Controlling rheology of 3D printable concrete through vibration

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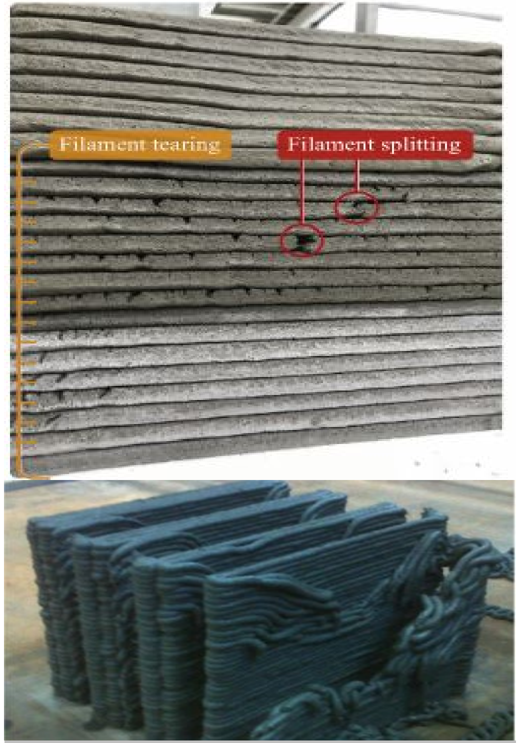
Is concrete 3D printing ready for large scale construction?

- Lack of vertical reinforcement
- Jamming in the extruder head
- Gaps in extrusion, tears in the layers
- Bond between layers (‘Cold joints’)
- Environmental control (e.g. drying shrinkage)
- Time Sensitive

- How to print faster with less defects?
- How to make printable concrete more durable?
- How to reduce cost?



Defects in 3D Printed concrete
(Buswell, Leal de Silva, Jones, & Dirrenberger, Cem. Concr. Res., vol. 112, pp. 37–49, Oct. 2018)

Can we 3D print CONCRETE?

Benefits of having coarse aggregate in 3D printed concrete:

- Green Strength
- Durability
  - Dimensional stability
  - Wear resistance
- Cost
  - Economical filler

But (coarse) aggregate poses a challenge in material delivery

- Flow through the printer
- Jamming of nozzle

B-Hut, US Army Corp of Engineers, CERL, 2017

So, the 3D printable concrete needs to be:

Fluid enough to flow through the nozzle,

BUT

Solid enough to withstand its own weight and the weight of additional layers

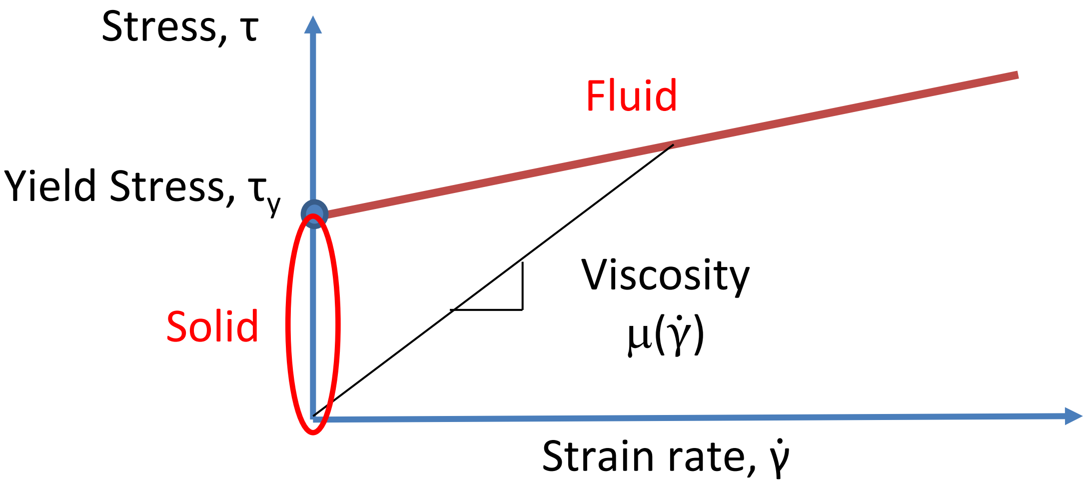
Is fresh concrete a fluid or a solid?

Self Consolidating Concrete

No Slump Concrete

Background

Concrete is a **yield stress fluid**.



