34	OE	OE	1.81	0.16	1.71	0.13
FAC50	E	NE	1.19	0.08	NE*	NE
FAC75	E	NE	1.05	0.00	NE	NE
FAC75-FA13	OE	E	1.70	0.08	1.41	0.05
FAC75-FA29	OE	E	1.76	0.15	1.61	0.16
FAC100-FA36	E	E	1.53	0.04	1.41	0.05



Printability

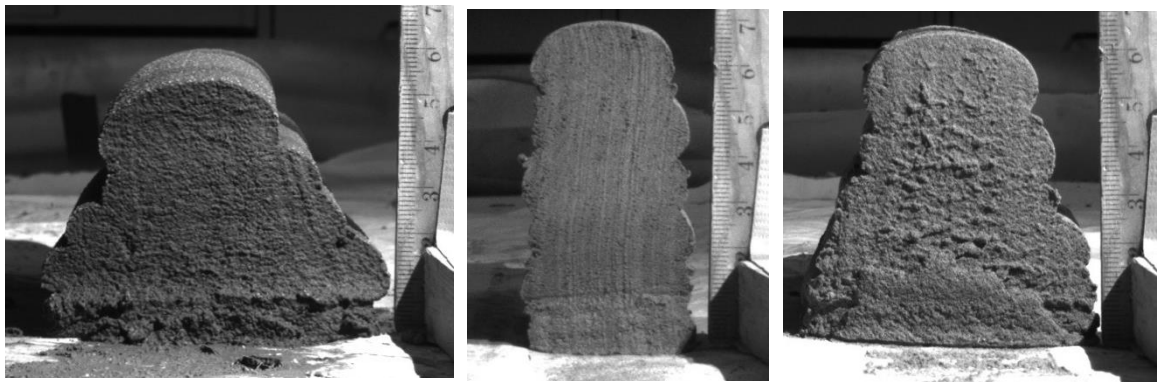
Buildability

(a)

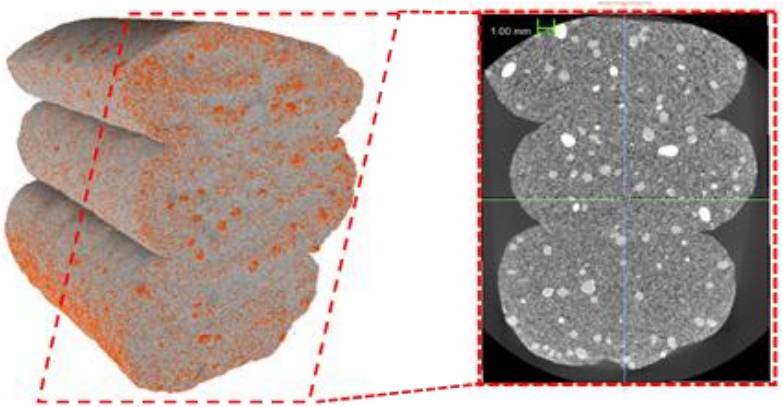


(b)

(c)

