Numerical Simulation of Hardening Chemo-Mechanics During 3D Printing of Concrete

ACI Spring 2025 Convention

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Civil and Environmental Engineering

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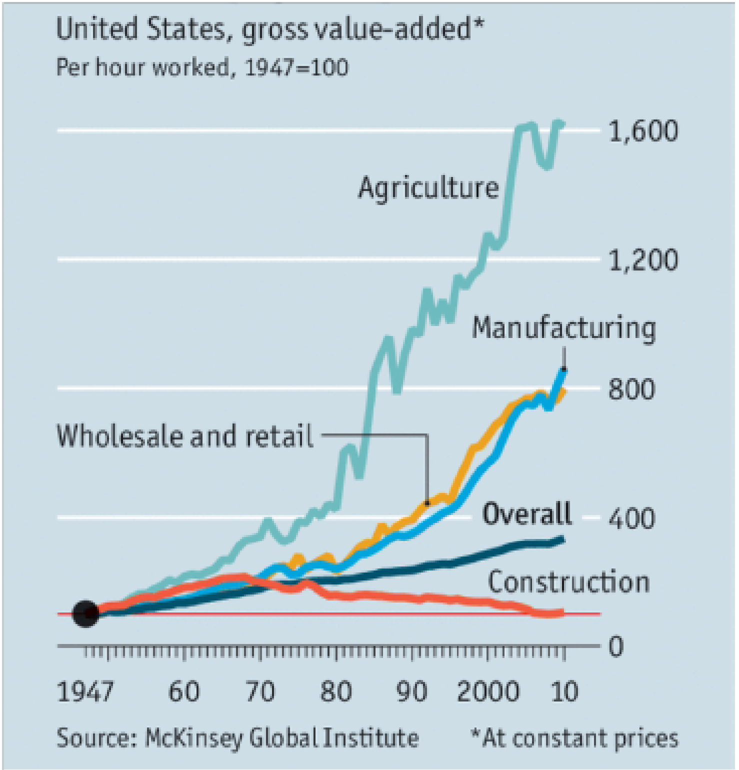
Concrete 3DP: Revolution in Construction?



Economist.com

- The construction industry is the only industry that has had a reduction in productivity in the last 40 years.
- This is mostly due to lack of automation.
- Automated additive manufacturing of infrastructure materials is poised to revolutionize the construction sector.
- New materials for existing additive manufacturing technologies.
- New additive manufacturing technologies for existing materials.
- Combined optimization of materials and additive manufacturing technologies.

Is "Concrete" Additive Manufacturing Ready for Primetime?

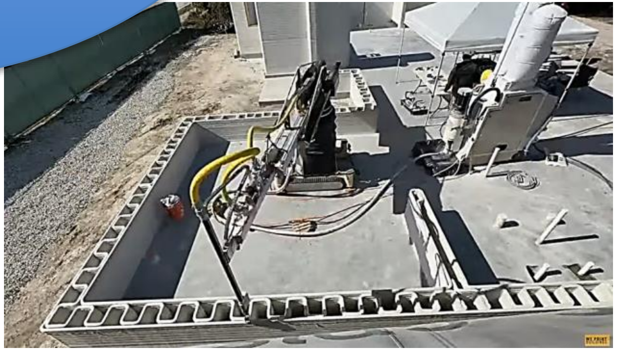
ICON

(USA)

How can we accurately design the printing process and calculate the load carrying capacity of these printed structures?

WINSUN

(China)



Design of the Printing Process and Prediction of Structural Capacity: Is Trial-And-Error and Large Scale Testing the Answer?

Mechanical properties of 3D printed concrete components: A review

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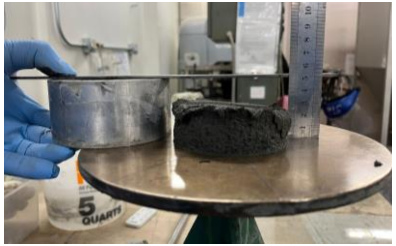
Fig. 14. 3DPC spliced beams in different experimental states: (a) Scale model specimen in bending set-up (Salet et al., 2018), (b) Setup of the structural mock-up test (Ahmed et al., 2022), (c) Uniform load test on post-tensioned prestressed girder (Vantyghem et al., 2020), (d) Straight beam for the three-point bending test (Asprone et al., 2018), (e) Failure pattern for 3DPC beam (Assaad et al., 2020).

We have been there already!