Bingham model

$\dot{\gamma} = {(\tau - \tau_y)}/{\mu(\dot{\gamma})}$ if $\tau > \tau_y$

$\dot{\gamma} = 0$ otherwise

Vibrating granular fluids

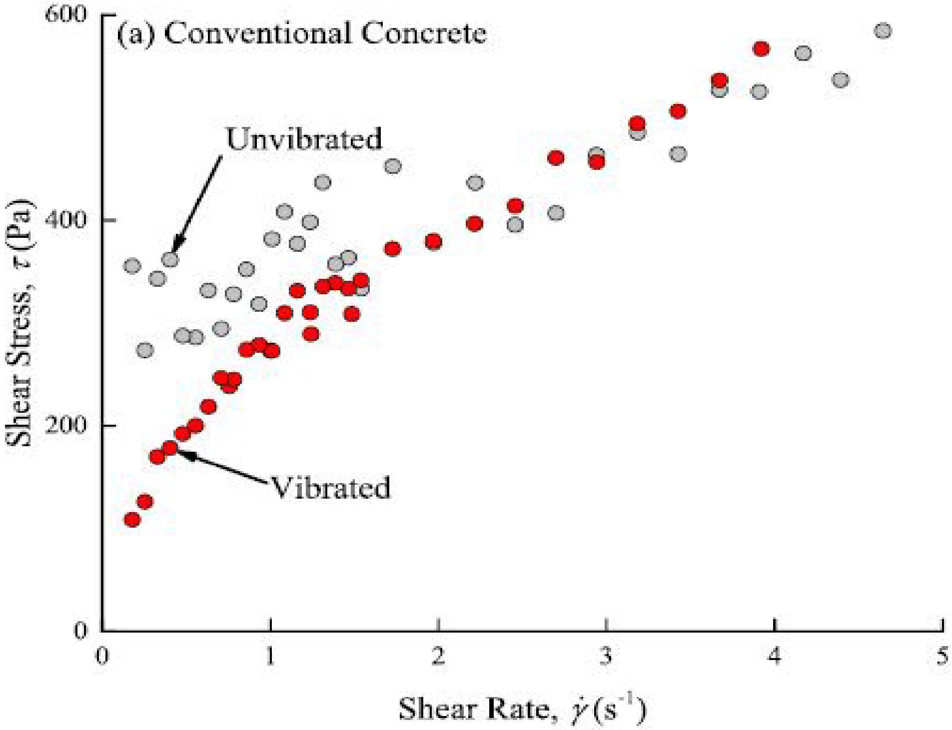
Concrete Vibrator

Vibratory Compactor

Vibratory Conveyor Belt

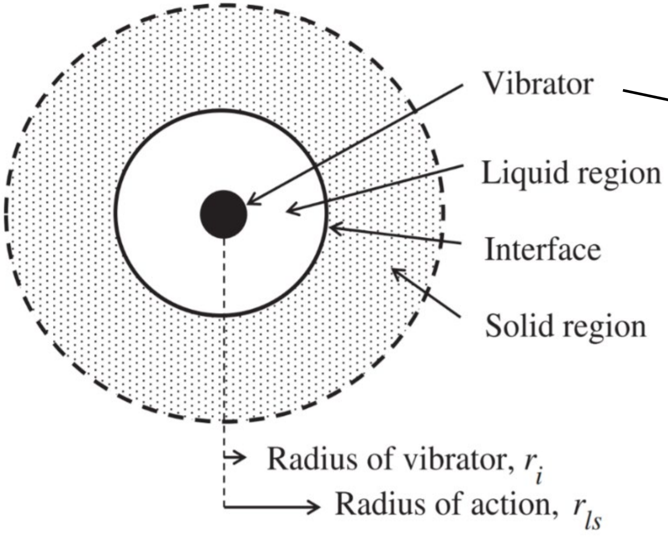
Vibrating granular fluids

- At low shear rate, yield stress is seemingly eliminated
- Once vibration ceases, initial yield stress is immediately recovered

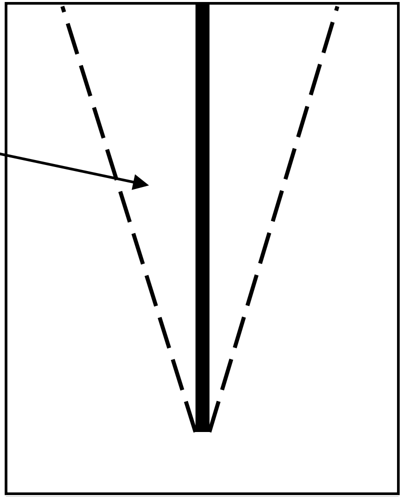


Shear stress vs. Shear rate of conventional concrete with and without vibration.
(Koch, Castaneda, Ewoldt, & Lange, Cem. Concr. Res., vol. 115, pp. 31-42, Jan. 2019)

How does vibration propagate in concrete?