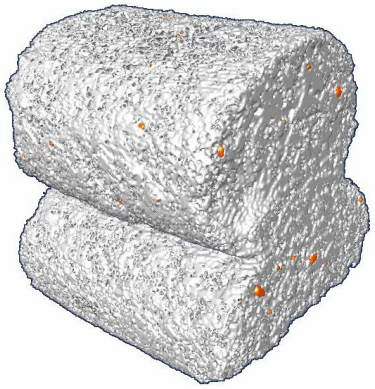


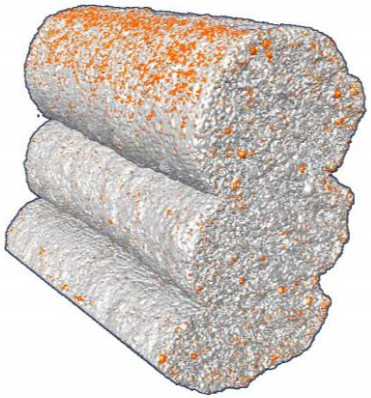
Microstructure

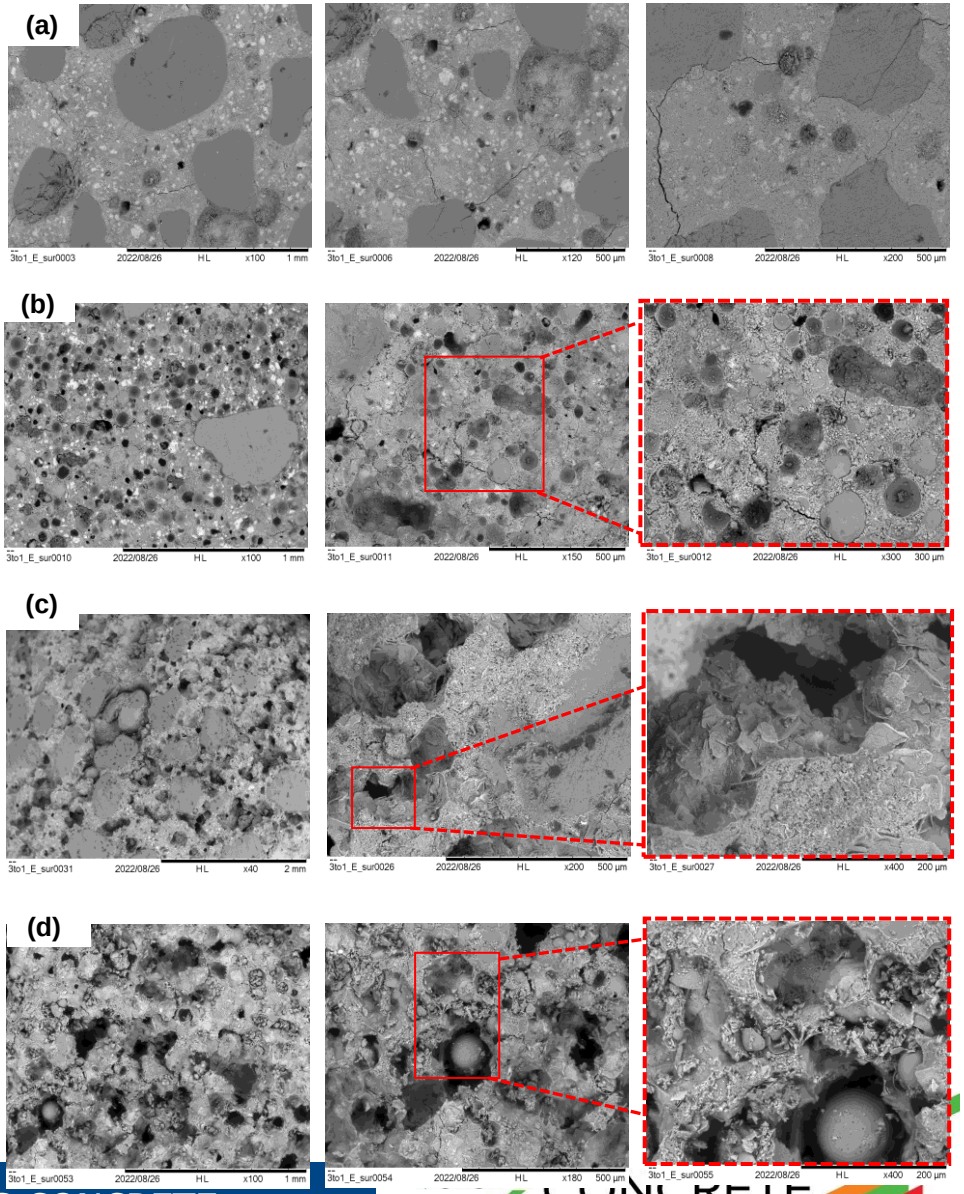


3D micro-CT

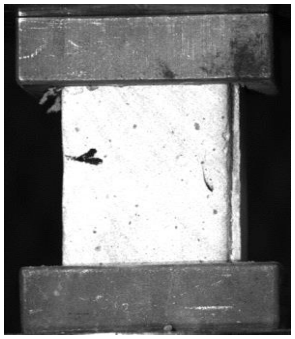
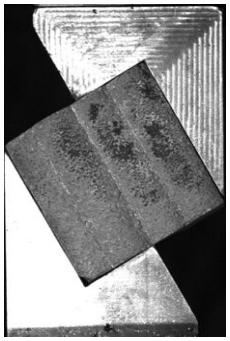
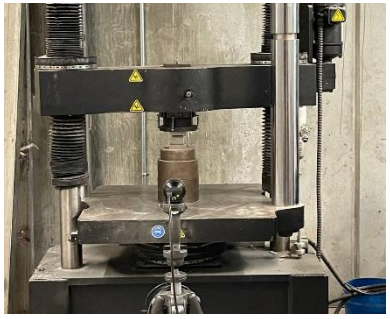
Cross-section

