RC 2018 XVII Reunión del CONCRETO

El evento del Cemento, el Concreto y los Prefabricados

American Concrete Institute

Always advancing

The Future of 3-D Printing of Concrete Structures

Prof. David A. Lange

University of Illinois at Urbana-Champaign

ACI President for 2018-2019

President's
Memo

Ventures in 3-D

David A. Lange
ACI President

Recent headlines suggest that three-dimensional (3-D) printing technologies for concrete construction are coming fast. In the past month, a news item reported that a family in France moved into their new 3-D printed home that took 2 days to print. In the Netherlands, an initiative called "Project Milestone" aims to build five 3-D printed houses starting in 2019. A startup in Austin, TX, demonstrated low-cost houses that are printed in 24 hours. An article on the *3D Natives* website listed 11 companies that aspire to print houses in a matter of days. The photos that accompany these news articles show compelling architectural shapes that further differentiate new age 3-D printed houses from their traditional stick frame counterparts. The trajectory for an emerging industry may be impressive, but time will tell how the market response unfolds.

All this is no surprise to researchers and visionaries that have watched the early technology rollouts. ACI member Pete Carrato was the inaugural Chair of ACI Committee 131, Building Information Modeling of Concrete Structures, which had its first meeting in November 2009. Carrato is also head judge of the NASA 3D Printed Habitat Challenge that is now underway. The NASA Challenge Phase 3 will cap off with the printing of 3-D structures at the Caterpillar facilities in Peoria, IL, in April 2019. ACI members Anne Ellis, Joe Biernacki, and I are members of the judging team. With a purse of $2M in prize money, NASA promises fame and fortune to the winners of Phase 3.

The NASA Challenge follows a format with a rich tradition. Dangling a carrot of big prize money has been used in the past to spur innovation. In 2004, SpaceShipOne was the winner of a $10M prize for sending a reusable spacecraft into space twice within 2 weeks. In 1927, Charles Lindbergh claimed the $25,000 Orteig Prize when he flew solo from New York to Paris nonstop. And history tells us that in 1795, Napoleon paid 12,000 francs to an inventor of technology for long-term sealed food storage.

The current NASA Challenge is not just about public relations, but is aimed at spurring developing creative solutions with real commercial impact. I attended the NASA

Testing 3-D printed concrete for Project Milestone, an initiative with the goal of building 3-D printed houses starting in 2019 *(photo courtesy of 3dprintedhouse.nl)*

Phase 2 competition in Peoria in August 2017. It was a frenetic event for the competing teams, but there was plenty of time for the judges to visit and contemplate the impact that 3-D printing may have on the construction industry as the technology matures and the markets develop. I learned that venture capital (VC) firms are being attracted to this technology space. I expect to hear about VC firms funding medical device start-ups in Silicon Valley, but it was unusual to hear about this funding mechanism turning toward technologies used in construction.

High growth and high return opportunities in construction include new BIM software, 4-D planning, material tracking systems, efficient crane control, wearable devices for the construction site, smart vests that monitor worker heart rate and respiration for work in confined spaces, and virtual reality tools to aid construction sequencing. Carrato tells me, "The Dot Com era for construction is here." ACI member Florian Barth agrees. He recently wrote me that VC partnerships try to identify disruption like smart asset management, smart operations controls, smart products, and smart enterprises. Big Data, artificial intelligence, cybersecurity, cloud computing, and nanotechnology have roles to play in concrete construction, and we are only at the beginning of a wave of advances.

I am finalizing this memo during a break at a Gordon Research Conference in Hong Kong, and the discussion this week has underscored that there are many, many academic and industry researchers trying to address a myriad of challenges that lie ahead. It has been an exciting week. There is a lot yet to do. But hopes are high, and the future is bright.

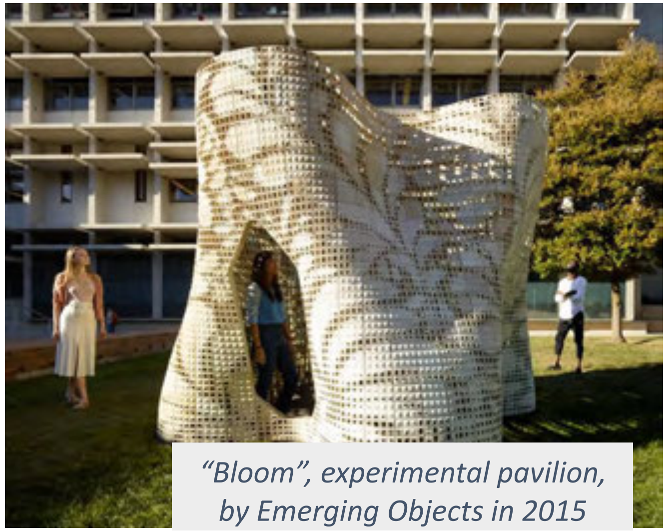
David A. Lange
American Concrete Institute

Images: Apis Cor

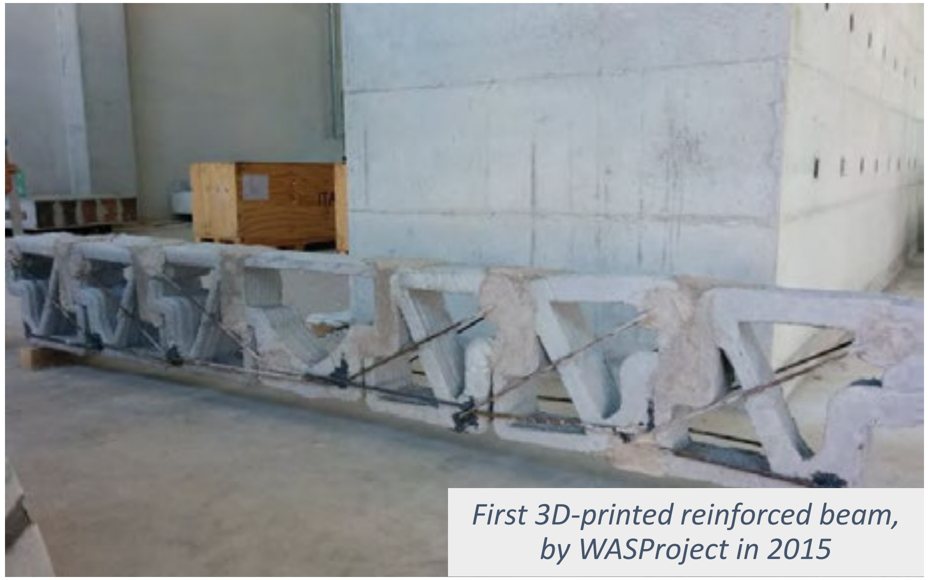
Why is 3D printing concrete attractive?

- Reduces:
  - Construction time
  - Labor required
  - Formwork
  - Waste and CO_2 emissions
  - Rigidity of design
  - Cost
- Good applications:
  - Cheap and quick housing
  - Hostile or dangerous construction environments (nuclear plants, extraterrestrial lands)
  - Artistic architecture – "organic"

Post for school in Aix-en-Provence, by XtreeE in 2017



"Bloom", experimental pavilion, by Emerging Objects in 2015



First 3D-printed reinforced beam, by WASProject in 2015

Why is 3D-printing concrete difficult?

- Cold joints – time-sensitive!
- Incorporation of reinforcement
- Consistent flow in the extruder head
- Gaps in extrusion, tears in the layers
- Environmental control (e.g. drying shrinkage)

And these are just the civil engineering concerns! Highly **interdisciplinary** because of machinery, power requirements, robotics, monitoring…

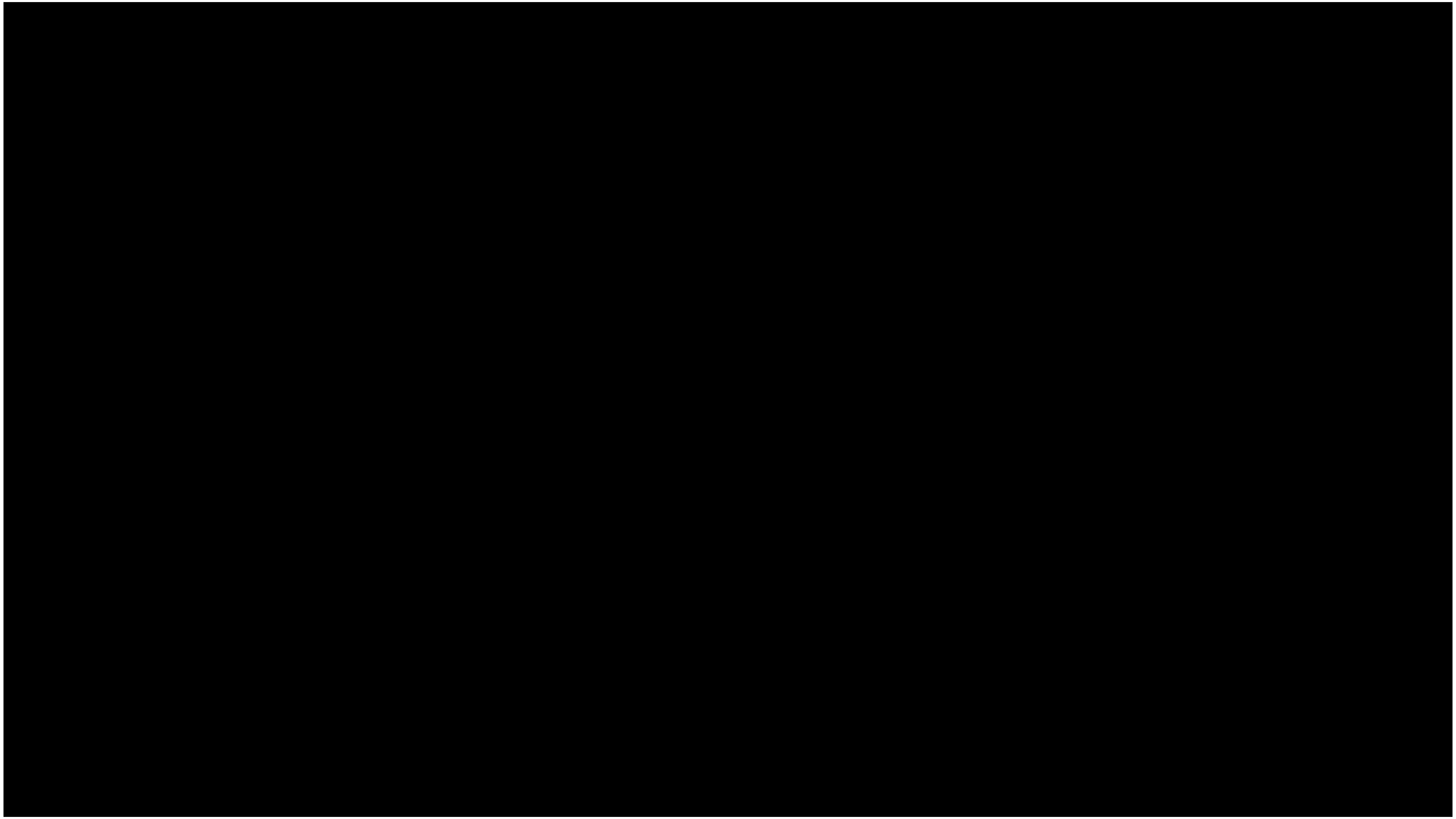
Image from 3D printing experiment at Eindhoven University of Technology

Classic example of a 3D-printed plastic model failure

Oct. 6, 2016

NASA Offers Prize Money for Winning 3D-Printed Habitat Ideas

NASA is offering $1.1 million in prize money in Phase 2 of the 3D-Printed Habitat Challenge for new ways to build houses where future space explorers can live and work. The three-part competition asks citizen inventors to use readily available and recyclable materials for the raw material to print habitats.



Video from Engineer Research and Development Center ERDC (https://www.youtube.com/watch?v=LjBS6b7ZeF8)

- A 3d printer "Automated Construction of Expeditionary Structures (ACES)" at CERL

- A barracks hut constructed with the 3D printer "ACES" at CERL

Where do we stand today?