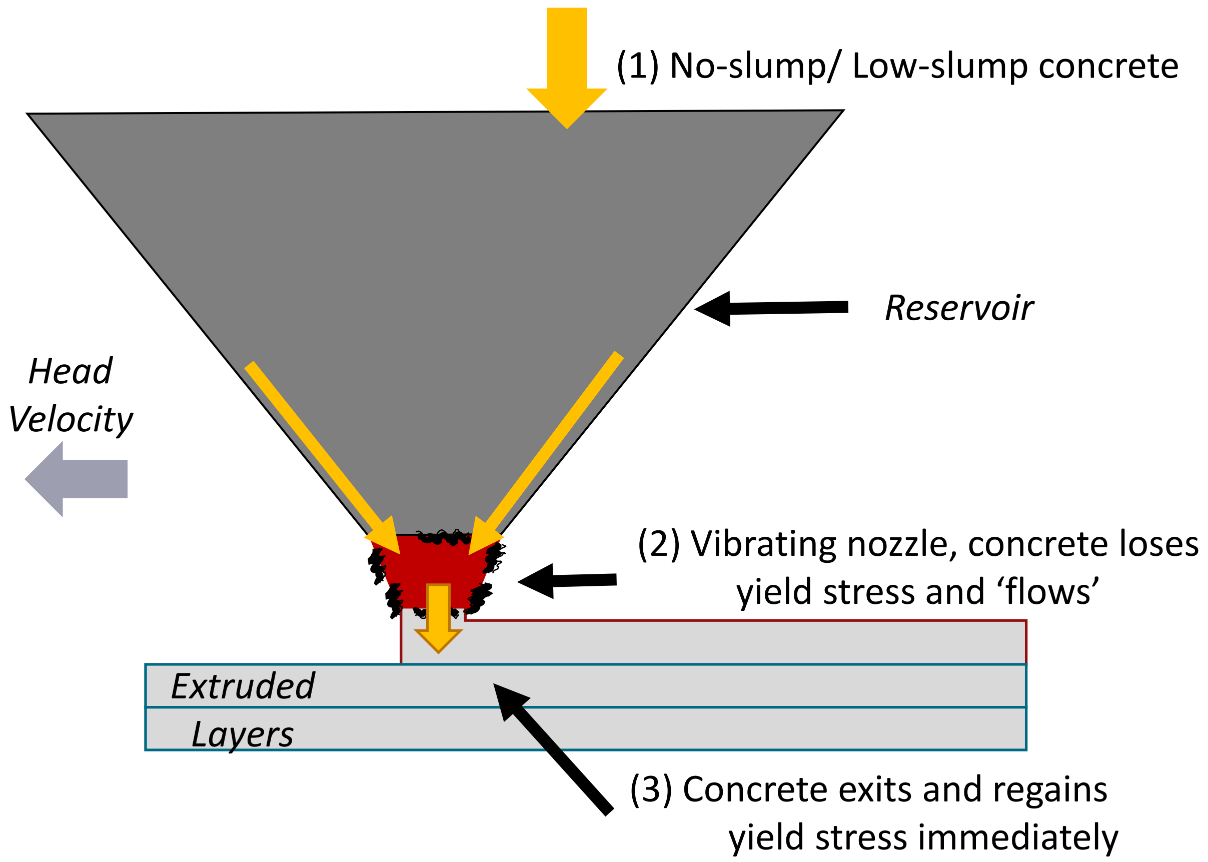


Schematic of how vibration propagates through fresh concrete
(Banfill, Teixeira, & Craik, Cem. Concr. Res., vol. 41, no. 9, pp. 932–941, 2011)



Depth dependent behavior of vibration propagation in concrete
(Koch, Castaneda, Ewoldt, & Lange, Cem. Concr. Res., vol. 115, pp. 31-42, Jan. 2019)

Schematic of proposed 3D printer



Measuring yield stress during vibration

International Center for Aggregate Research (ICAR) concrete rheometer was modified to reliably measure yield stress during vibration.

Modified ICAR Rheometer

Vibration table – 60 Hz, 0.001 m max. amplitude

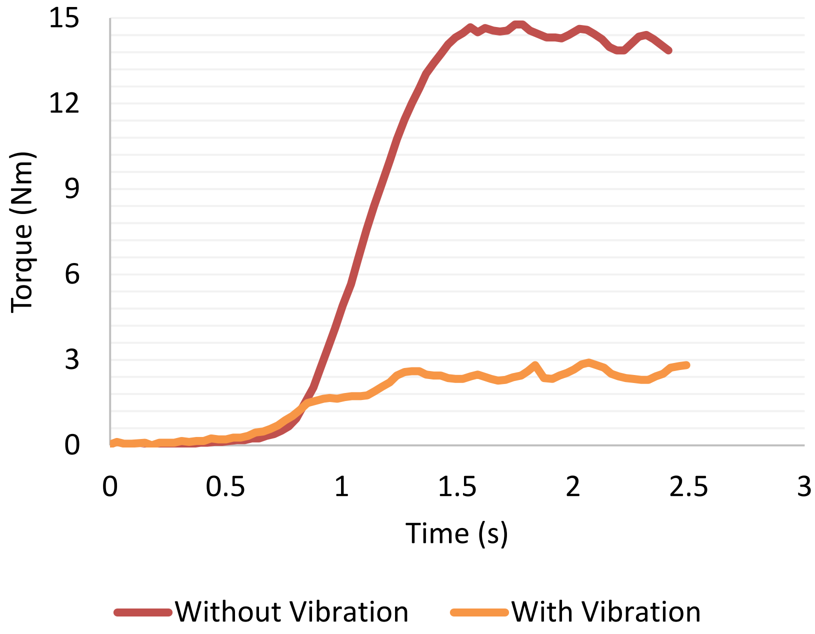
ICAR static yield stress test

$$\tau_y = \frac{2}{\pi D^3 (\frac{H}{D} + \frac{1}{3})} \times \mathrm{T_{max}}$$

For the ICAR used, we have:

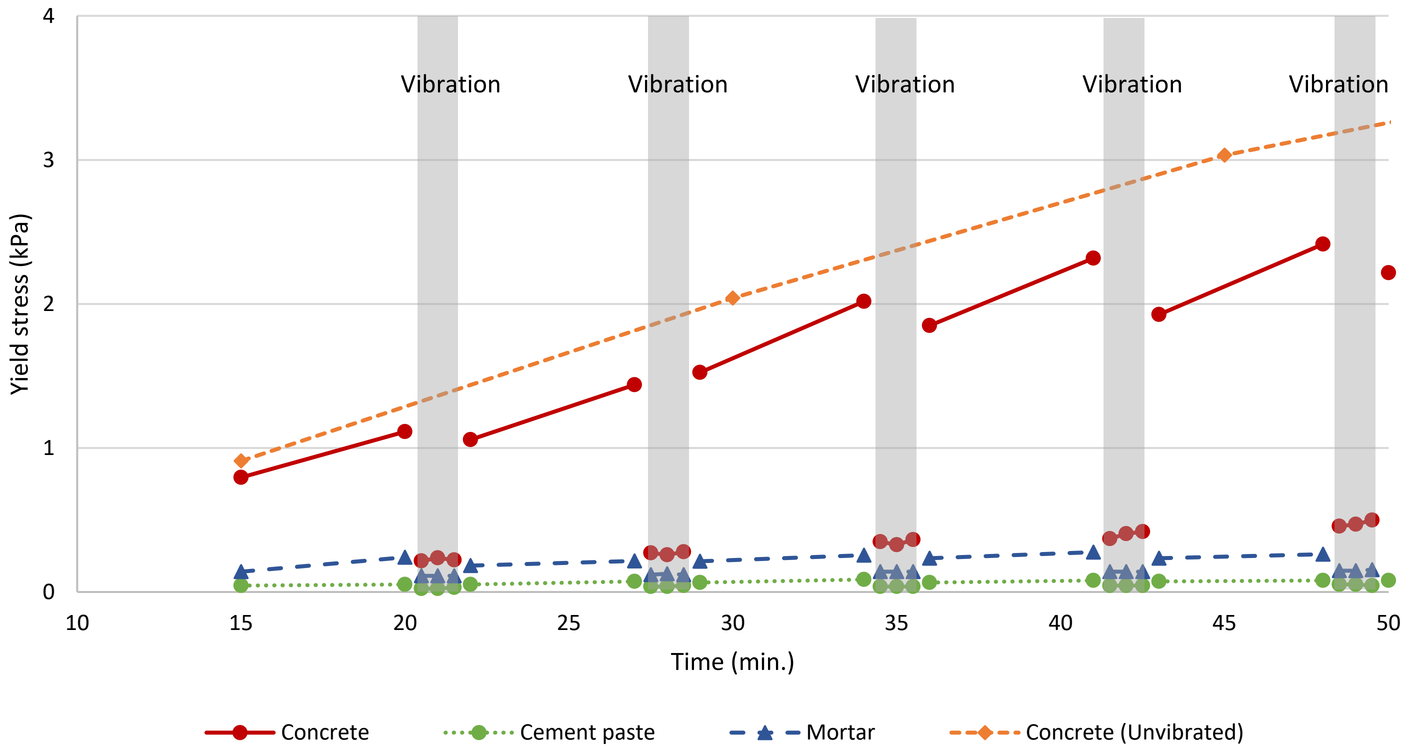
$$\tau_y = 233.68\ \mathrm{T_{max}}$$

(where, τ_y is yield stress in Pa,
T is torque in Nm)



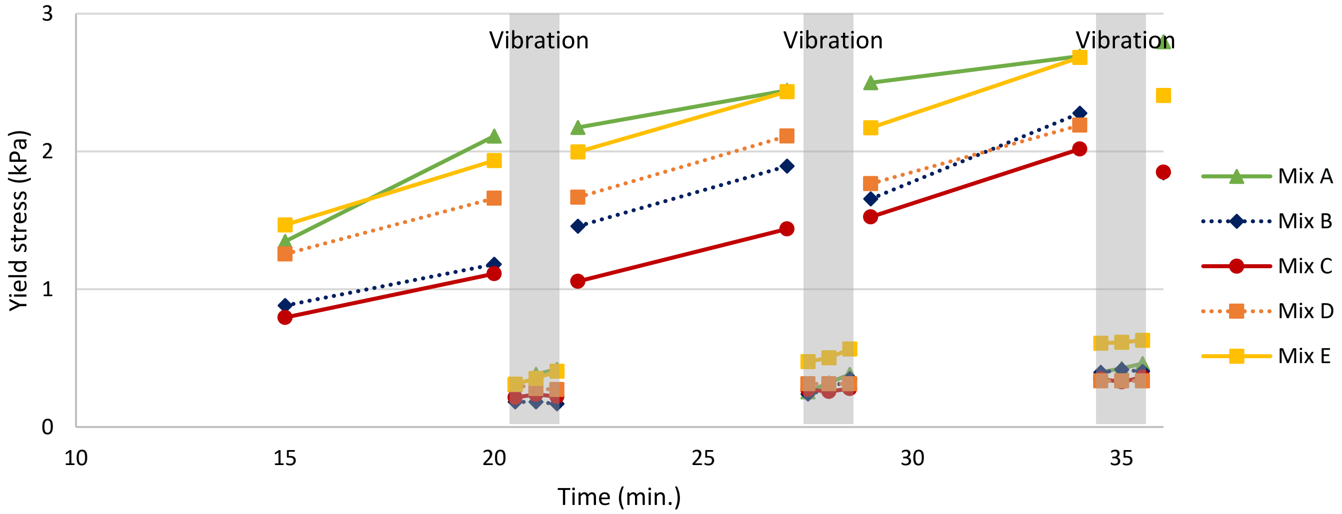
Torque versus time: sample raw data - ICAR stress growth test