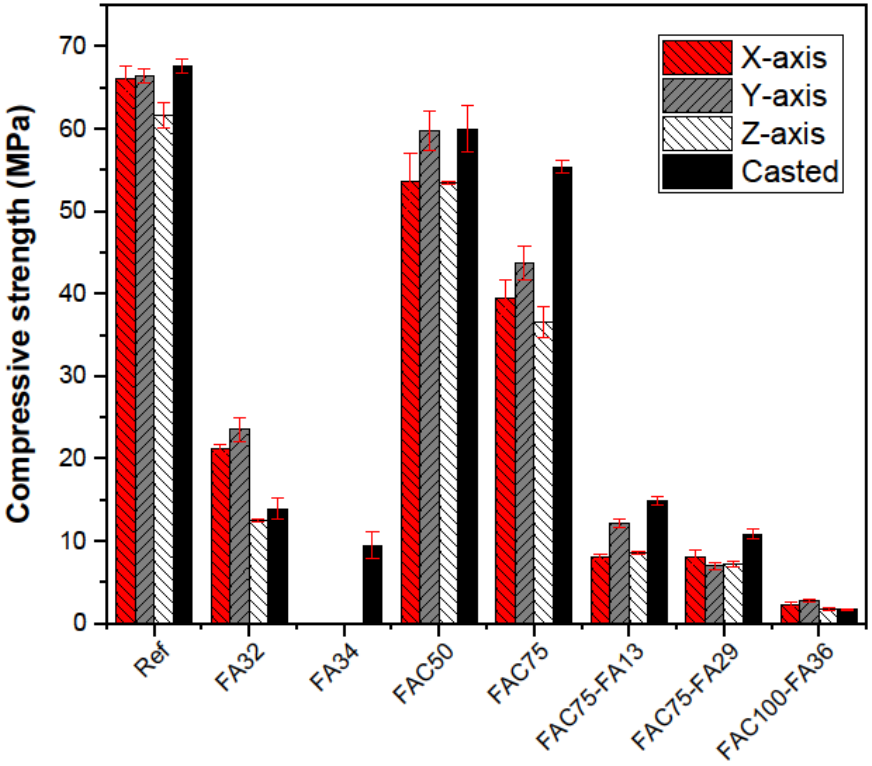






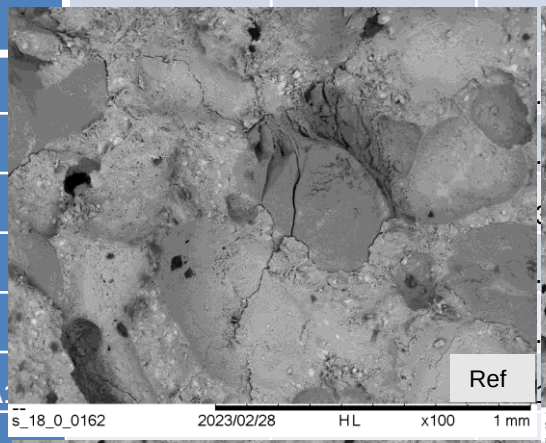
Mechanical Properties

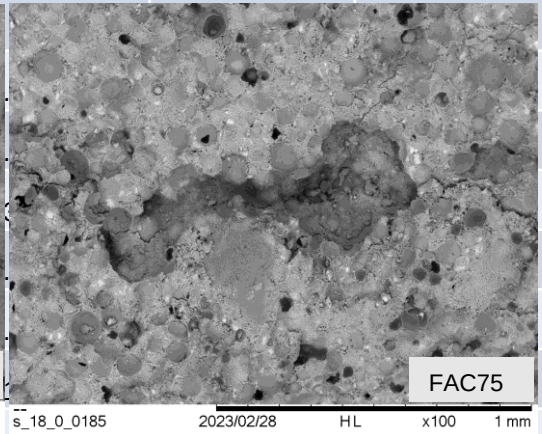





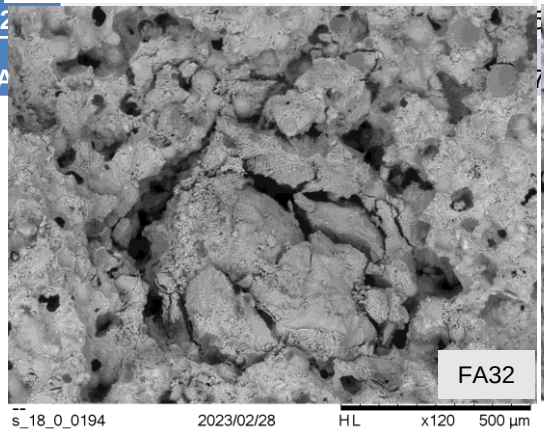



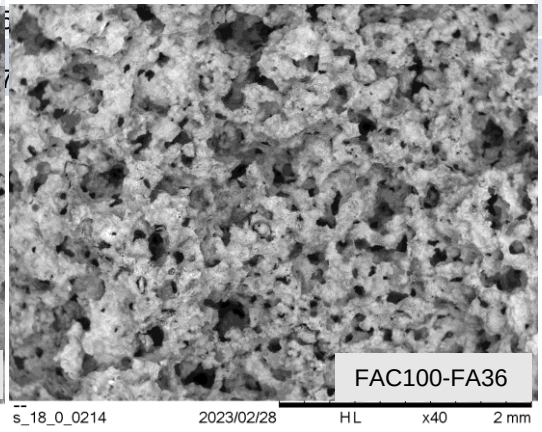
Mecha

Mix ID	Compressive strength (y-axis)	Compressive strength (z-axis)	Direct shear strength
	(MPa)	(MPa)	(MPa)
Ref	66.40 ± 0.91	61.60 ± 1.55	20.79 ± 0.51
FA32	23.50 ± 1.46	12.54 ± 0.17	6.01 ± 0.14
FA34	NP*	NP*	NP
FAC50	59.75 ± 2.47	53.46 ± 0.21	15.49 ± 0.41
FAC75	43.69 ± 2.08	36.57 ± 1.87	8.75 ± 0.68
FAC75-FA	12.11 ± 0.53	8.19 ± 0.18	3.14 ± 0.17
FAC75-FA2	8.30 ± 0.44	7.23 ± 0.36	1.74 ± 0.09
FAC100-FA	2.79 ± 0.14	1.76 ± 0.15	0.79 ± 0.02