Current action:

"Proof of Concept" projects

US Marines, US Army

Developing underlying science

Rheology, flow, pumpability, set

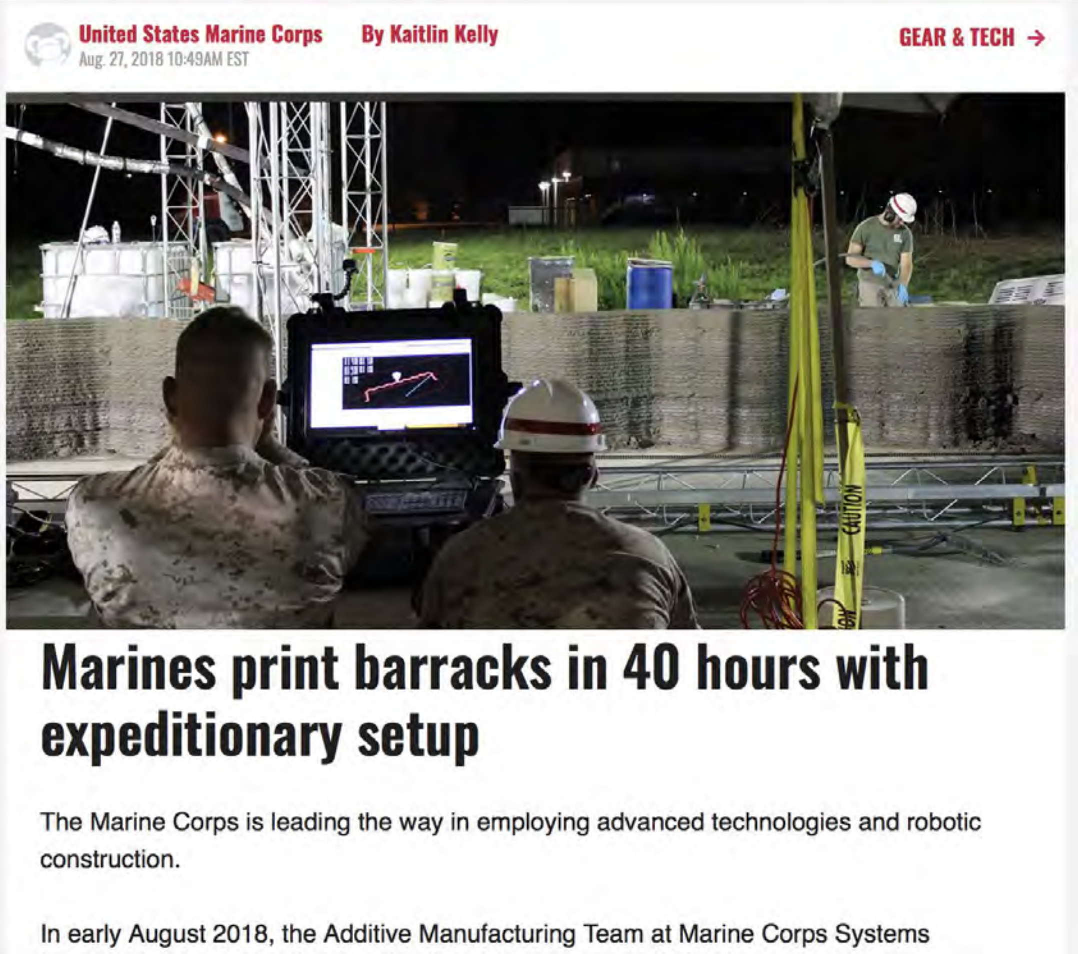
Placement technology

3D control – "an easy problem"

Interface quality

Surface finish

Integration of admixtures for set control


United States Marine Corps   By Kaitlin Kelly
Aug. 27, 2018 10:49AM EST
GEAR & TECH →

Marines print barracks in 40 hours with expeditionary setup

The Marine Corps is leading the way in employing advanced technologies and robotic construction.

In early August 2018, the Additive Manufacturing Team at Marine Corps Systems

Where do we stand today?

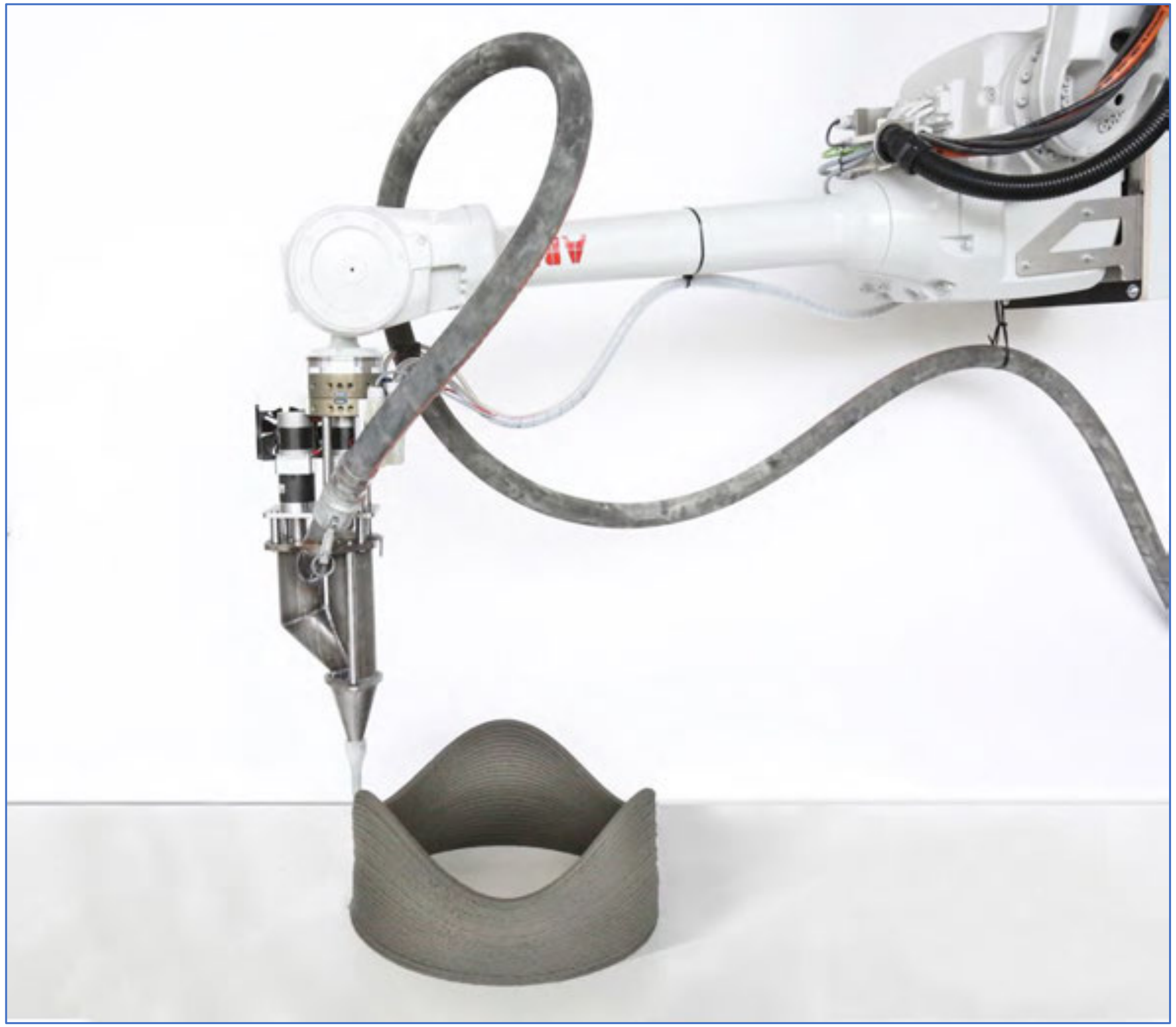
Current action:

Educational activities

- 3D printing workshops
  - ETH Zurich, NIST, Purdue, RILEM

Professional activities

- 3D printing conferences
- ACI committee work
- RILEM committee work



Challenges

Extrudable concrete must be:

Fluid enough to flow through the extruding nozzle,

BUT

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

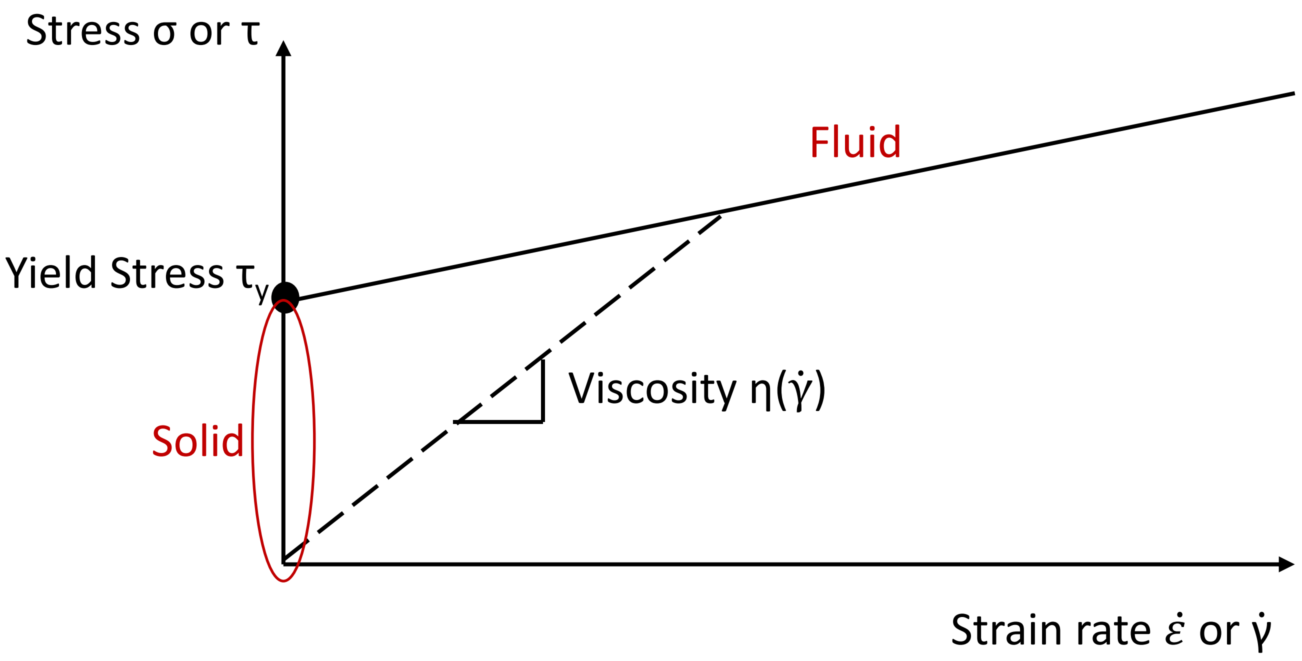
AND

Stiff enough so it doesn't deform too much during printing

A printer head from the 3D printer ACES at CERL

Rheology Basics

Neither! It is a yield stress (aka viscoplastic) fluid:



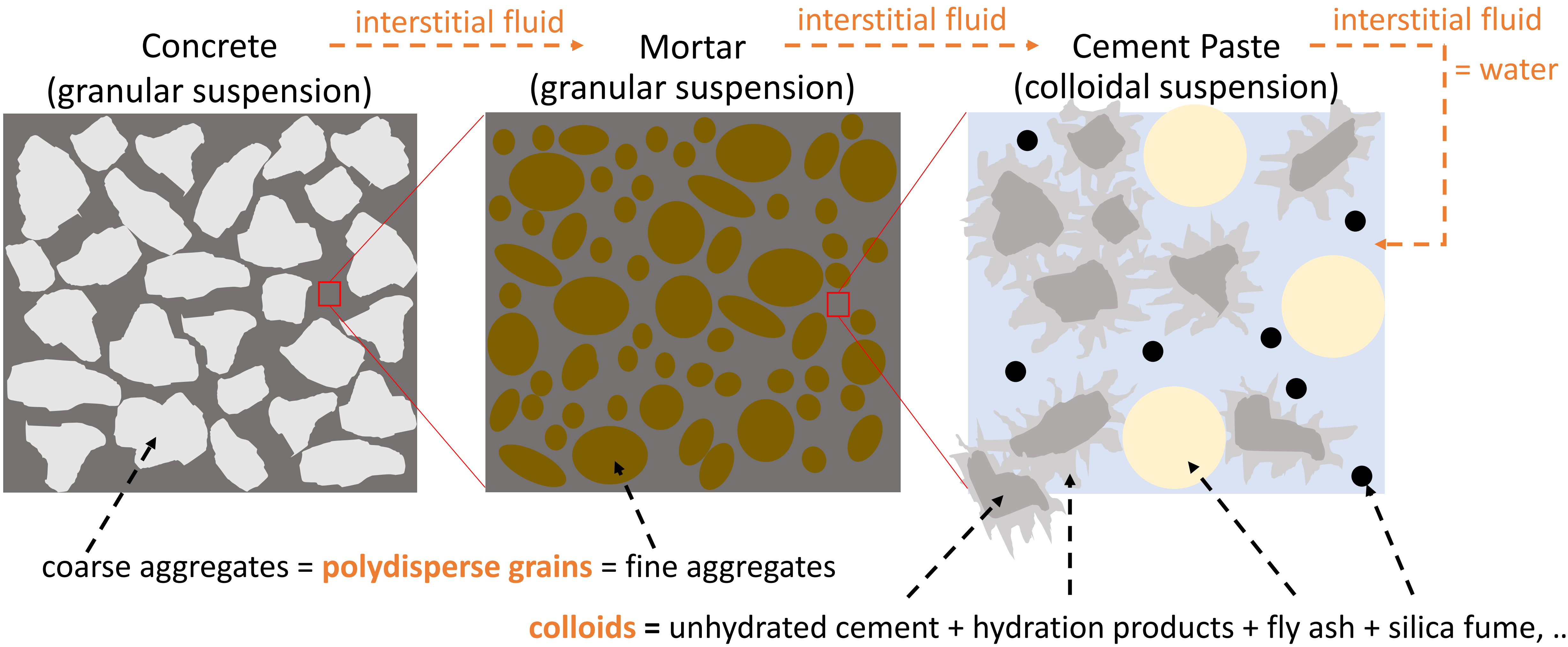
Bingham model

$$\dot{\gamma} = \frac{\tau - \tau_y}{\eta(\dot{\gamma})} \quad \text{if } \tau > \tau_y$$

$$\dot{\gamma} = 0 \quad \text{otherwise}$$

Note how we can control fluid/solid state with applied stress

Microstructure of fresh concrete



Rheology is our tool

- Yield stress (and viscosity)
  - Bingham model used for concrete; Herschel-Bulkley for paste
  - Cement flocs behave as jammed system
  - Friction and interlock between grains
- Thixotropy
  - Hydration reaction builds C-S-H bridges
  - Cement flocs increase in size with time
  - Break-down under shear; build-up at rest
- Viscoelasticity
  - Elastic: C-S-H bridges will store a little energy by deforming before breaking
  - Viscous: flow in the bulk material

Wide range of fluidity of fresh concrete

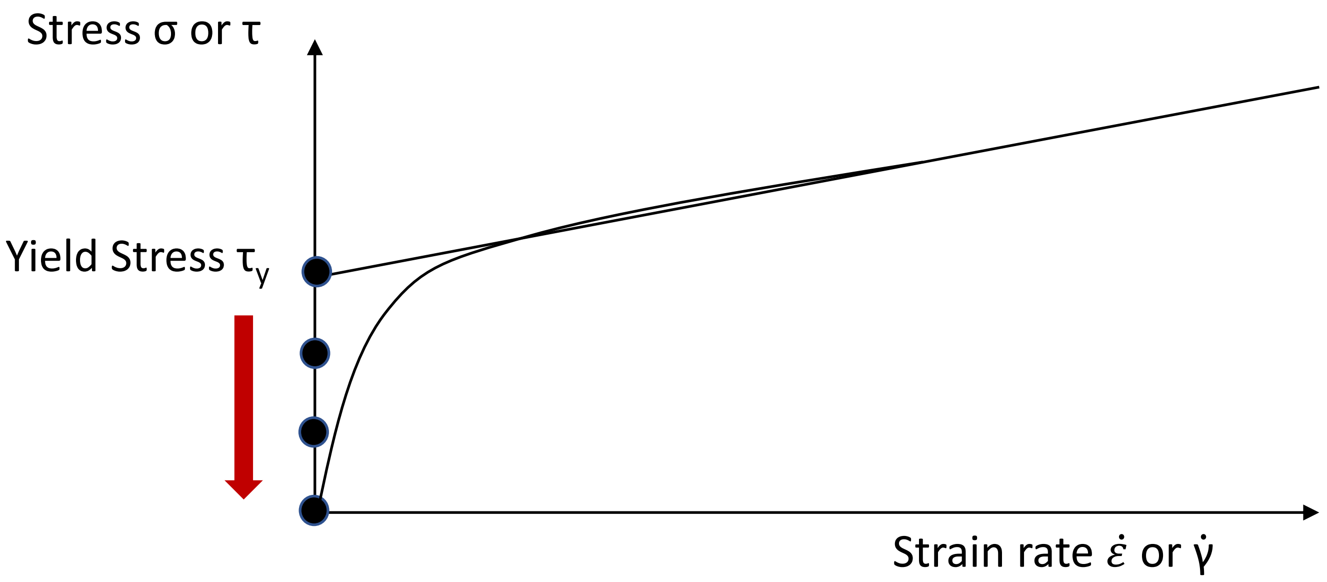
Slip form paving concrete

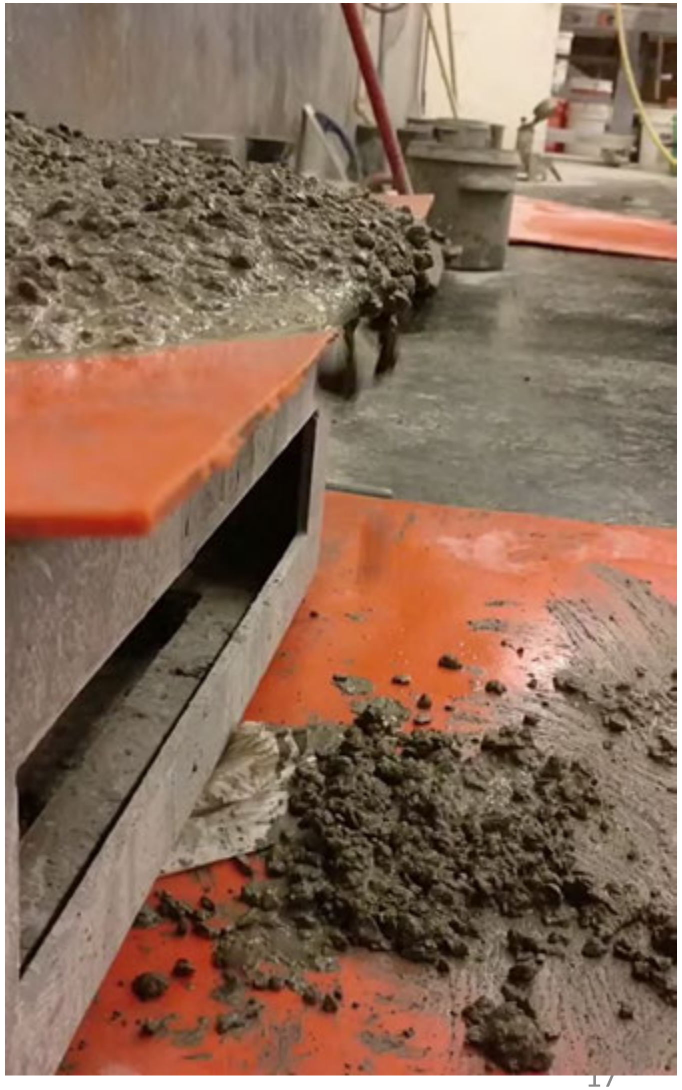
Video from https://www.youtube.com/watch?v=UykcqOFe0zk

Self-consolidating concrete (SCC)

Control yield stress with vibration

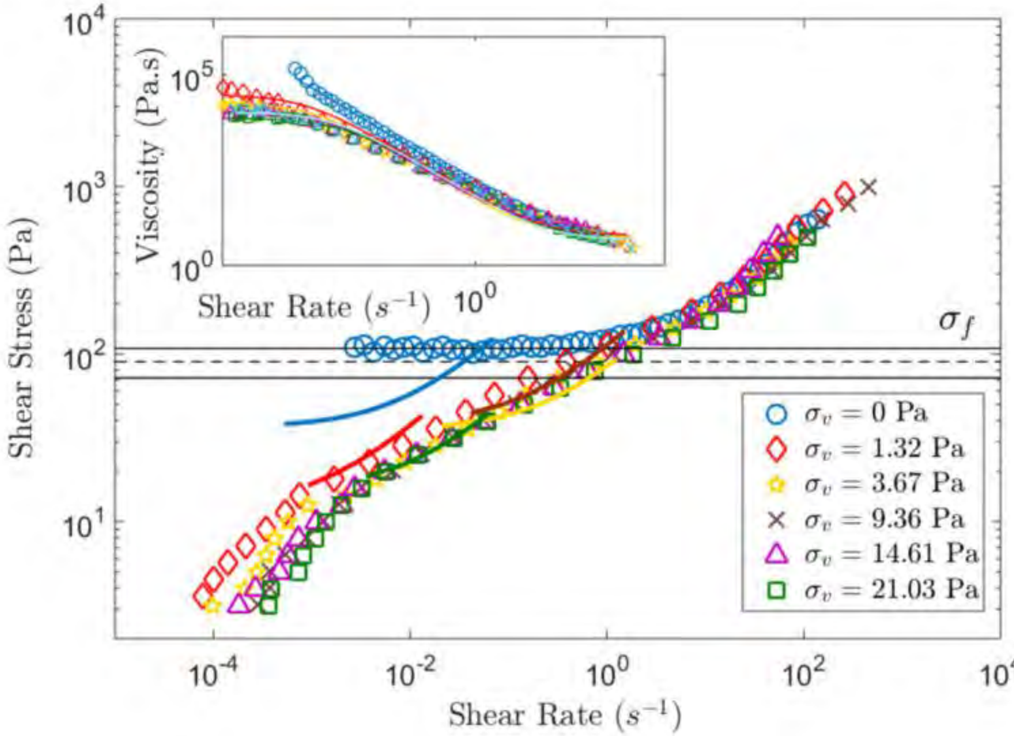
- Applying vibration can control the yield stress of fresh concrete



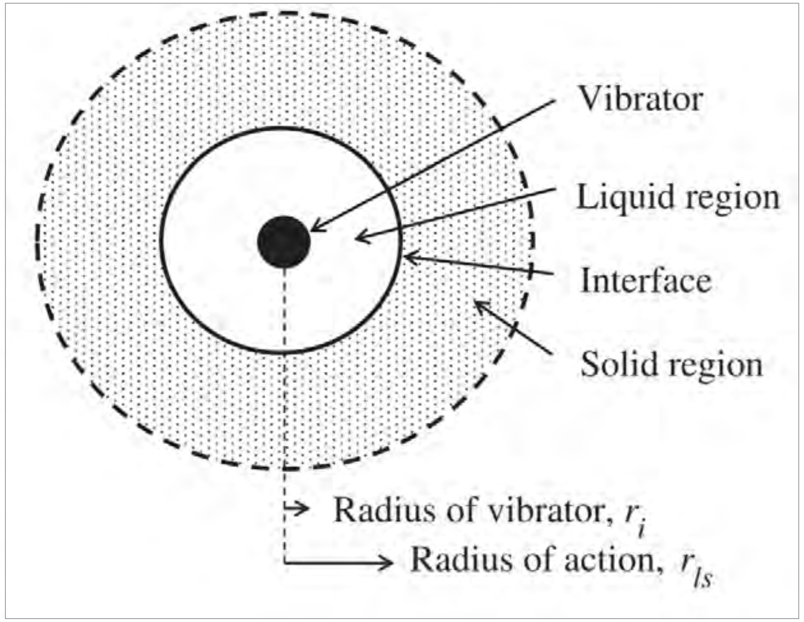


How does vibration affect rheology?