Duomo di Milano
Construction began 1386
Completion 1805

Small-Scale Experimentation & Computation to Drive Innovation

Rheological Properties



Setting and Fluid-Solid Transition

Hardened Properties

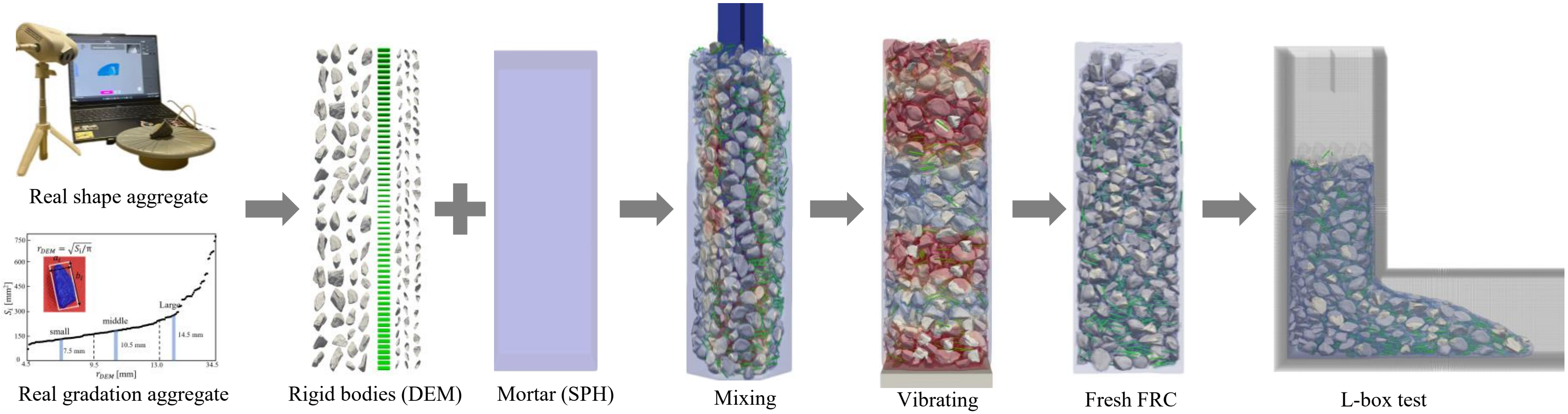
Comprehensive Computational Framework

- Validated models (for fresh state, setting, and hardened behavior)
- Data for UQ
- Robust Computational Solvers
- Artificial Intelligence
- Cloud Integration
- Innovative Computing Technologies (e.g. Quantum Computing)

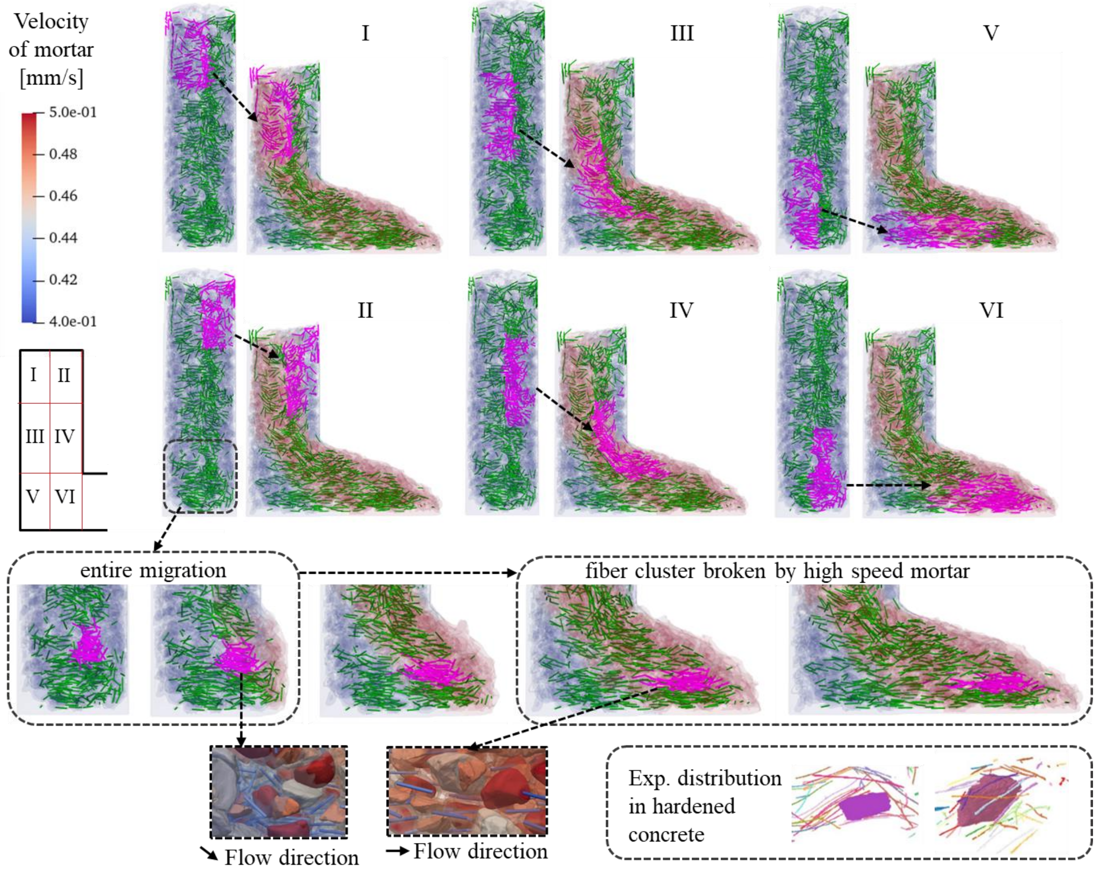
Prediction of Load Carrying Capacity of Printed Structures

High-Fidelity Modeling of Fresh Concrete: Coupling SPH and DEM

- Aggregate pieces with real shape
- Real aggregate size distribution
- Fluid fine mortar
- Rigid aggregate particles
- Fiber explicitly simulated

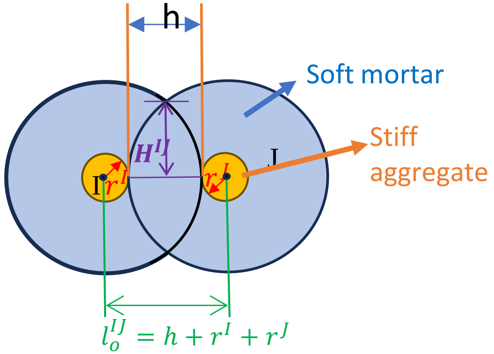


High-Fidelity Simulations: Fiber Orientation



Discrete Fresh Concrete (DFC) Model + Fibers

- **Aggregate approximated as spheres**
- **Real aggregate size distribution**
- **Fluid mortar not explicitly resolved**
- **Rigid aggregate particles**
- **Fiber explicitly simulated**