Effect of aggregate on yield stress

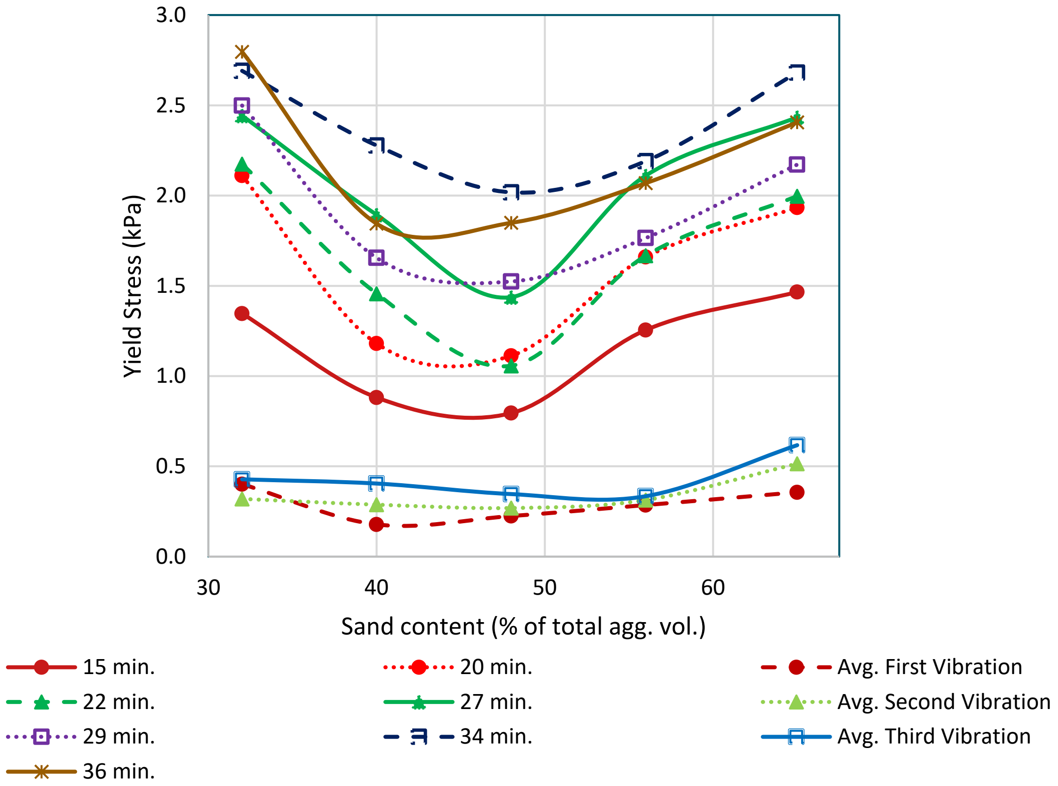


Effect of aggregate packing on yield stress

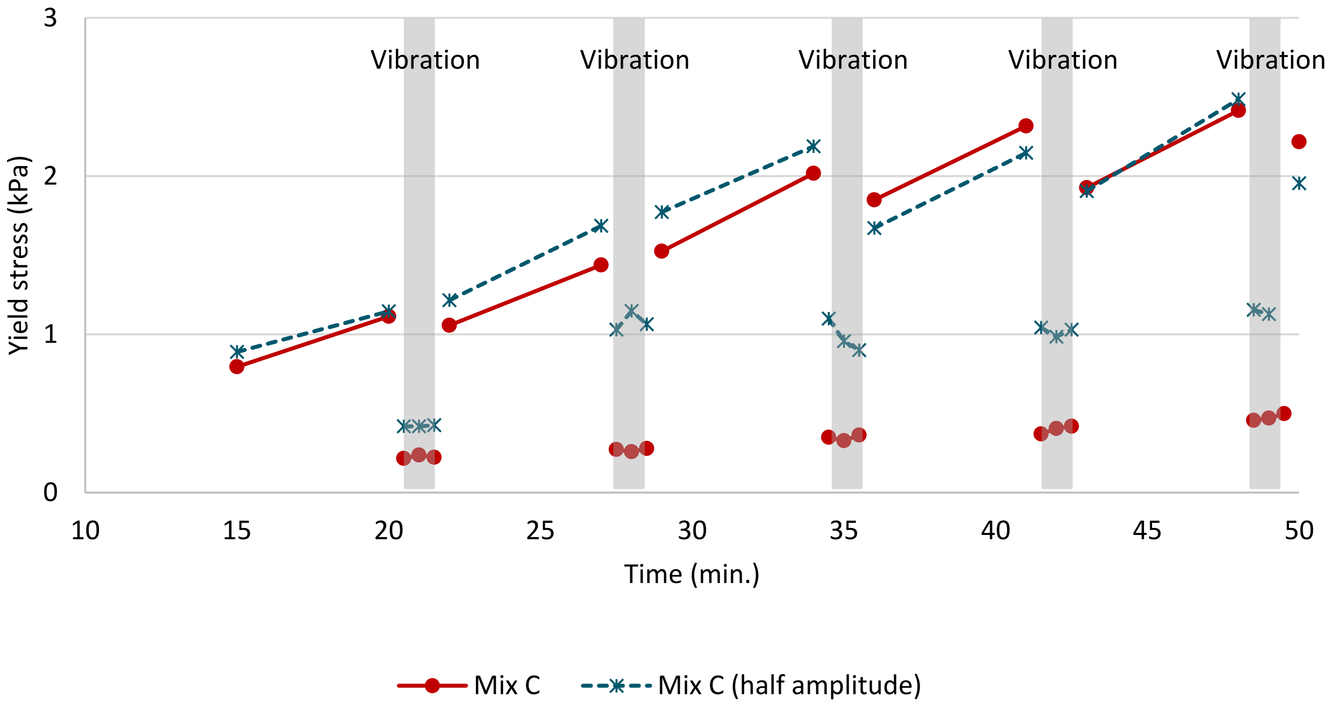
Mix ID	Volume (% of total concrete vol.) [w/c = 0.4]						% Sand (of total agg., by vol.)
	Paste	Air	Agg.	Mortar	Sand	Coarse agg.	
A	35	3	62	55	20	42	32
B				60	25	37	40
C				65	30	32	48
D				70	35	27	56
E				75	40	22	65