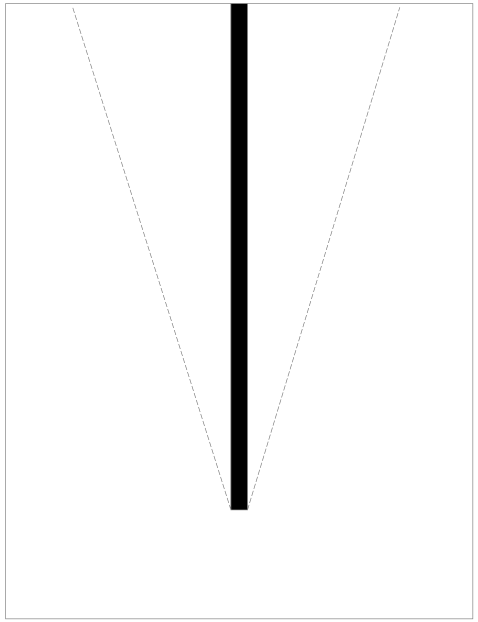
- Cement paste: destroys emerging solid structure, resets shear history
- Grains: gives particles greater "free volume" in which they can move
- **Granular suspension:** lowers viscosity, overcomes yield stress



Data demonstrating how vibration overcomes yield stress *(Gaudel et al. 2017)*



Schematic of how vibration propagates through fresh concrete *(Banfill et al. 2011)*



Depth-dependent! *(Based on work by Jeremy Koch)*

The "old way"

Measuring yield stress: slump test

Pros:

- Repeatable
- Relied on in industry
- Pretty good indicator of yield stress

Cons:

- Only one measured value to describe at least 2 parameters = inadequate
- Very coarse, bulk test

✓ Conducted according to ASTM C143
✓ Done within first 10 minutes of hydration age
✓ Used primarily as quality control

No-slump concrete

The "new way"

Measuring yield stress: ICAR rheometer

Pros:

- Provides quantities for yield stress and viscosity

Cons:

- Current software is not transparent
- Each measurement disturbs the sample
- Cannot be used for low-slump concrete

✓ Conducted stress growth test at 0.025 rpm to get static yield stress
✓ Hydration age carefully monitored to ensure readings are comparable
✓ Steel stand used to isolate torque meter from vibration table

Set-up of ICAR rheometer and bucket with vibration table

Another "new way"

Measuring yield stress: Instron

Pros:

- Can quantify yield stress of very stiff concretes
- Easy to run

Cons:

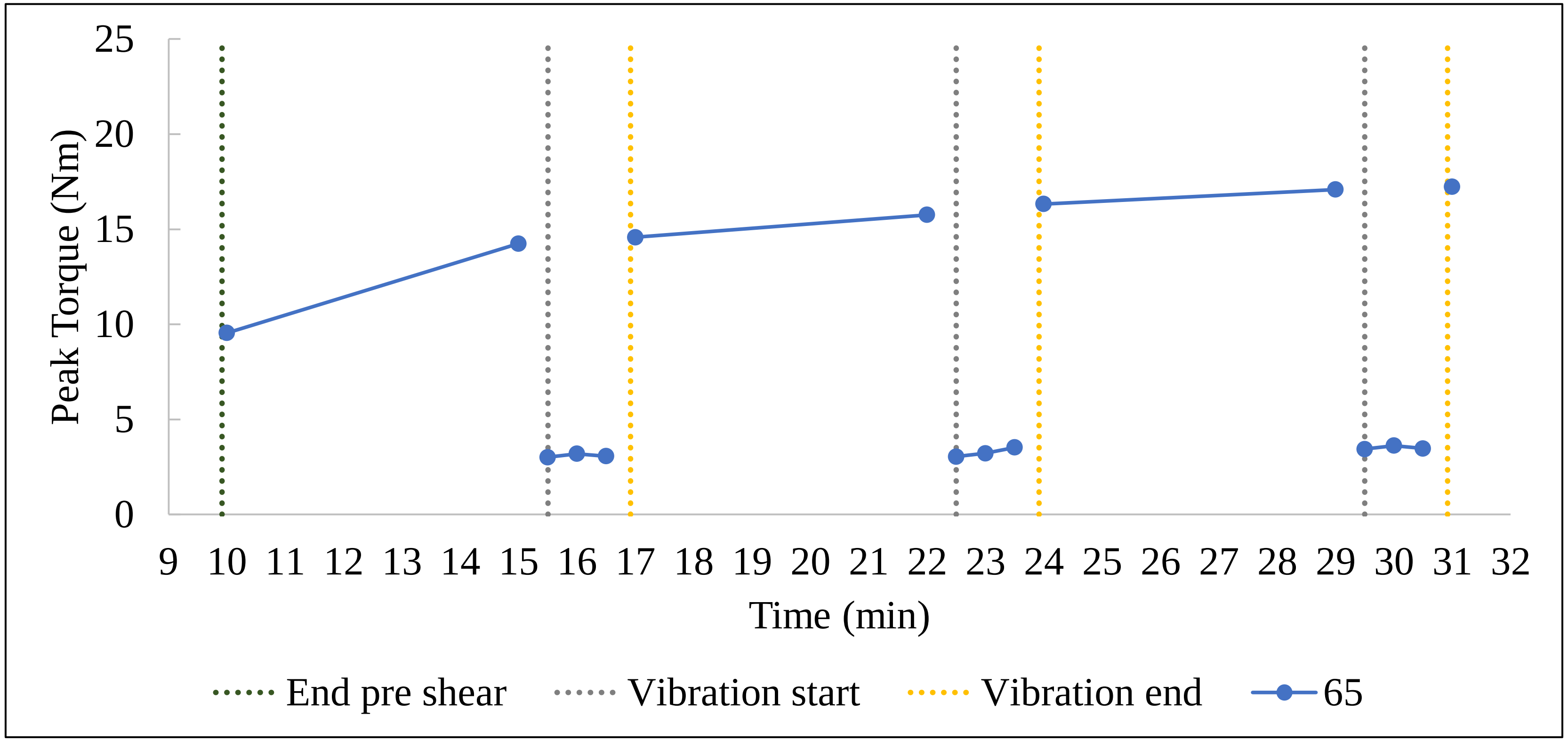
- Not a standard or well-studied method
- Repeatability is unknown
- Takes time to conduct (while hydration is proceeding)

✓ When neither slump test nor ICAR works

✓ Inspired by unconfined compression test used in soil mechanics (ASTM D2166)

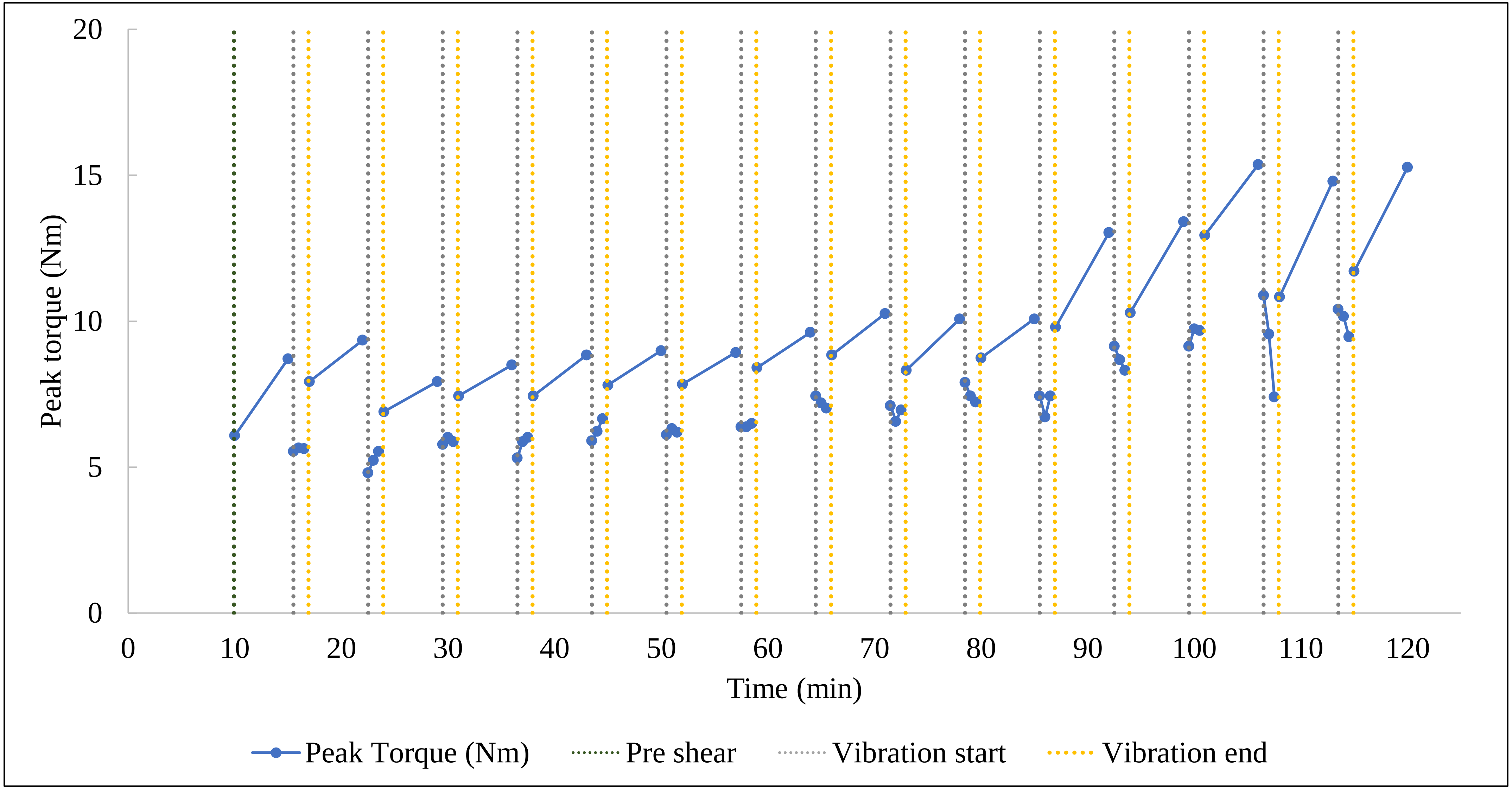
Demonstration of compressive loading of fresh, no-slump concrete

How does vibration reduce yield stress?