Compression

$h \le P < 2h$ soft contact

$$\dot{\sigma}_{Ns} = E_{NM}\dot{\varepsilon}_N$$
$$\dot{\sigma}_{Ms} = 0 \ \& \ \dot{\sigma}_{Ls} = 0$$

$P \ge 2h$ hard contact

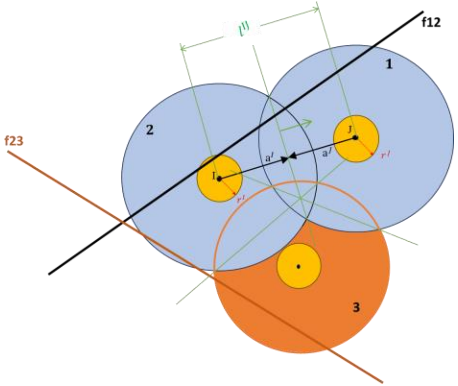
$$\dot{\sigma}_{Ns} = E_{Na}\dot{\varepsilon}_N$$
$$\dot{\sigma}_{Ms} = \alpha_a E_{Na}\dot{\varepsilon}_M$$
$$\dot{\sigma}_{Ls} = \alpha_a E_{Na}\dot{\varepsilon}_L$$

Stiffness stresses

Tension

$0 \le \boldsymbol{\sigma}_N < \boldsymbol{\sigma}_t$

$$\dot{\sigma}_{Ns} = E_{NM}\dot{\varepsilon}_N$$
$$\dot{\sigma}_{Ms} = 0 \ \& \ \dot{\sigma}_{Ls} = 0$$



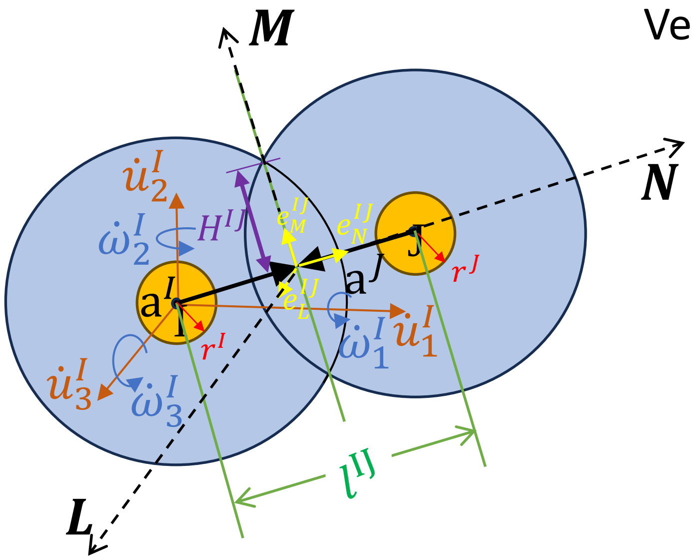
$l^{IJ} = l_o^{IJ}$ P=h then F_n=0 (zero configuration)

$l^{IJ} < l_o^{IJ}$ $P = h + \Delta$ then compression and viscous force is active.

$P = 2h \rightarrow l^{IJ} = r^I + r^J$ then hard contact

$l^{IJ} > l_o^{IJ}$ $P = h - \Delta$ then tension and viscous force is active.

Discrete Fresh Concrete (DFC) Model + Fibers



$\dot{u}_i^{I,J}$ translational velocities

$\dot{\omega}_i^{I,J}$ angular rates

Velocity jump vector at the centroid of the interaction area

$$[\![\dot{\mathbf{u}}]\!]_c^{IJ} = \dot{\boldsymbol{u}}^J + \dot{\boldsymbol{\omega}}^J \times \mathbf{a}^J - \dot{\boldsymbol{u}}^I - \dot{\boldsymbol{\omega}}^I \times \mathbf{a}^I$$

$$\dot{\varepsilon}_N^{IJ} = \frac{[\![\dot{\mathbf{u}}]\!]_c^{IJ} \boldsymbol{e}_N^{IJ}}{l^{IJ}}$$

$$\dot{\varepsilon}_M^{IJ} = \frac{[\![\dot{\mathbf{u}}]\!]_c^{IJ} \boldsymbol{e}_M^{IJ}}{l^{IJ}}$$

$$\dot{\varepsilon}_L^{IJ} = \frac{[\![\dot{\mathbf{u}}]\!]_c^{IJ} \boldsymbol{e}_L^{IJ}}{l^{IJ}}$$

$$\sigma_N = \sigma_{NS} + \sigma_{N\tau}$$

$$\sigma_M = \sigma_{MS} + \sigma_{M\tau}$$

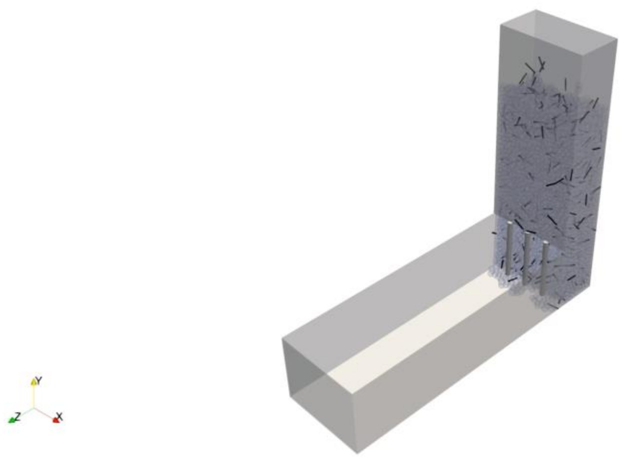
$$\sigma_L = \sigma_{LS} + \sigma_{L\tau}$$