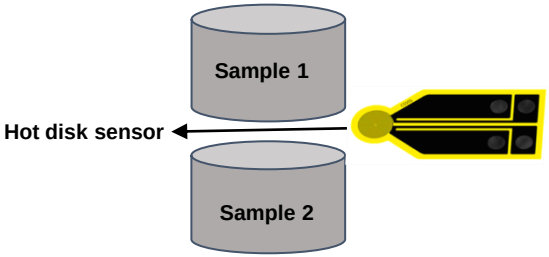


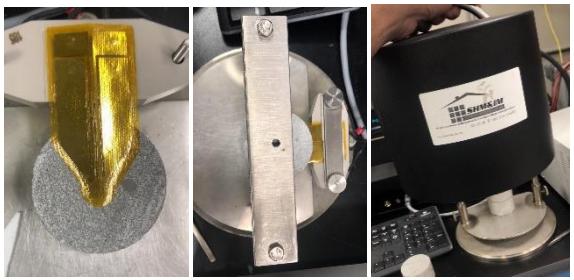


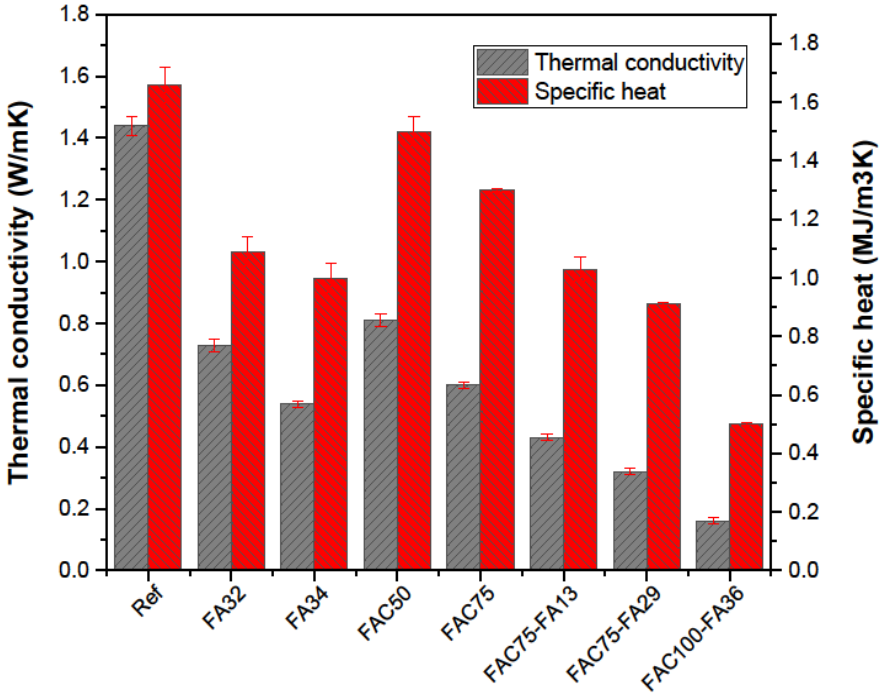




Thermal Properties

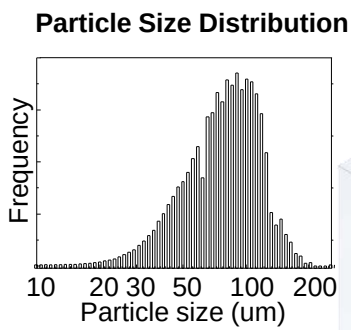


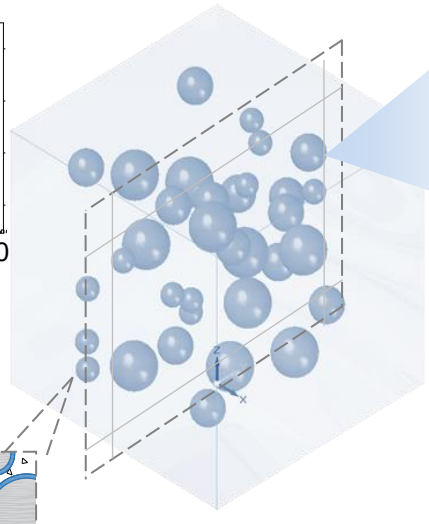


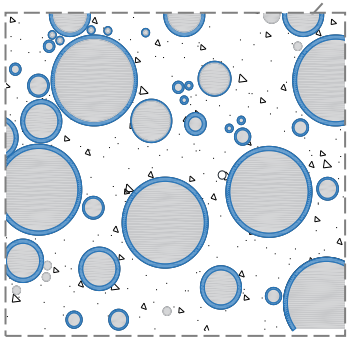