Peak torque T

Yield stress τ_0

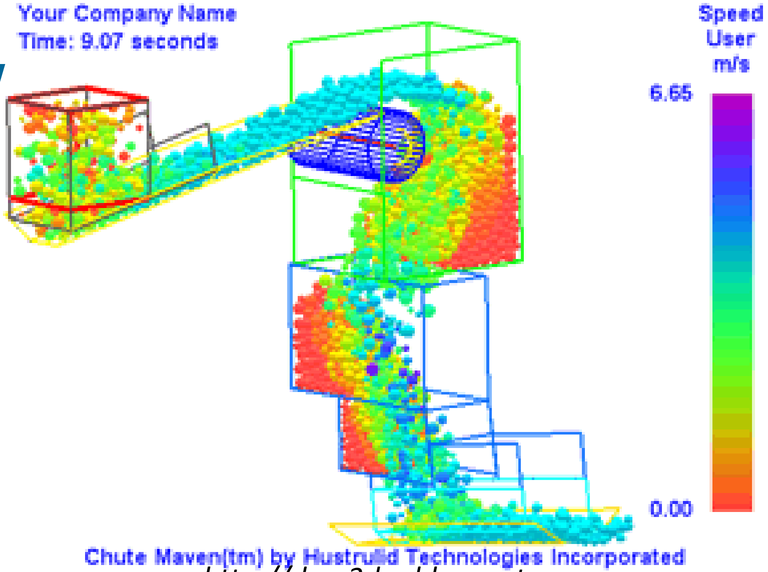

Peak torque (Nm)
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (min)
Peak Torque (Nm)
Pre shear
Vibration start
Vibration end

Computer modeling of concrete flow with *Discrete Element Model*

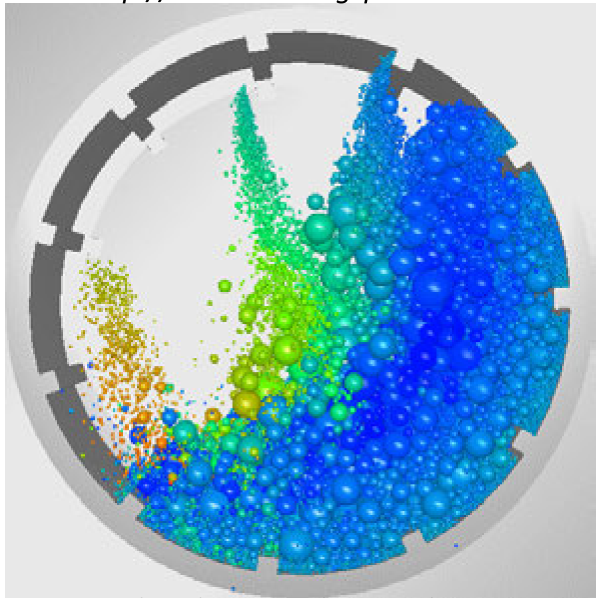
Discrete Element Modeling of granular flow

- DEM is a particle-scale numerical method
  - Can simulate granular flow
  - Behavior of each particle and interactions count
  - For incompressible material

- Applications
  - Simulate and analyze flow behavior
  - Predict impact forces on particles and boundaries
  - Particle distribution in segregation and blending

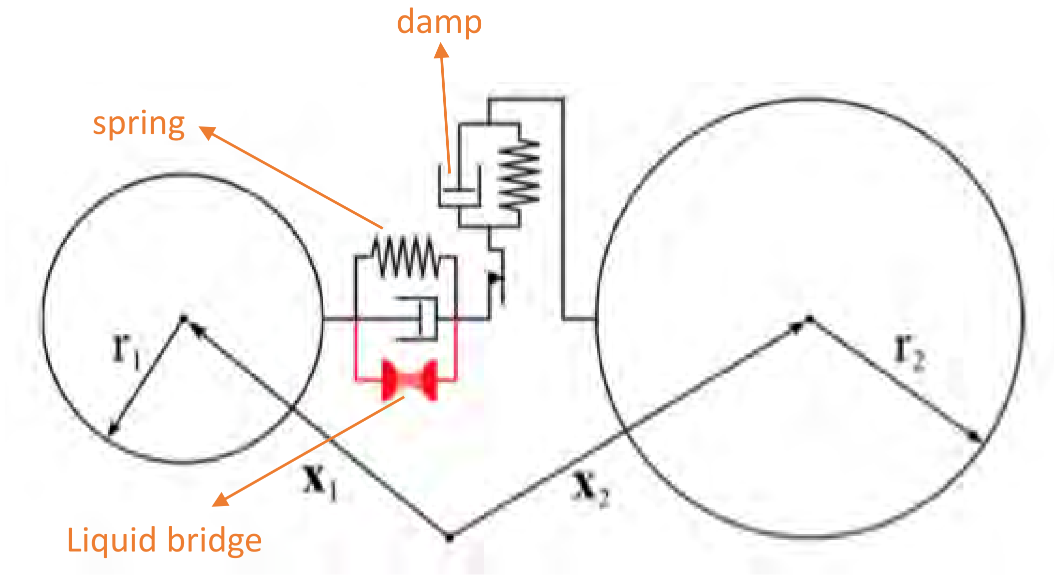


http://dem3dm.blogspot.com

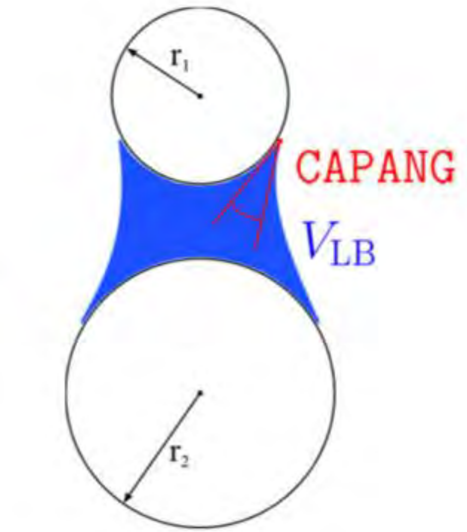


http://www.phy.uct.ac.za/phy/research/applied/computationalmodelling/

- **Particle to particle contact model**
  - Damping contribution
  - Frictional contribution
  - Elastic contribution
  - Capillary force contribution for wet particles

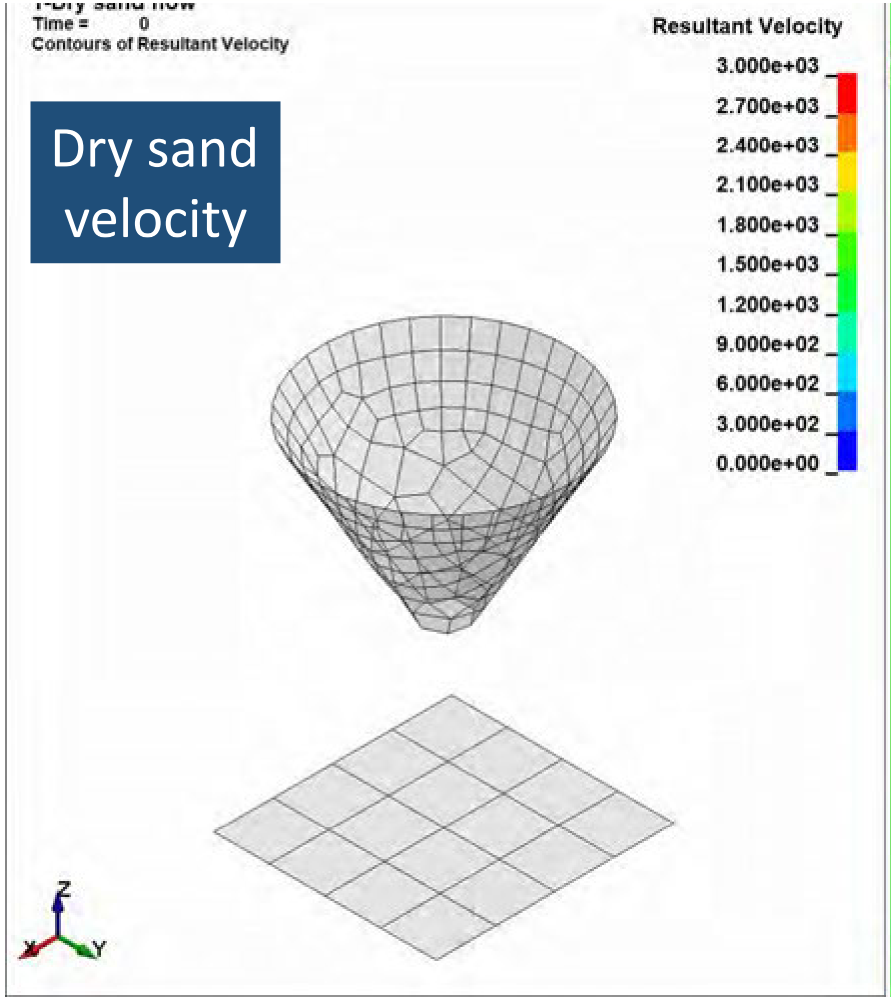


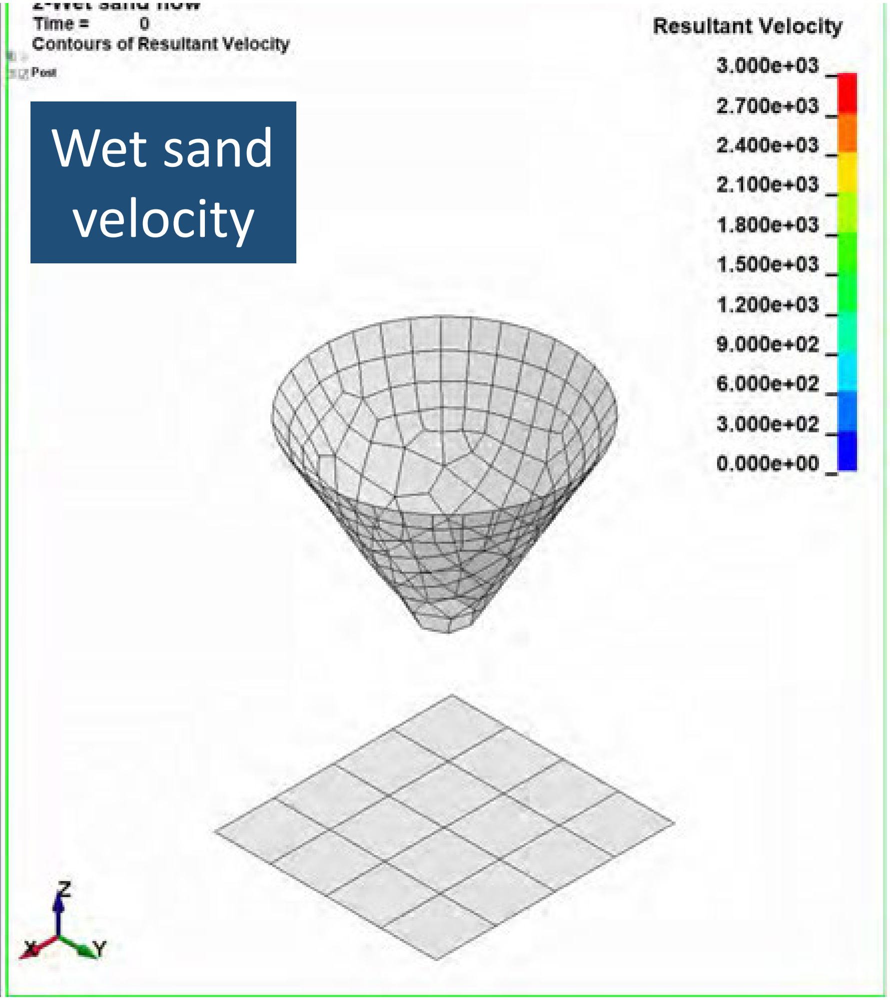
Particle to particle contact model
(Rabinovich, Esayanur and Moudgil 2005)