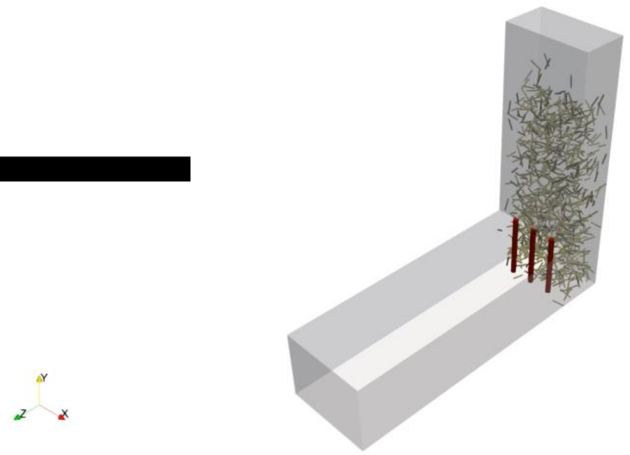
Stiffness stress : $\sigma_{NS}, \sigma_{MS}, \sigma_{LS}$

Viscous stress : $\sigma_{N\tau}, \sigma_{M\tau}, \sigma_{L\tau}$

Discrete Fresh Concrete (DFC) Model: Slump Test

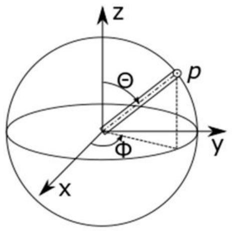
Discrete Fresh Concrete (DFC) Model: L-box Test





Effective Discrete Fresh Concrete (DFC) Model

- Aggregate approximated as spheres
- Real aggregate size distribution
- Fluid mortar not explicitly resolved
- Rigid aggregate particles
- Fiber not explicitly simulated



$$\mathbf{p} = \begin{bmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{bmatrix}$$

The dynamics of an ellipsoidal particle in a viscous fluid is governed by Jeffery's equation

$$\dot{\mathbf{p}} = \boldsymbol{\omega} \cdot \mathbf{p} + \lambda(\dot{\boldsymbol{\varepsilon}} \cdot \mathbf{p} - \mathbf{p} \cdot \dot{\boldsymbol{\varepsilon}} \cdot \mathbf{pp})$$

$$\eta = \eta_o \left[(1-c) + \frac{\pi c r^2}{3\ln(2r)} \right]$$

$$\sigma_{\tau o} = \tilde{\sigma}_{\tau o} \left(1 - \frac{c}{\phi_{fm}} - \frac{\phi_s}{\phi_{sm}} \right)^{-2}$$

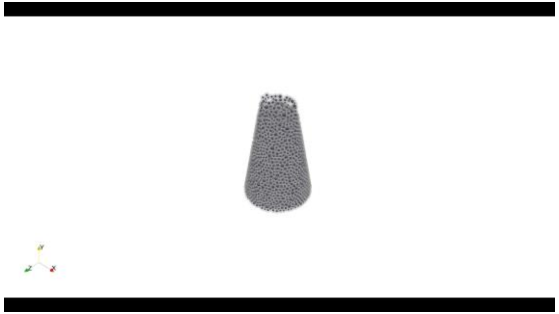
Jeffery, George Barker.
"The motion of ellipsoidal particles immersed in a viscous fluid."
Proceedings of the Royal Society of London. Series A, Containing papers of a mathematical and physical character 102.715 (1922): 161-179.

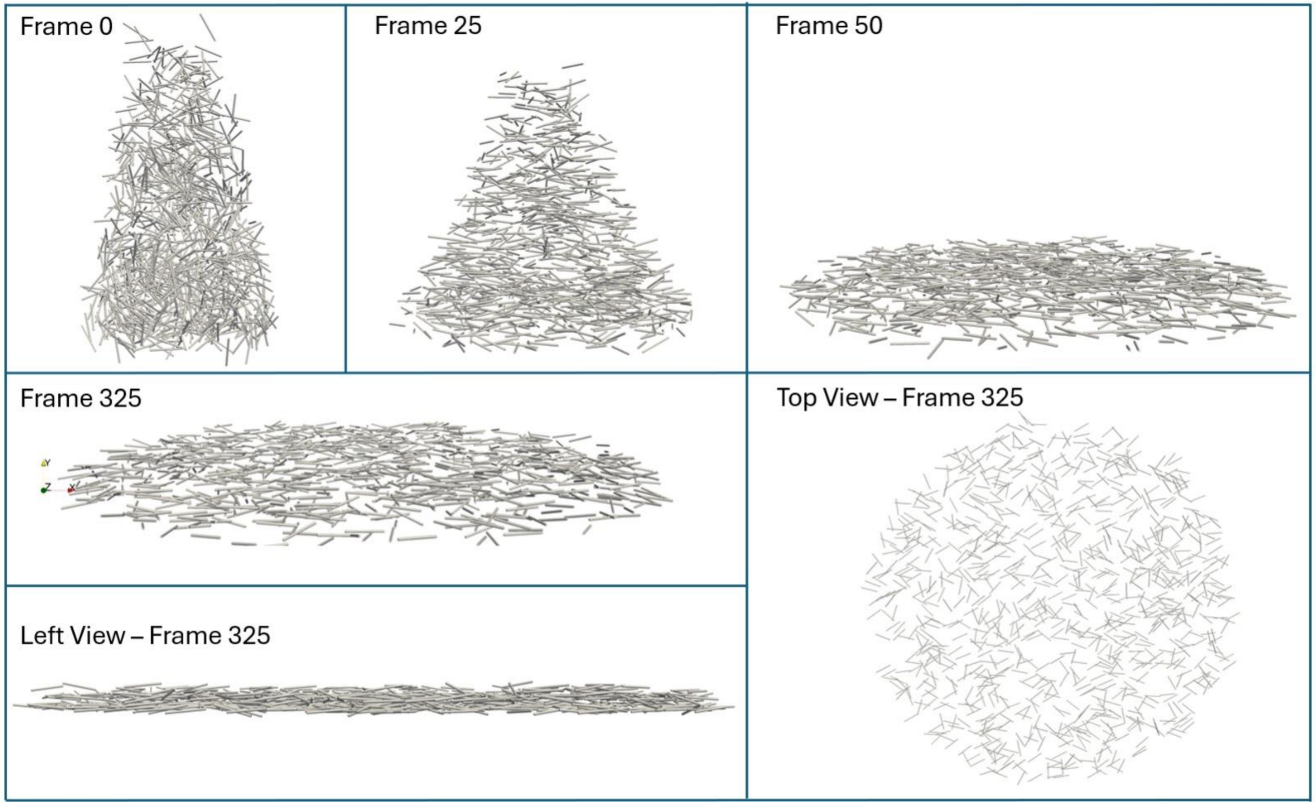
Reinold, Janis, Vladislav Gudžulić, and Günther Meschke.
"Computational modeling of fiber orientation during 3D-concrete-printing."
Computational Mechanics 71.6 (2023): 1205-1225.