Microstructure-Guided Modeling

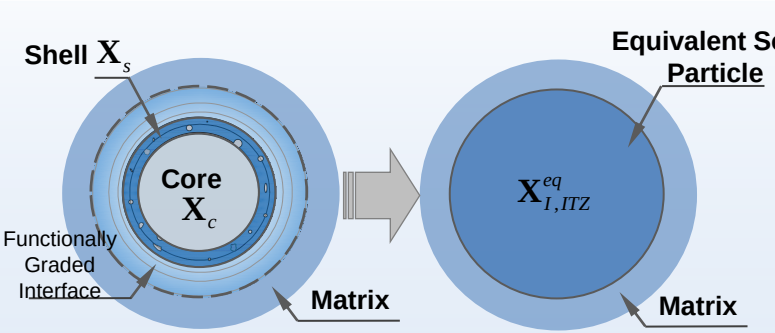
Micro-/Nano-Sized Hollow/ Core-Shell Inclusions in Cementitious Matrix







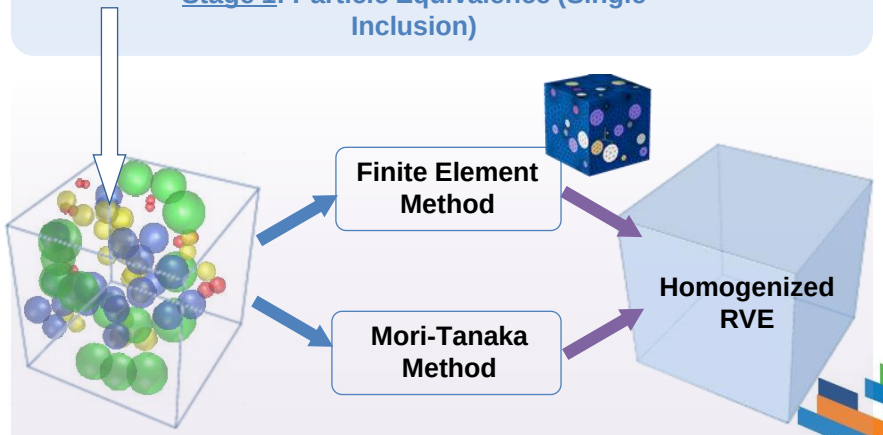
Cementitious Composite with Polydispersed CSP