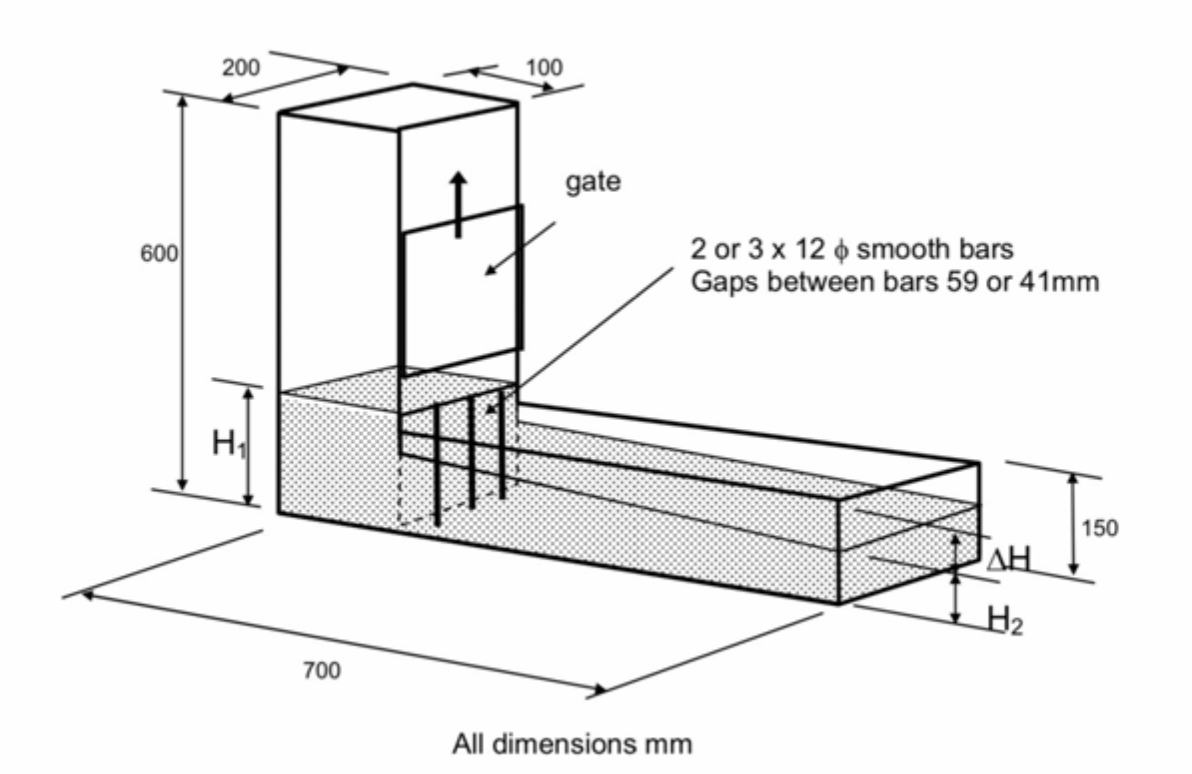
Liquid bridge for wet particles

Funnel sand flow: dry vs wet

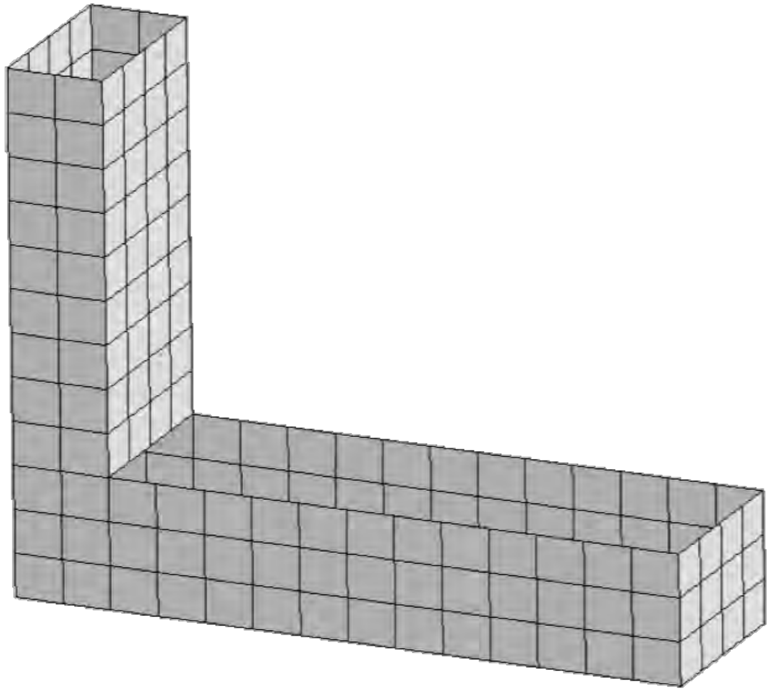




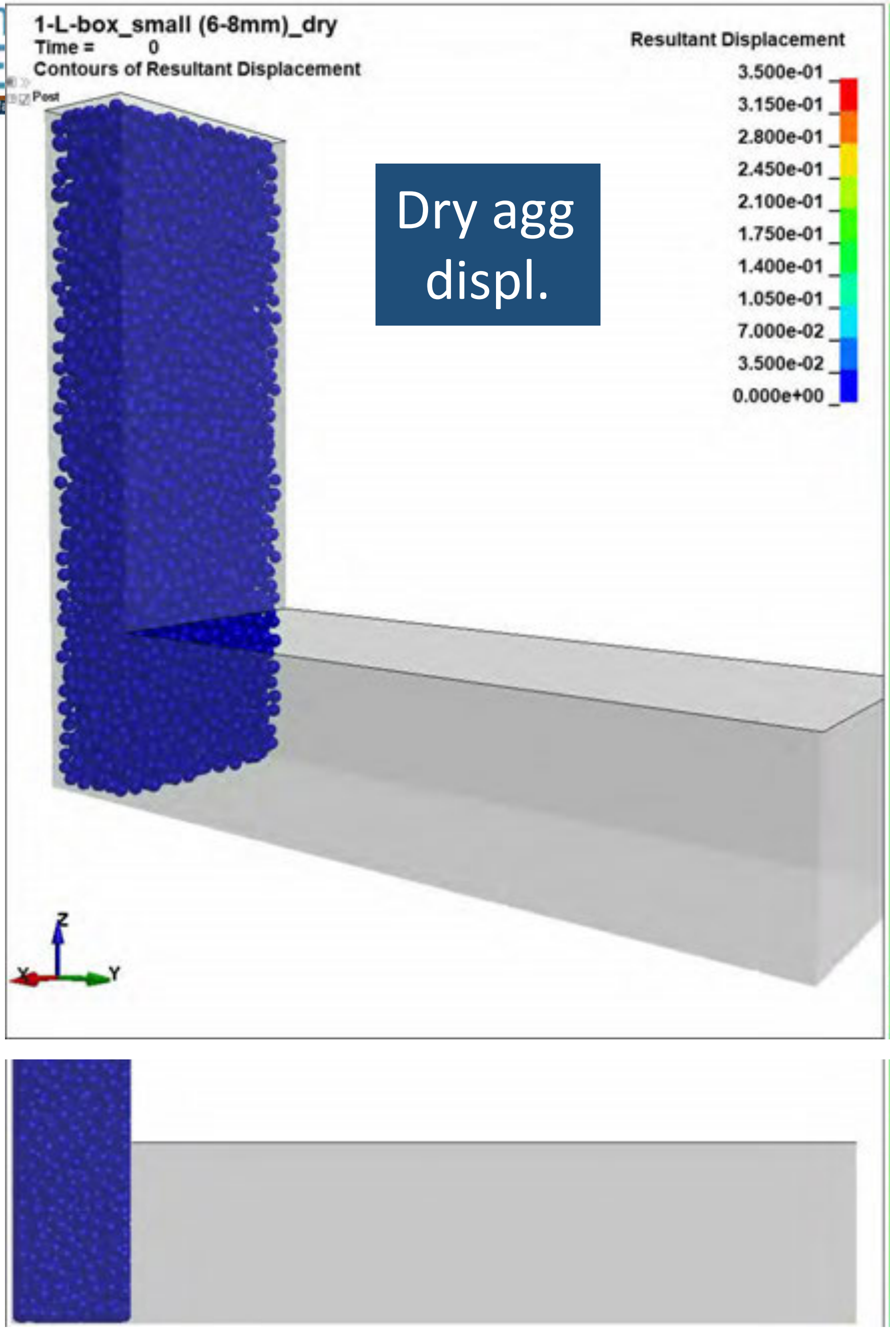
- L-box test is used to assess the flowability of SCC