Mixture Design Implications

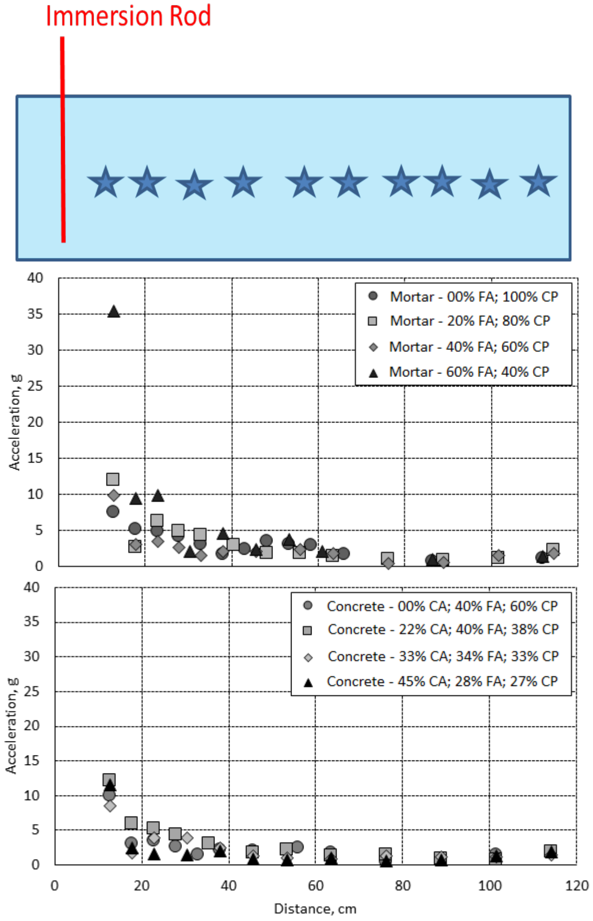


Effect of Vibration Amplitude



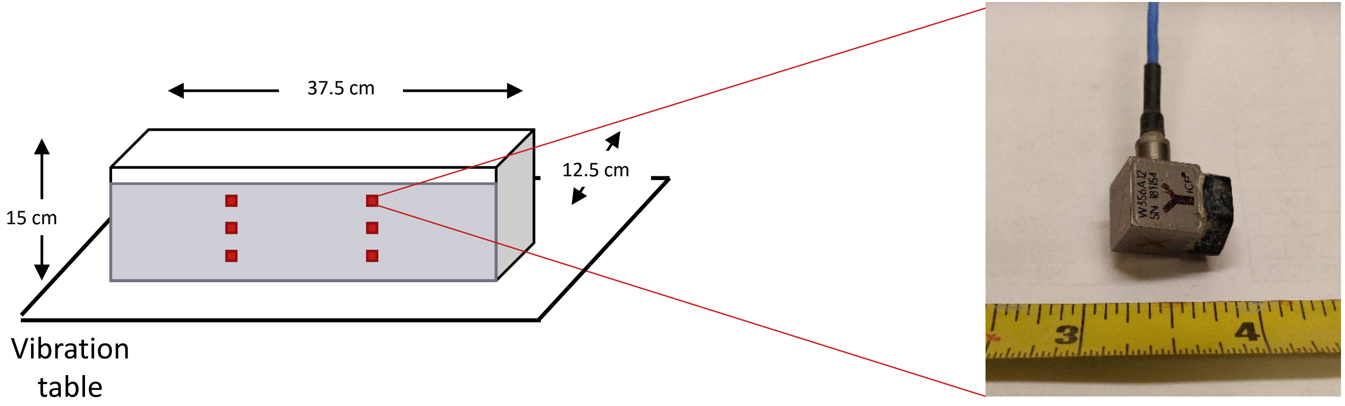
Propagation of vibration in concrete

A prior study showed how accelerometers placed in concrete to measure the vibration through it displays a radius of influence around the vibrator.

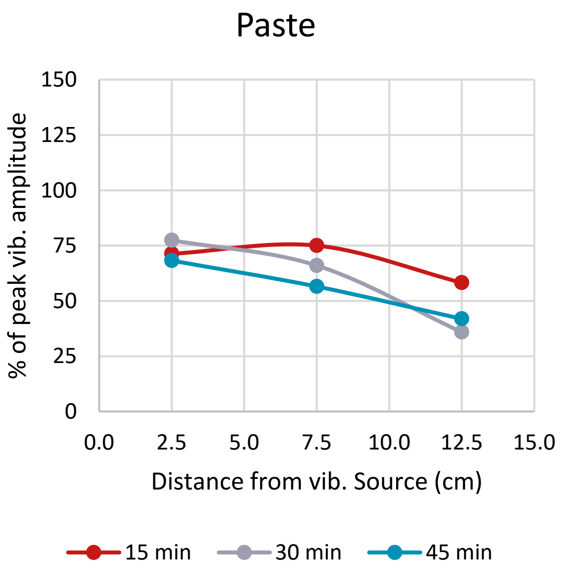


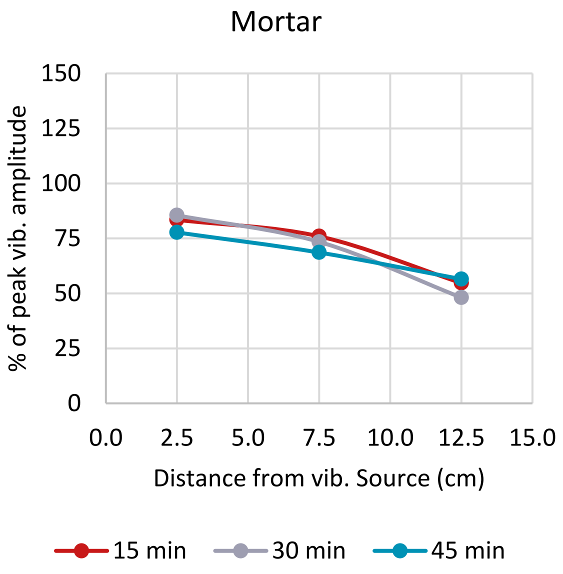
D. Castaneda et al. (2016)