Hollow/ Core-Shell Inclusion with Functionally Graded Interface

Equivalent Particle with Perfect Interface

Stage 1: Particle Equivalence (Single Inclusion)

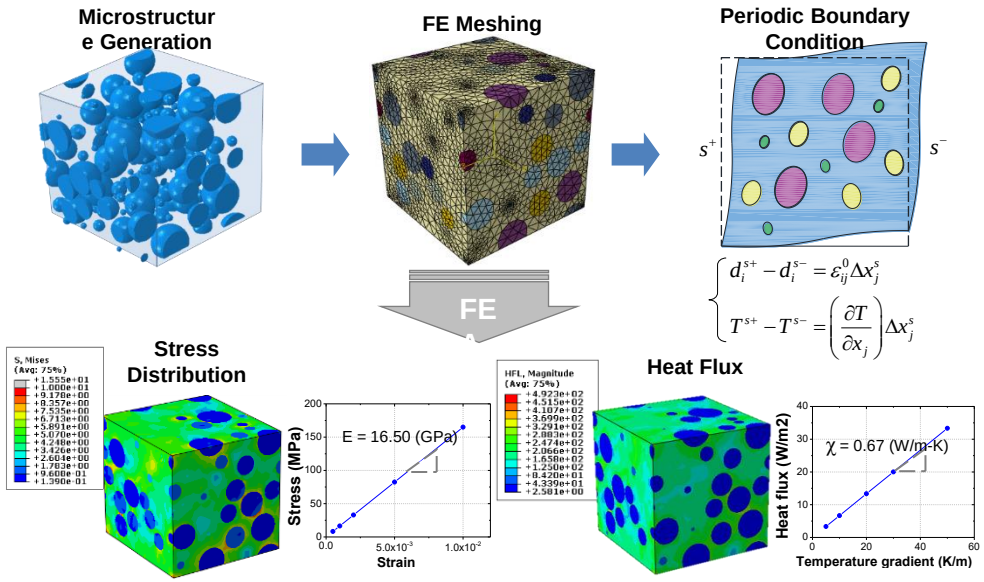


Stage 2: Numerical and Analytical Homogenization

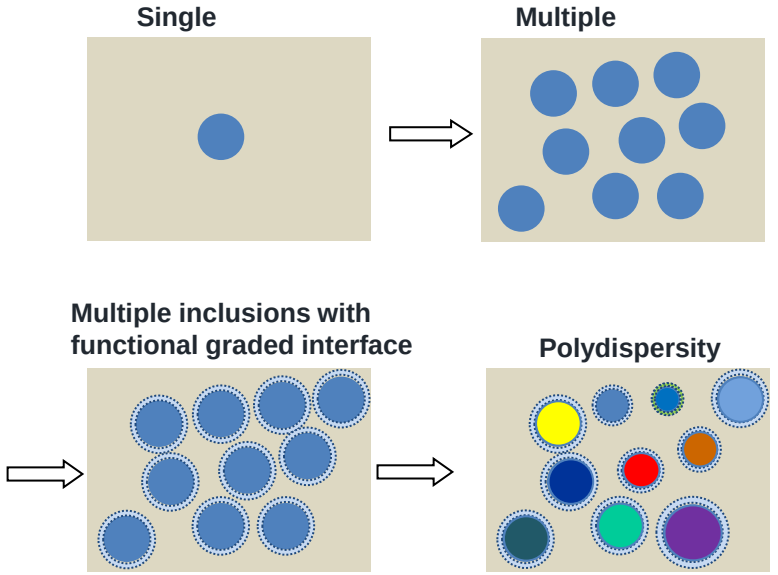
Shen, Z., and **Zhou, H.*** (2020), *Cement and Concrete Composites. 105, 103439*.