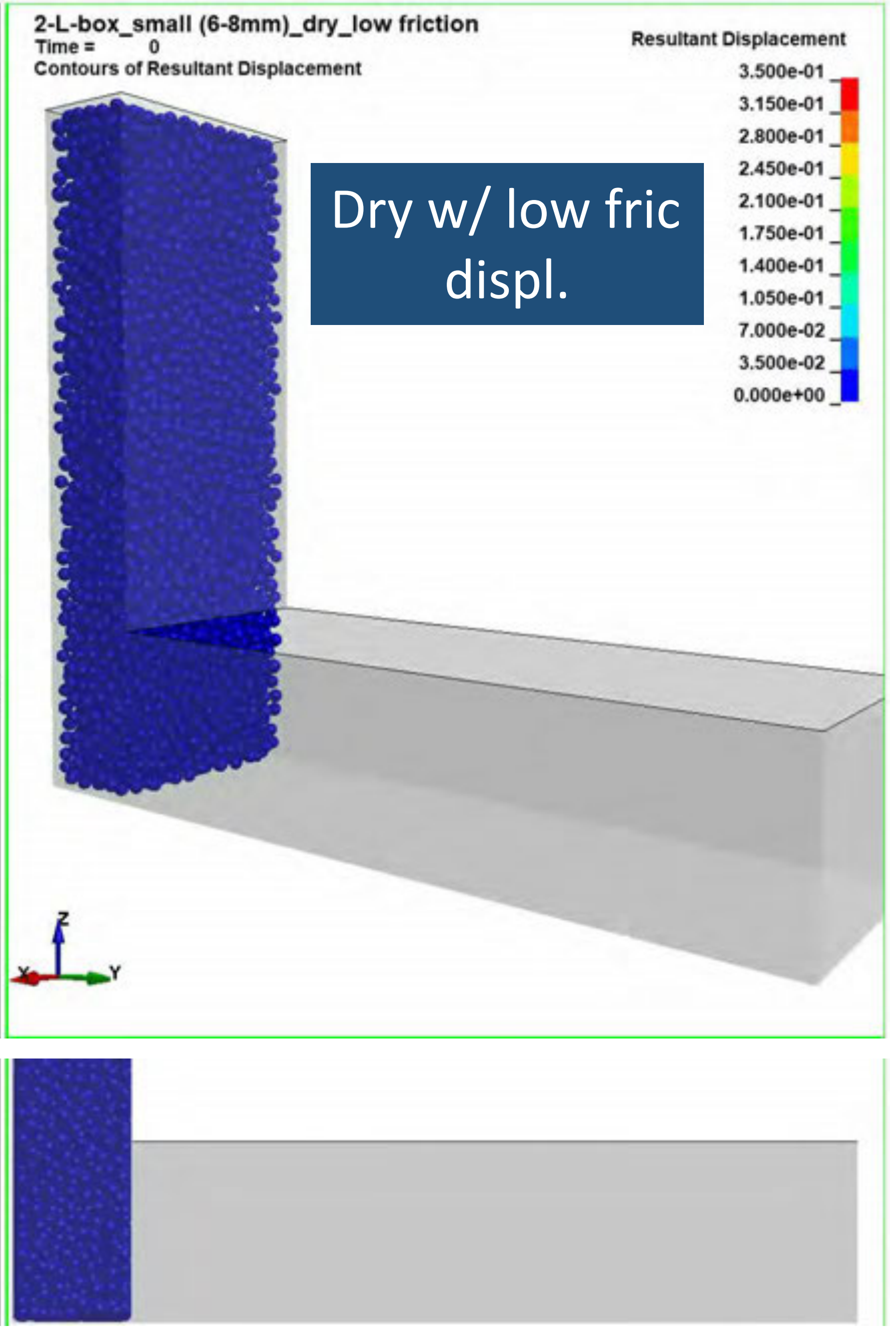


L-box geometry
Image from the European guidelines

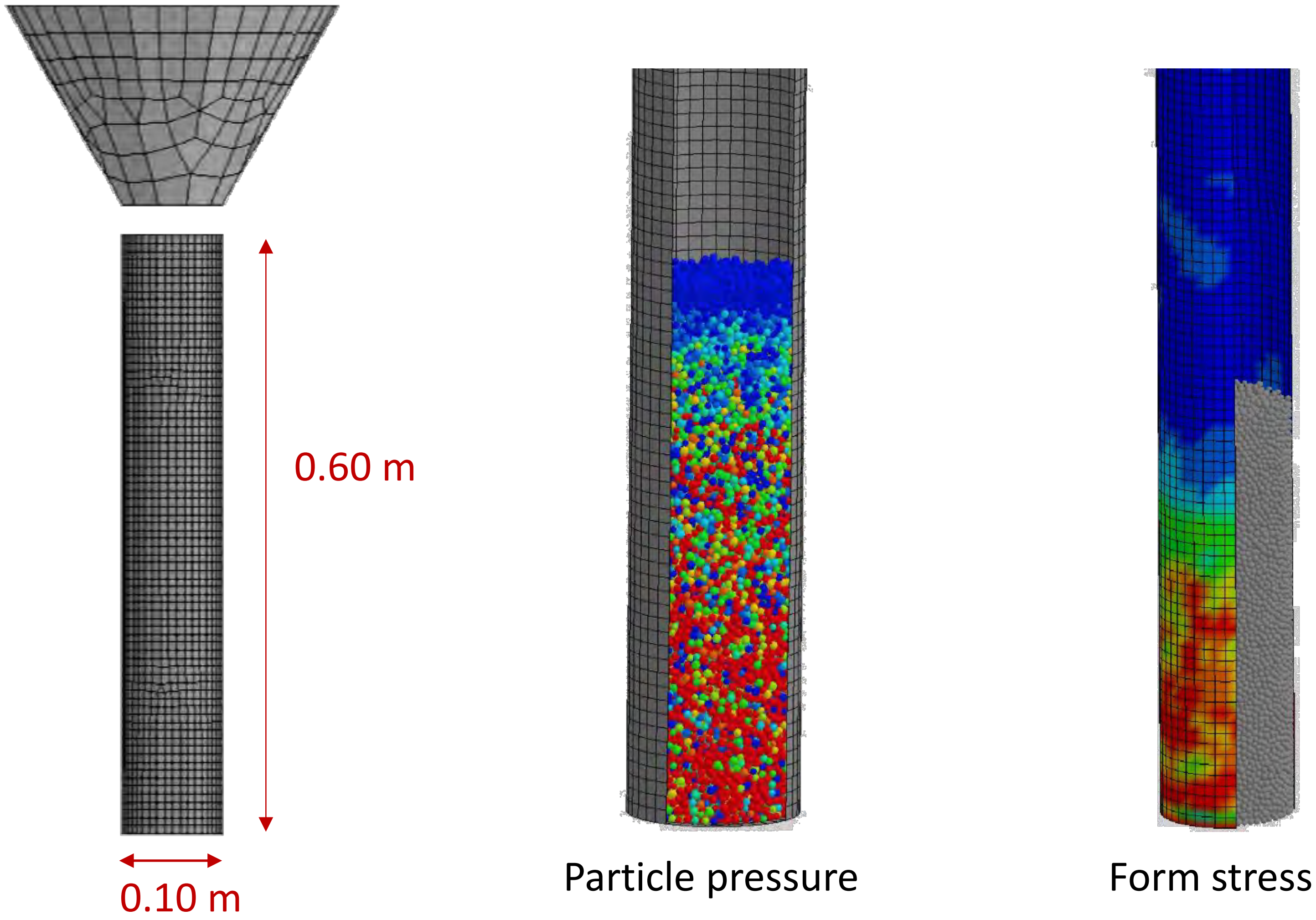


A simplified L-box model without reinforcements


1-L-box_small (6-8mm)_dry
Time = 0
Contours of Resultant Displacement
Resultant Displacement
3.500e-01
3.150e-01
2.800e-01
2.450e-01
2.100e-01
1.750e-01
1.400e-01
1.050e-01
7.000e-02
3.500e-02
0.000e+00
Dry agg displ.


2-L-box_small (6-8mm)_dry_low friction
Time = 0
Contours of Resultant Displacement
Resultant Displacement
3.500e-01
3.150e-01
2.800e-01
2.450e-01
2.100e-01
1.750e-01
1.400e-01
1.050e-01
7.000e-02
3.500e-02
0.000e+00
Dry w/ low fric displ.

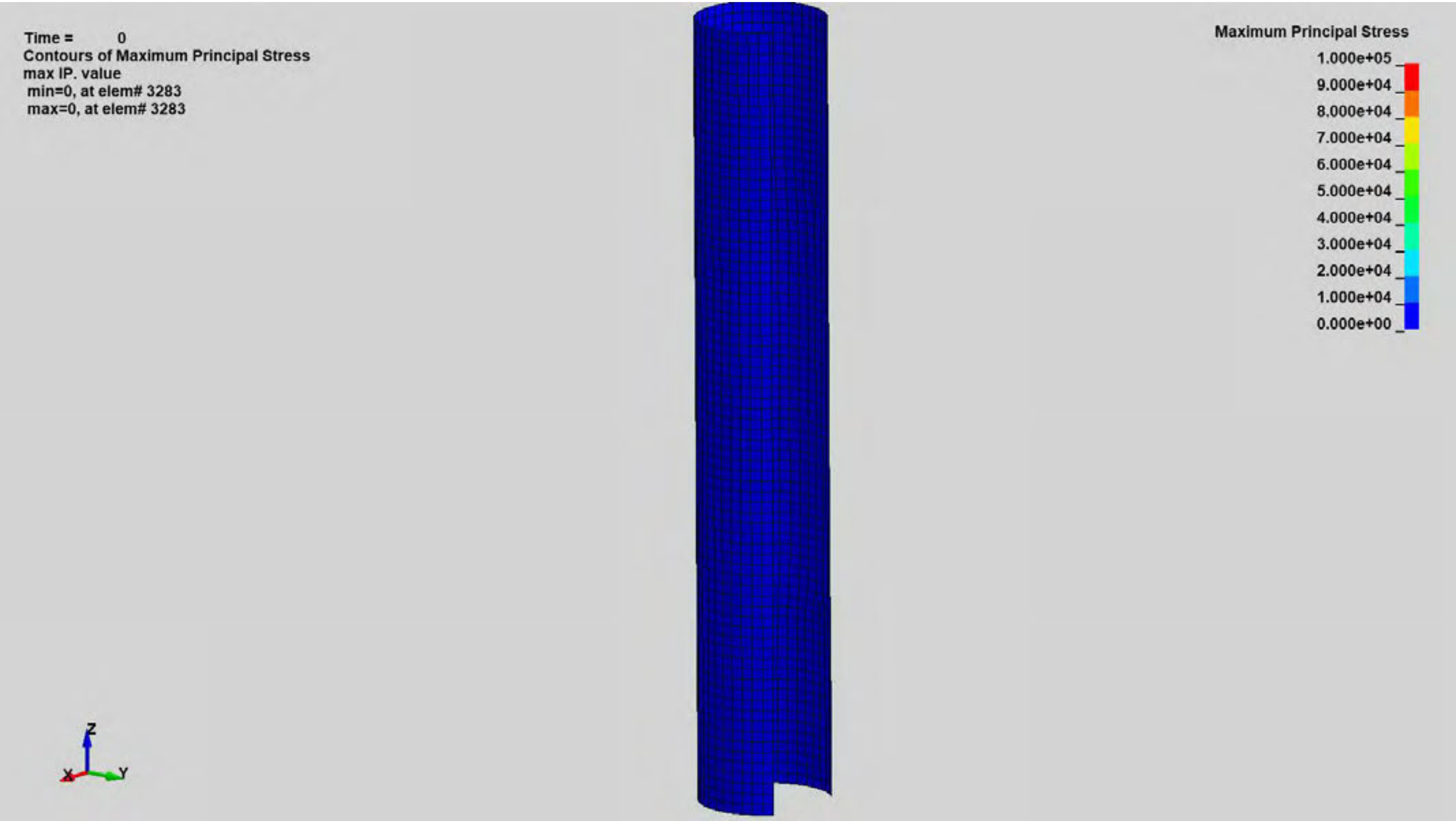
- FORM PRESSURE: Fresh concrete exerts pressure on the surfaces of vertical forms
- Assessments on form pressure are critical for form designs



Particle pressure

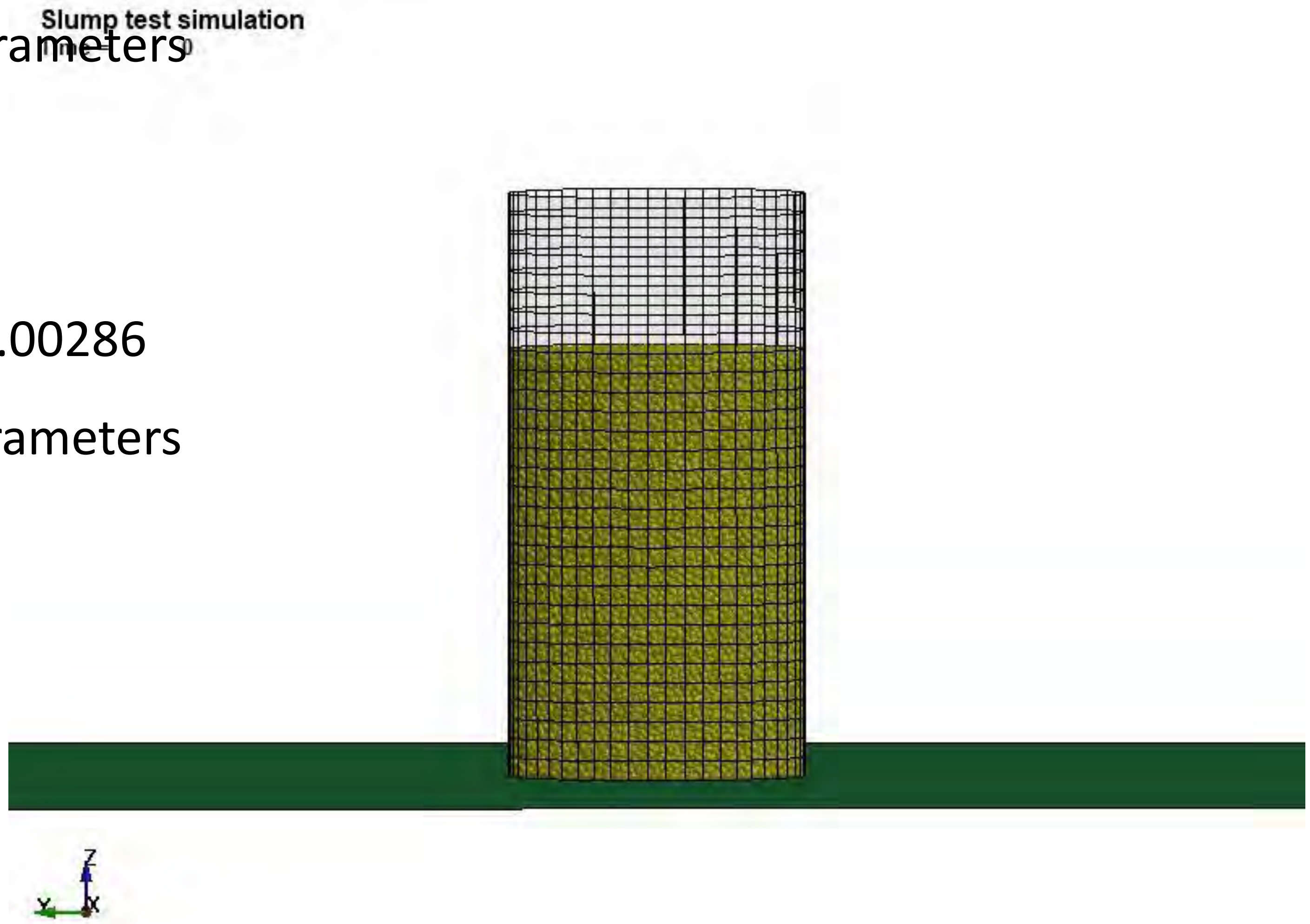
Form stress

Stress


Time = 0
Contours of Maximum Principal Stress
max IP. value
min=0, at elem# 3283
max=0, at elem# 3283
Maximum Principal Stress
1.000e+05
9.000e+04
8.000e+04
7.000e+04
6.000e+04
5.000e+04
4.000e+04
3.000e+04
2.000e+04
1.000e+04
0.000e+00
Z
X
Y

Calibrating the DEM model with simple test

- Particle to particle contact parameters
  - NDAMP=TDAMP=0.7
  - Fric = 0.6, FricR = 0.1
  - NormK = 0.01, ShearK = 0.00286
- Particle to surface contact parameters
  - FricS = 0.3
  - FricD = 0.3
  - Damp = 0.9



	Height (mm)	Spread (mm)
Experiment	47	190.5
Simulation	46.3	178.9
% deviation	1.5	6.1

An agreement is found between the experimental and simulation results

Computer modeling of concrete flow with *Incompressible Computational Fluid Dynamics (ICFD)*

- DEM cannot fully simulate fluid behavior
- Incompressible fluid dynamics can simulate liquid flow
  - Assume incompressible fluid flow
  - Use Navier-Stokes equations