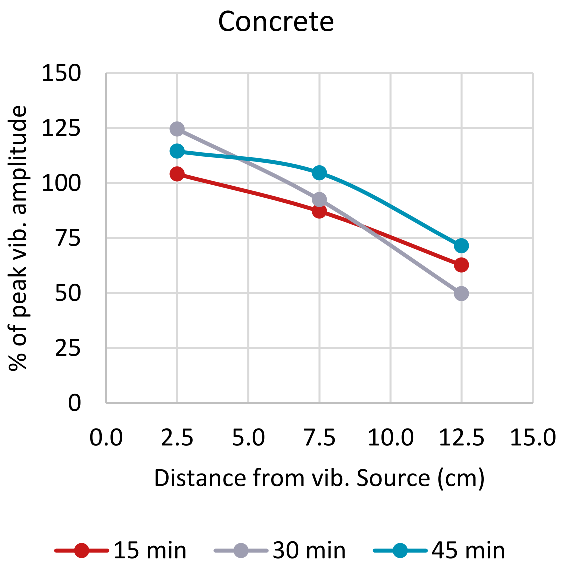
Propagation of vibration in concrete



Propagation of vibration in concrete





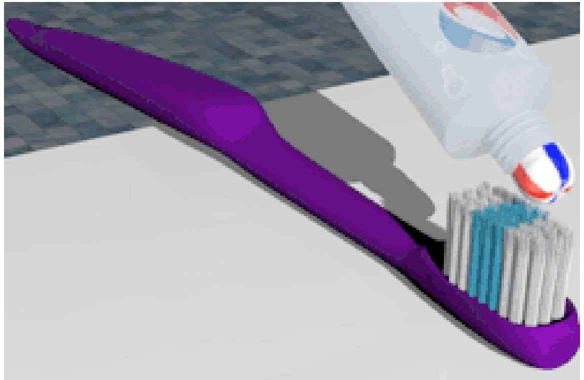


Modelling concrete 3D printing

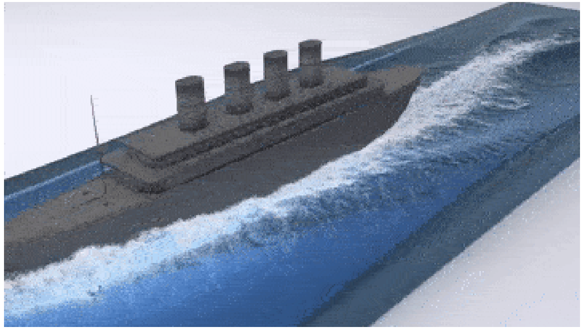
Smoothed Particle Hydrodynamics (SPH)

- SPH is a mesh-free Lagrangian method
  - Can simulate both fluid and solid continuum
  - Can handle very large deformations
  - Supports for most of the material models

- Applications
  - Free surface fluid flow
  - High strain-rate and large-deformation problems
  - Wide application in solid mechanics, astrophysics



Simulation of toothpaste with SPH (rebloggy.com)



Simulation of wave with SPH (DualSPHysics)

SPH fundamentals

Smoothed

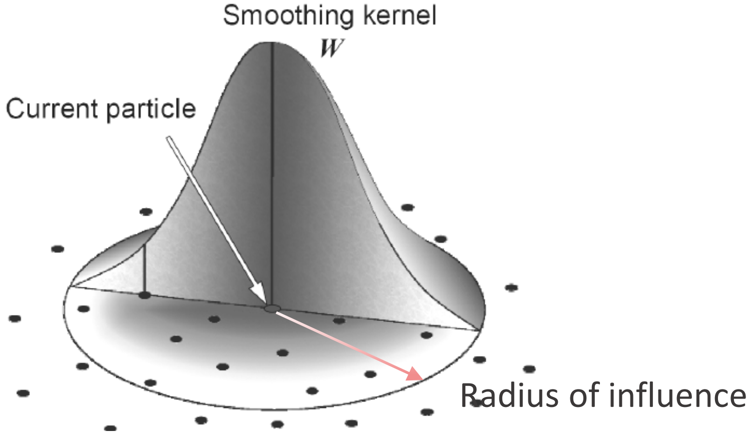
- Some particle properties are determined by neighboring particles using a smooth function