η : effective viscosity of the suspension
η_o : base viscosity
c : volume fraction of fibers
r : aspect ratio of the fibers

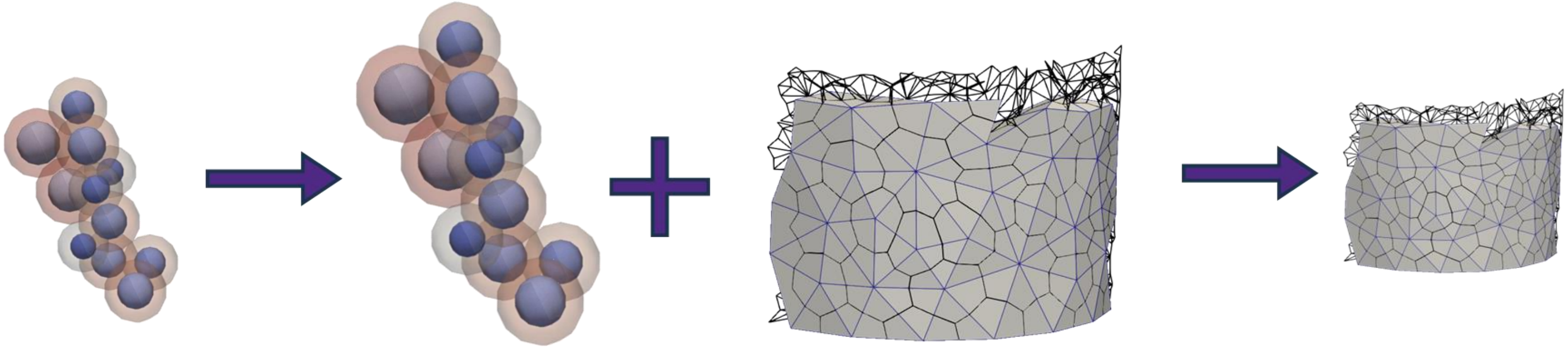
$\sigma_{\tau o}$: yield stress of the fiber-containing mortar
$\tilde{\sigma}_{\tau o}$: base yield stress of the matrix
ϕ_{fm}, ϕ_{sm}: material-specific constants
ϕ_s : volume fraction of solid particles(solid, aggregate)

DFC Model > Fiber Orientation





Fluid to Solid Transition (setting): DFC to LDPM



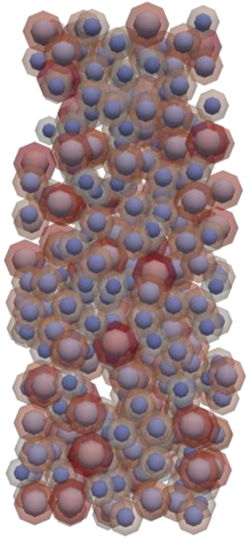
Fluid concrete simulated by DFC model

Concrete setting includes properties of both fluid and solid concrete, will be described by combination of DFC model and LDPM

Solid concrete simulated by LDPM

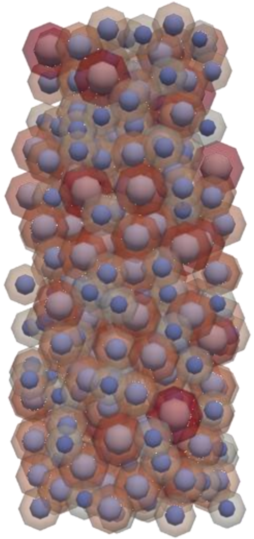
Fluid to Solid Transition (setting): DFC to LDPM