Microstructure-Guided Modeling

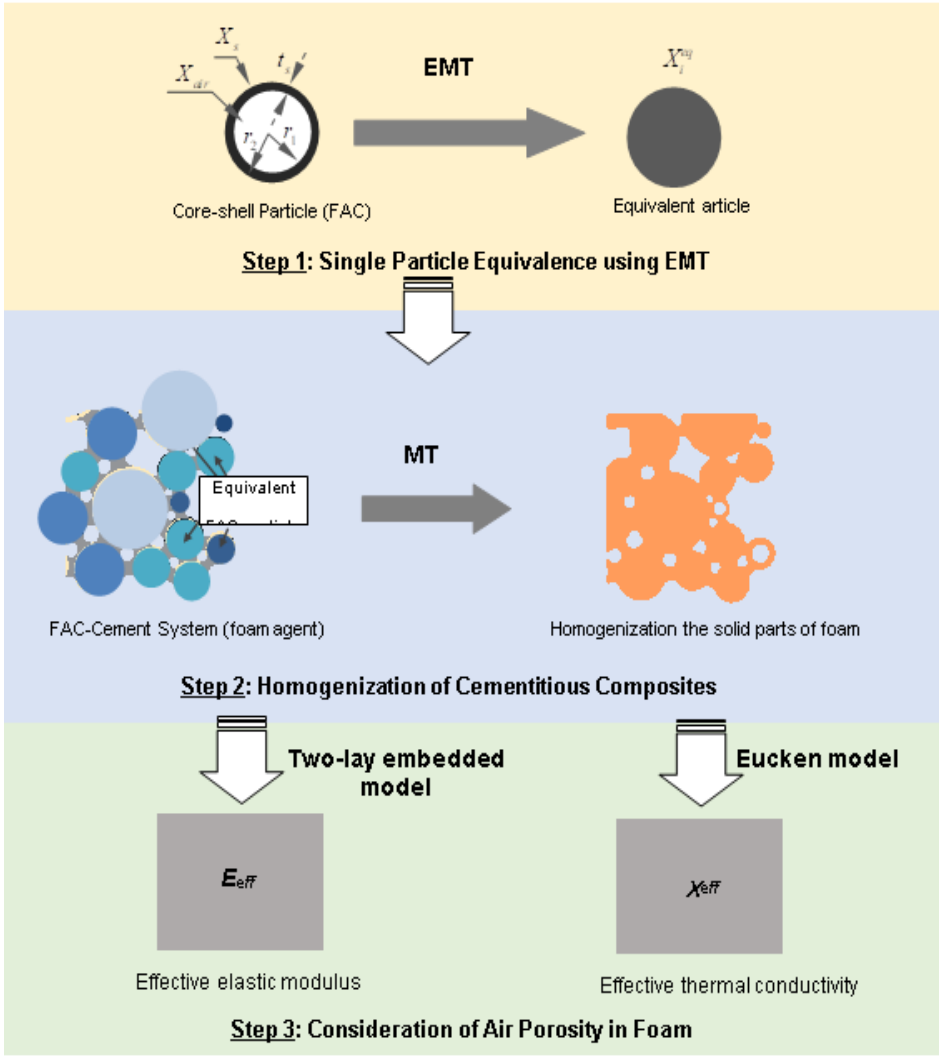
Microstructure-guided FEA (Numerical)