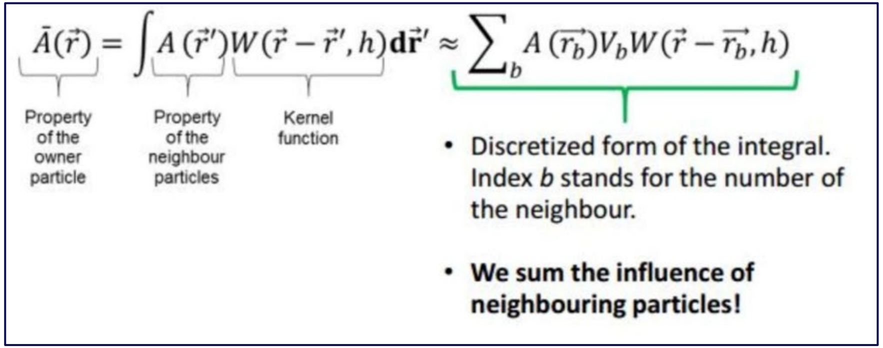
Particle

- The domain is represented a particle system

Hydrodynamics

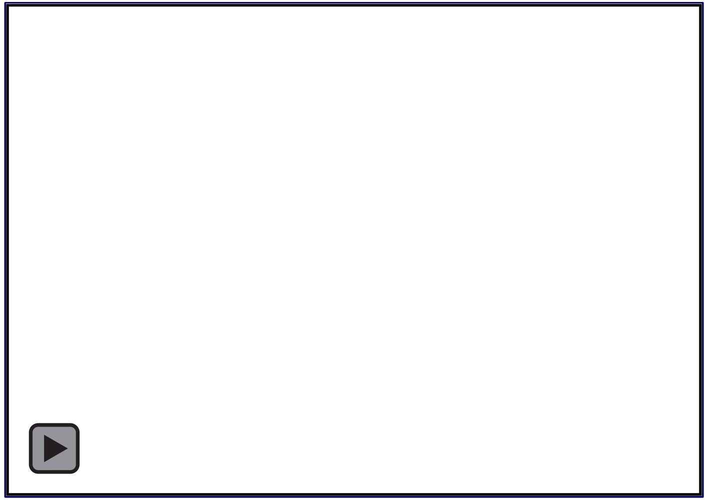
- The theory uses fluid dynamics

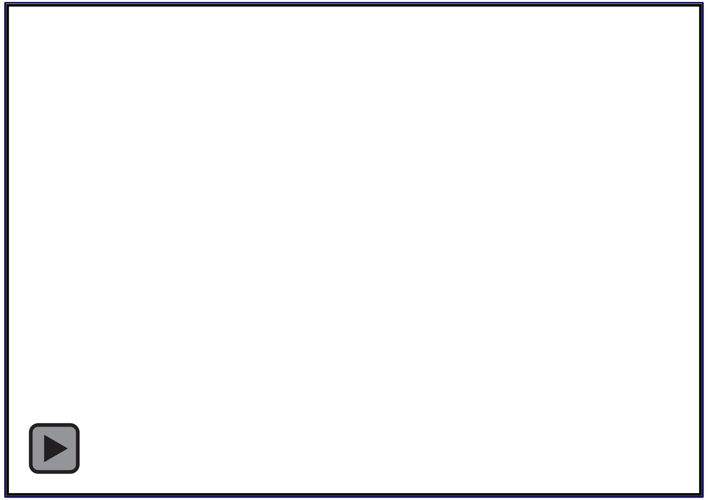




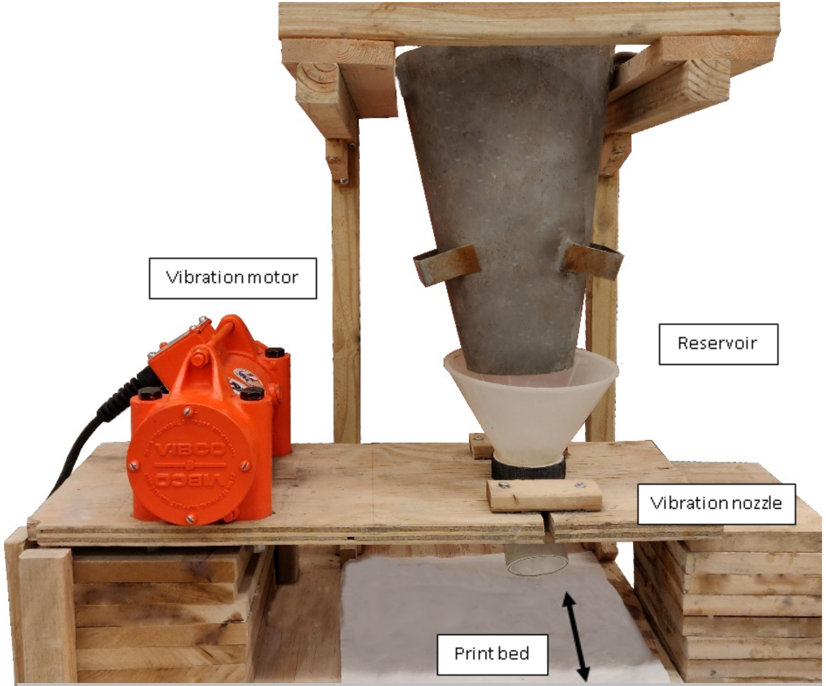
- https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/12527/Gearing-Up-for-Smoothed-Particle-Hydrodynamic-Simulation-Workflows.aspx
- Villumsen, Morten F., and Torben G. Fauerholdt. "Simulation of metal cutting using smooth particle hydrodynamics." LS-DYNA Anwenderforum, C-III (2008): 17.

3D printing model: replicating motion





Prototype



Prototype of vibration based concrete 3D printer

Concrete printed by the prototype

Conclusions

- Using coarse aggregate in 3D printable concrete mixtures increases its yield stress considerably.
- Rheology of granular suspensions like concrete can be controlled with vibration.
- Loss of yield stress in concrete due to vibration is immediate and reversible.

Thank you!

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