- Inside particle generation
- Surface reconstruction



Initial particle placement generated either using casting simulation or FreeCAD

DFC model

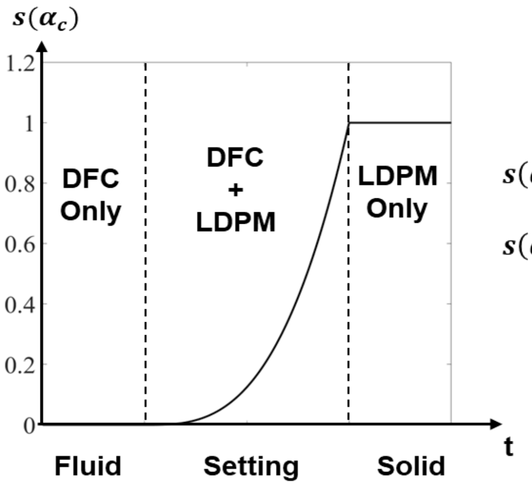


Final particle placement after flow

Surface reconstruction

Mesh for LDPM

Fluid to Solid Transition (setting): DFC to LDPM



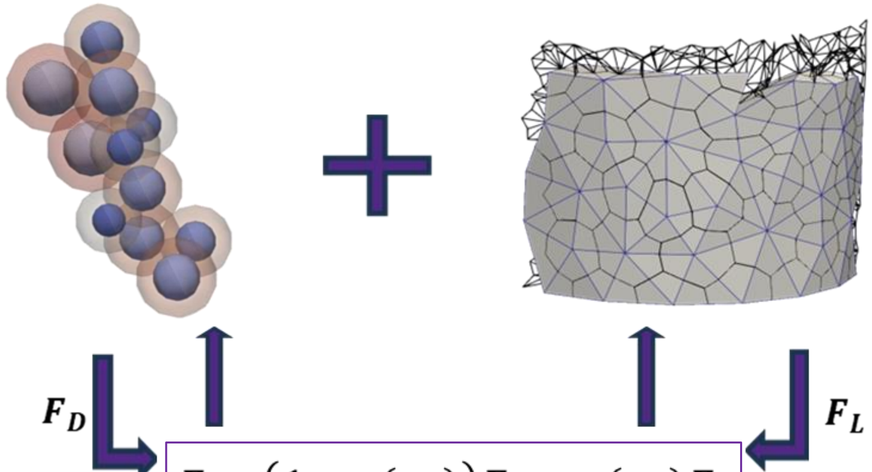
$s(\alpha_c) = 0$, DFC only

$s(\alpha_c) = 1$, LDPM only

$s(\alpha_c)$: Proportional function of LDPM

α_c : Degree of hydration

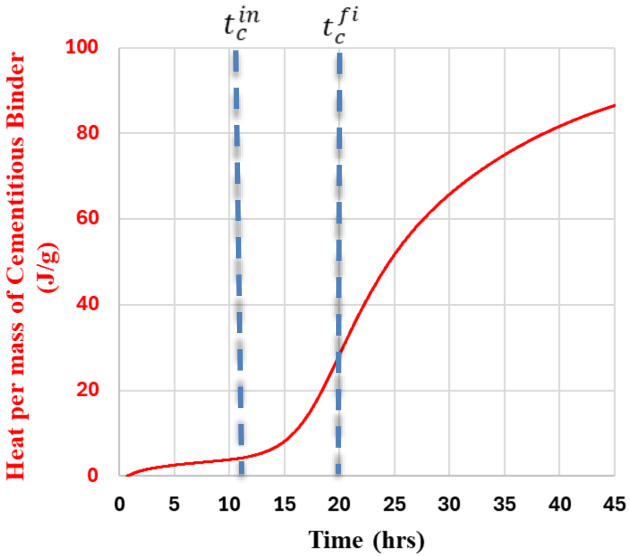
DFC model **LDPM**

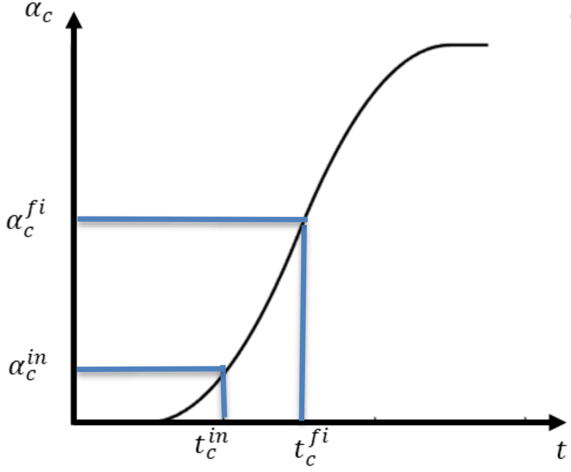


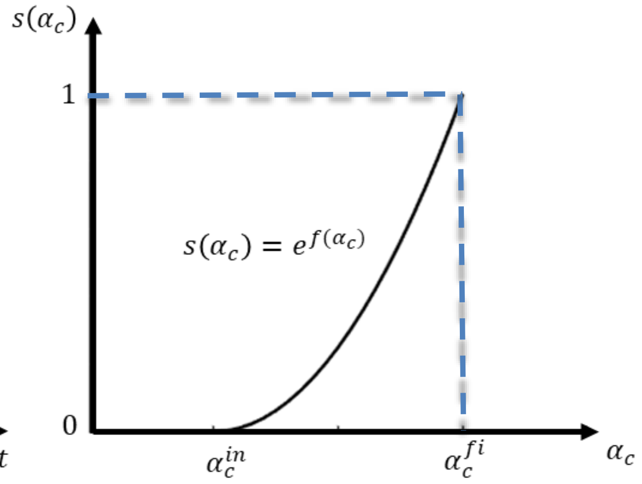
$$F = \left(1 - s(\alpha_c)\right)F_D + s(\alpha_c)F_L$$

Fluid to Solid Transition (setting): The Setting Function

$$s(\alpha_c) = e^{f(\alpha_c)}$$







Accumulated heat release → **Hydration degree** → **Setting function**

Measurement of Setting

1. Volume Change Measurements
- Measures the autogenous and chemical shrinkage and assumes the setting starts when the two curves diverge.
- The shrinkage measurements are error-prone.
- The chemical shrinkage probably doesn't exist, because self-desiccation and chemical hydration can happen at the same time