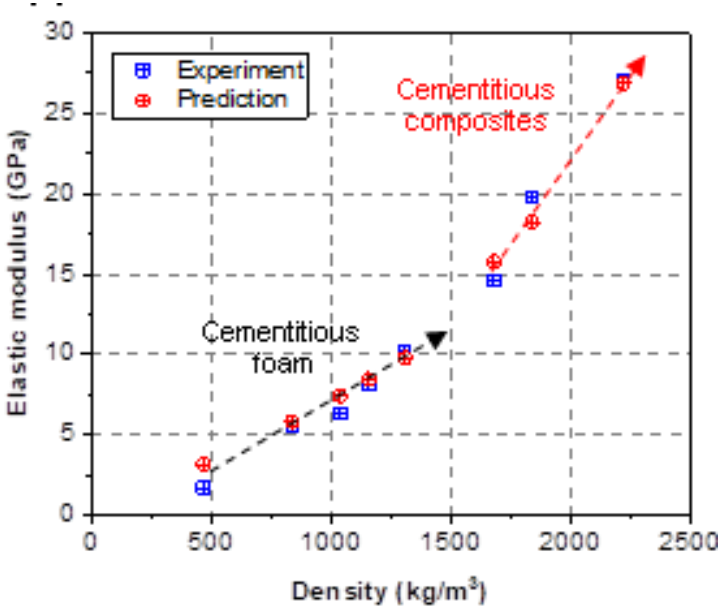


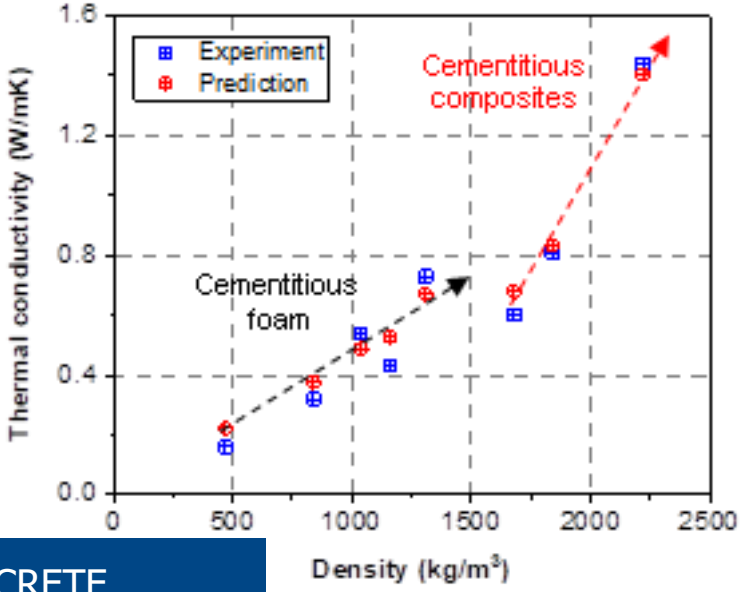
Mori-Tanaka Method (Analytical)



$$\bar{X}_{(\mathrm{MT})} = X_M + \sum_{i=1}^{N} \phi_i \left(X_{I,i} - X_M \right) \Gamma^X_{(\mathrm{MT}),i}$$


EMT
Core-shell Particle (FAC)
Equivalent article
Step 1: Single Particle Equivalence using EMT
MT
Equivalent
FAC-Cement System (foam agent)
Homogenization the solid parts of foam
Step 2: Homogenization of Cementitious Composites
Two-lay embedded model
Eucken model
Effective elastic modulus
Effective thermal conductivity
Step 3: Consideration of Air Porosity in Foam


Experiment
Prediction
Cementitious composites
Cementitious foam
Elastic modulus (GPa)
Density (kg/m³)
0
5
10
15
20
25
30
0
500
1000
1500
2000
2500


Experiment
Prediction
Cementitious composites
Cementitious foam
Thermal conductivity (W/mK)
Density (kg/m³)
0.0
0.4
0.8
1.2
1.6
0
500
1000
1500
2000
2500

Remarks & Outlook

- Three different strategies to achieve LCC and ULCC are investigated.
- The printability, mechanical properties, and thermal properties were studied. With only chemical foaming – the buildability of the mixture loses quickly as density reduces.
- The synergistic effect of chemical foaming and ‘synthetic foam’, the density of the mixture can be significantly reduced without compromising (too much) on the buildability and other printability parameters.
- Unprecedented low density (400kg/m^3) was achieved with the hybrid foaming strategy proposed.
- Studies are on-going in many other application involving micro-sized functional additives in 3D printable concrete.

References

1. AL Brooks, Y He, N Farzadnia, S Seyfimakrani, and H Zhou (2022). Incorporating PCM-enabled thermal energy storage into 3D printable cementitious composites. **Cement and Concrete Composites** (129), 104492
2. Z Shen, AL Brooks, Y He, J Wang, and H Zhou* (2021). Physics-guided multi-objective mixture optimization for functional cementitious composites containing microencapsulated phase changing materials. **Materials & Design** (207), 109842.
3. A Brooks, Y Fang, Z Shen, J Wang, and H Zhou* (2021). Enabling high-strength cement-based materials for thermal energy storage via fly-ash cenosphere encapsulated phase change materials, **Cement and Concrete Composite** (120), 104033.
4. Shen, Z., and Zhou, H.* (2020). Predicting effective thermal and elastic properties of cementitious composites containing polydispersed hollow and core-shell micro-particles. **Cement and Concrete Composites**, 105:103439.
5. Zhou H.* and Brooks A.L. (2019), Mechanical and thermal properties of lightweight concrete and cementitious composites containing lightweight aggregates and fly-ash cenospheres. **Construction and Building Materials**, 198: 512-526.
6. Brooks A.L., Zhou H.*, and Hanna D. (2018), Comparative study of the mechanical and thermal properties of lightweight cementitious composites, **Construction and Building Materials**, 159: 316-328.

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