2. Acoustic Emission (AE) Technique
- Detects microcracks and cavitation in concrete during setting and hardening.
- The signals increase too sharply to capture the details during the setting

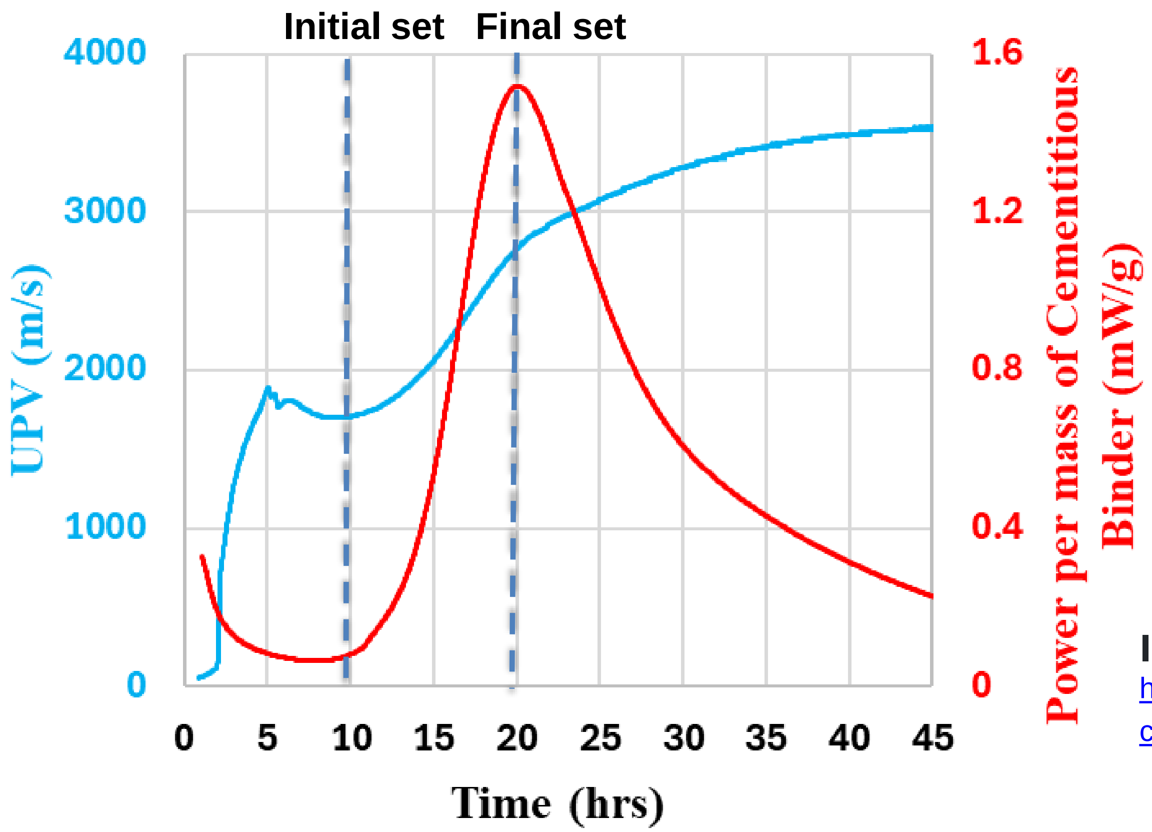
3. Electrical Conductivity
- Measures the connectivity of the pore solution and assumes a rapid decrease when a solid network forms.
- The initial setting time is at a point where the curve is decreasing and is hard to identify

4. Rheological Testing
- Measures yield stress and viscosity changes during hydration.
- A rapid increase in yield stress marks the transition from fluid to solid.
- Only useful for the early-age behavior of fresh concrete

6. Ultrasonic Pulse Velocity
- Tracks the increase in wave velocity as a solid structure forms.
- The point where wave velocity significantly increases correlates with the setting time.

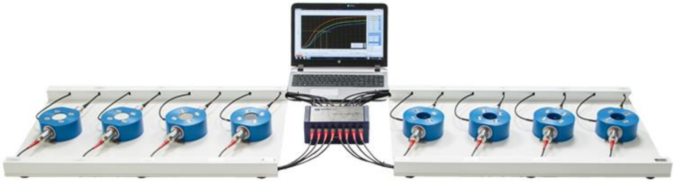
7. Isothermal Calorimetry
- Monitors heat release during hydration.
- Derives the hydration profiles that provides valuable insights into the setting characteristics of the concrete.

Ultrasonic Pulse Velocity (UPV) and Isothermal Calorimetry



IP-8 Ultrasonic-Multiplexer-Tester

https://testing.de/en/1.0380 at ORNL

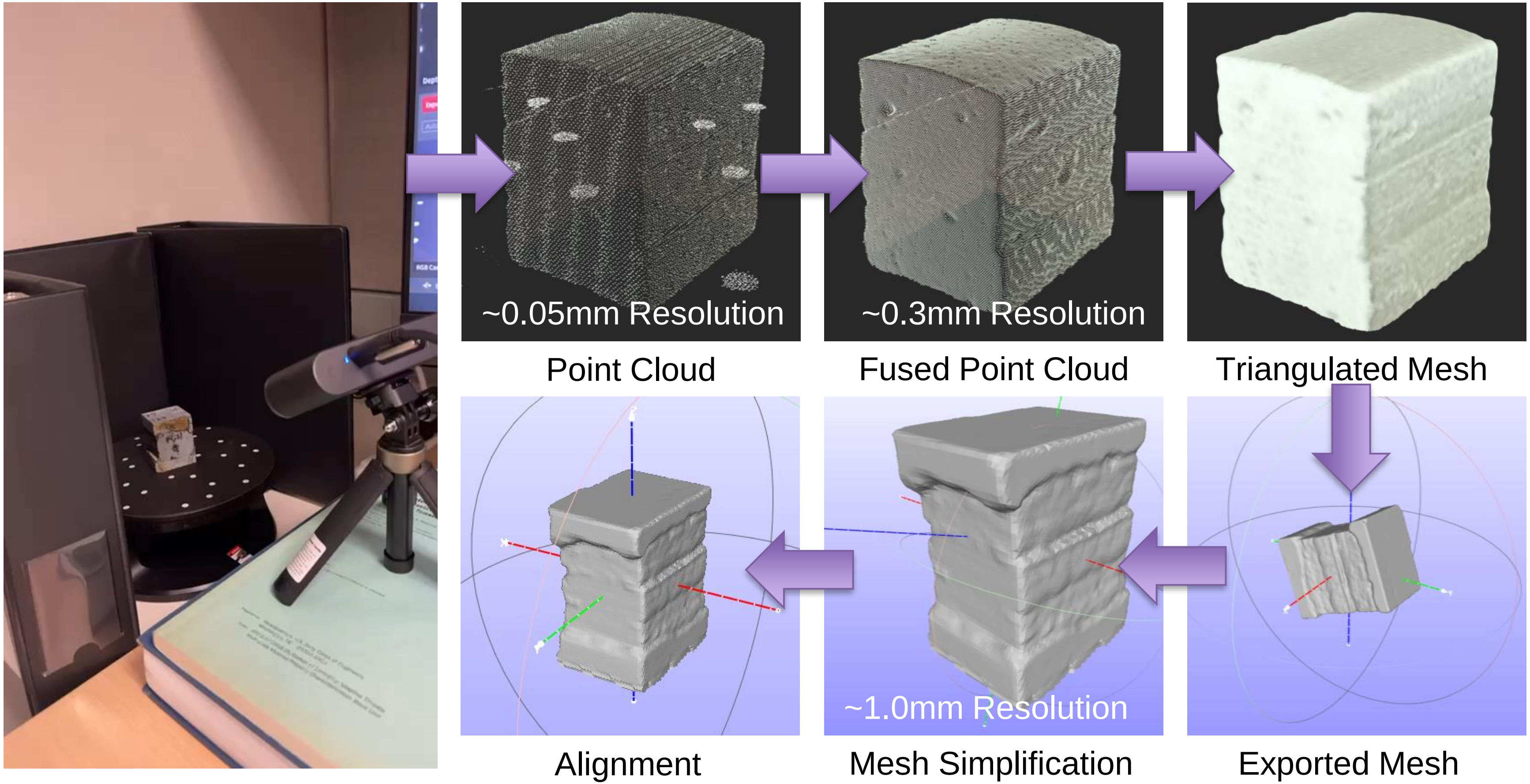


The setting periods indicated by UPV and isothermal calorimetry method are consistent.

I-Cal 2000 HPC

https://www.calmetrix.com/i-cal-2000-hpc at ORNL

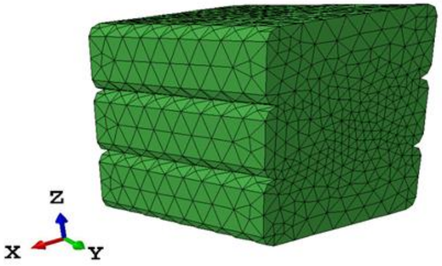
Simulation of Hardened Properties

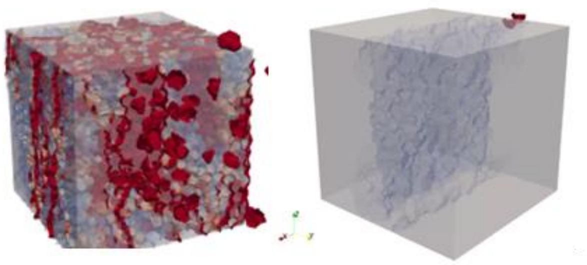


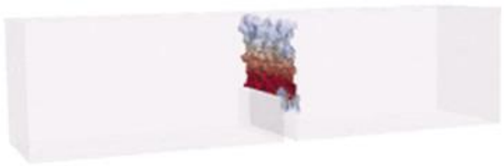
Hardened Properties

Digital Specimens

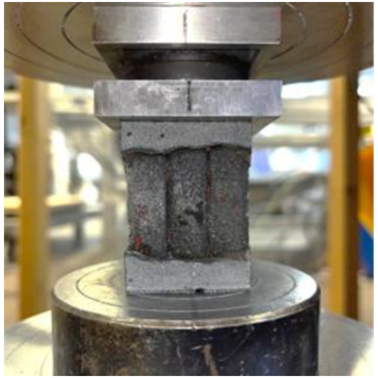
Performance Evaluation

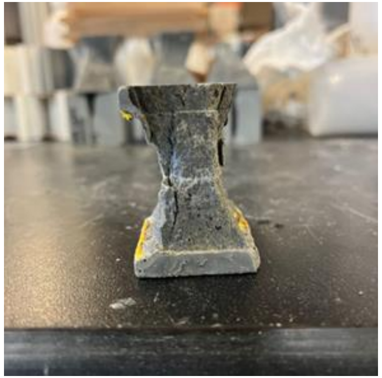






Experimental Data for Validation





Conclusions

- The future of concrete 3DP printing hinges on the adoption of performance-based design guidelines
- Comprehensive and accurate computational models are required to predict and design the printing process as well as the hardened mechanical properties
- In this presentation we showed work towards the first of its kind, multiscale computational framework able to simulate concrete fresh and hardened behavior as well as the transition form fluid to solid!

Questions?

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