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \rho f_i \quad \text{in} \quad \Omega$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{in} \quad \Omega$$

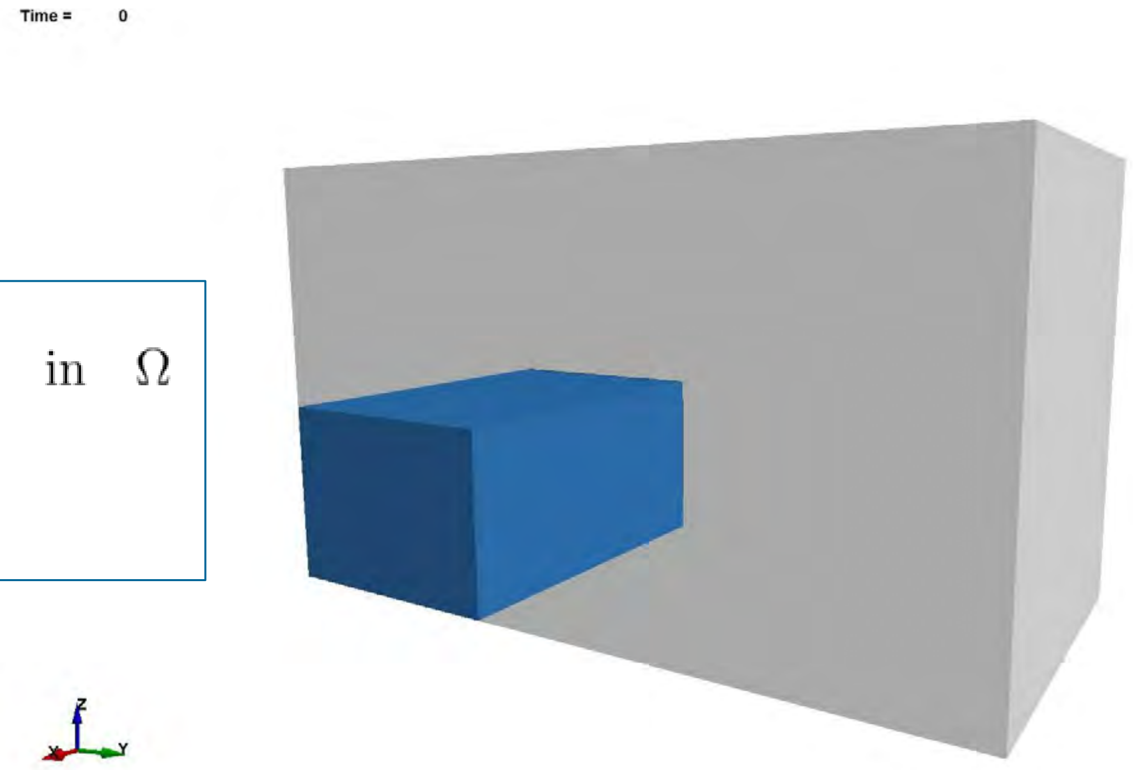
Where,

u: velocity

ρ: density

p: pressure

f: external body accelerations



General view of water flow

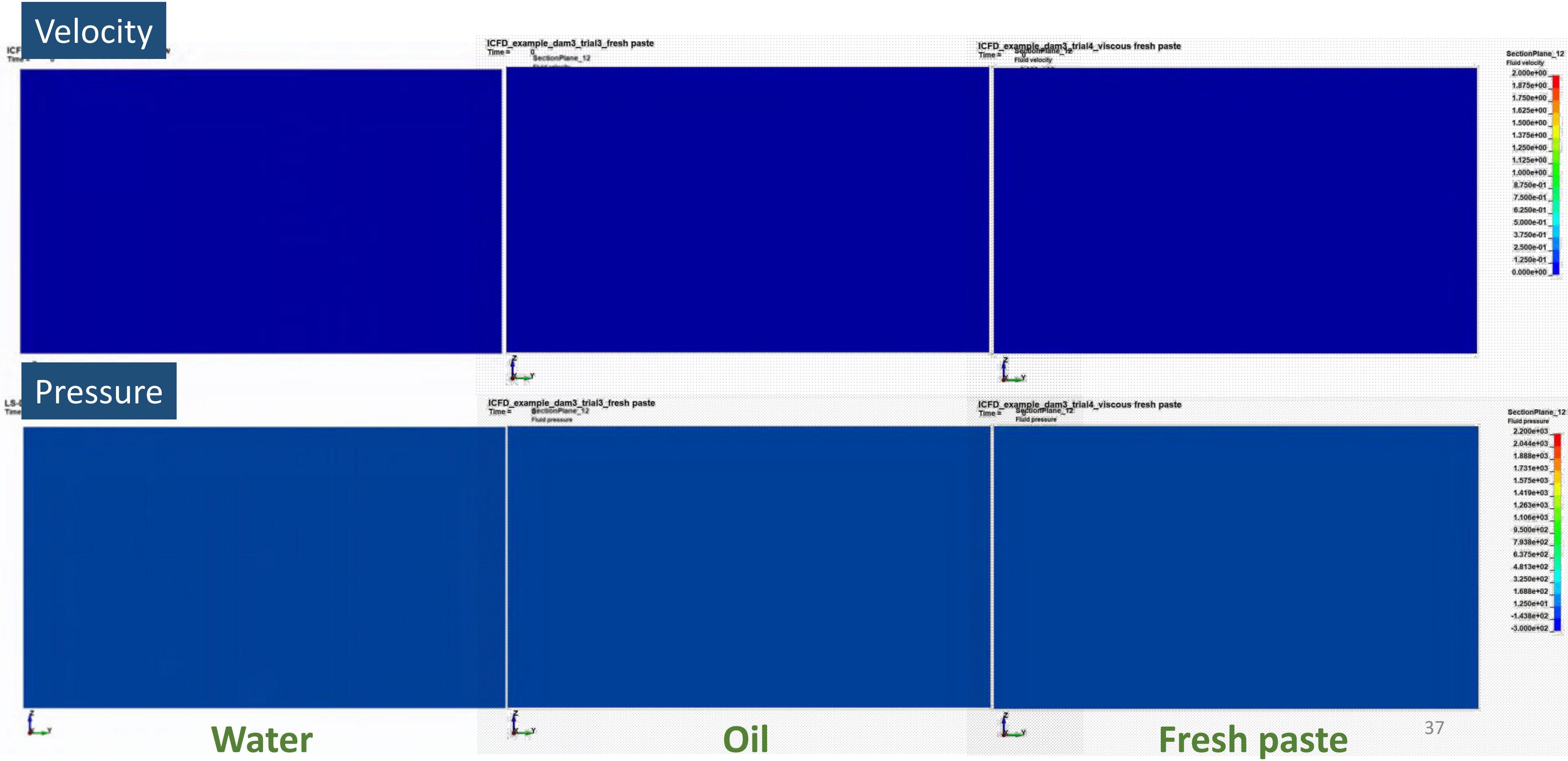
Comparison: water vs. oil vs. viscous paste

Water
Viscosity = 0

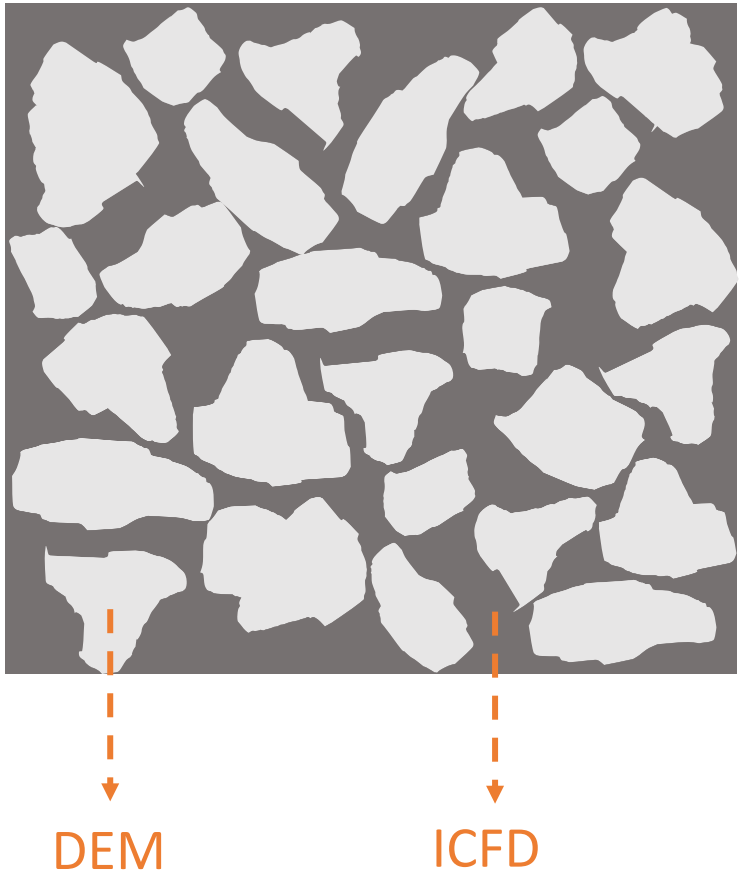
Oil
Viscosity = 1 Pa·s

Viscous fresh paste
Viscosity = 50 Pa·s

Velocity and pressure comparison



- Fresh concrete = aggregate + mortar



General view of fresh concrete model

Computer modeling of novel foam materials using *LS-DYNA discrete element method*

- Concrete vs. Foam Concrete
- Density, microstructure, strength, fracture behavior

- Novel applications
- Light-weight panel, thermal isolation… **energy absorber**

medium.com

EMAS, airport runway safety

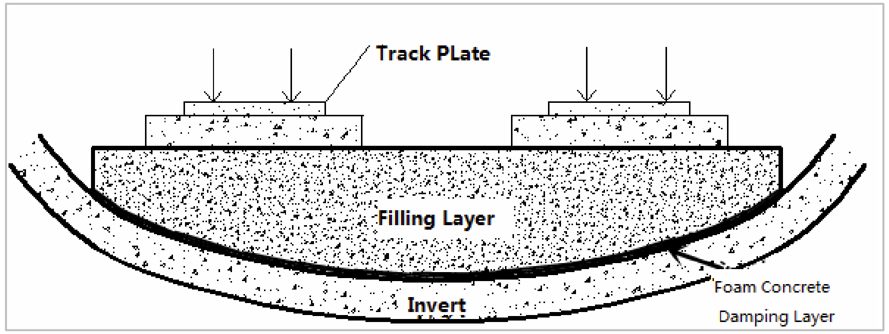
terrancorp.com

Shock-absorbing concrete, bullet traps

Kalina

Ballistic-proof foam concrete composite

Qiao et al.

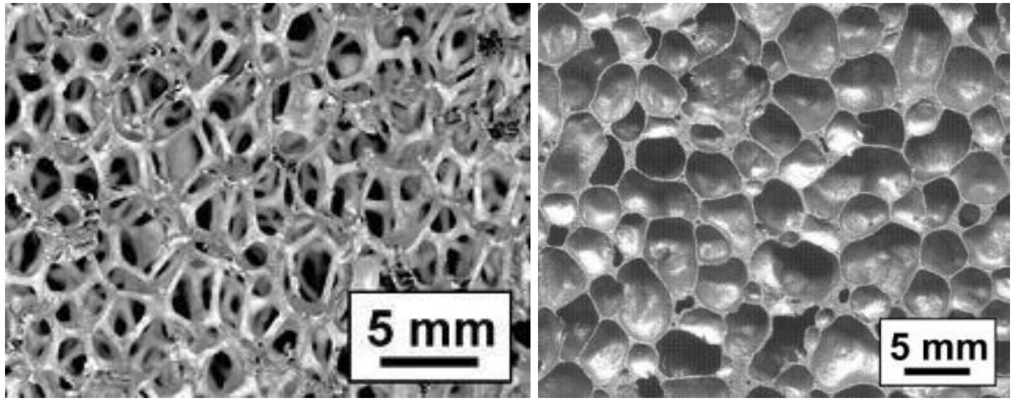


High-speed rail damping

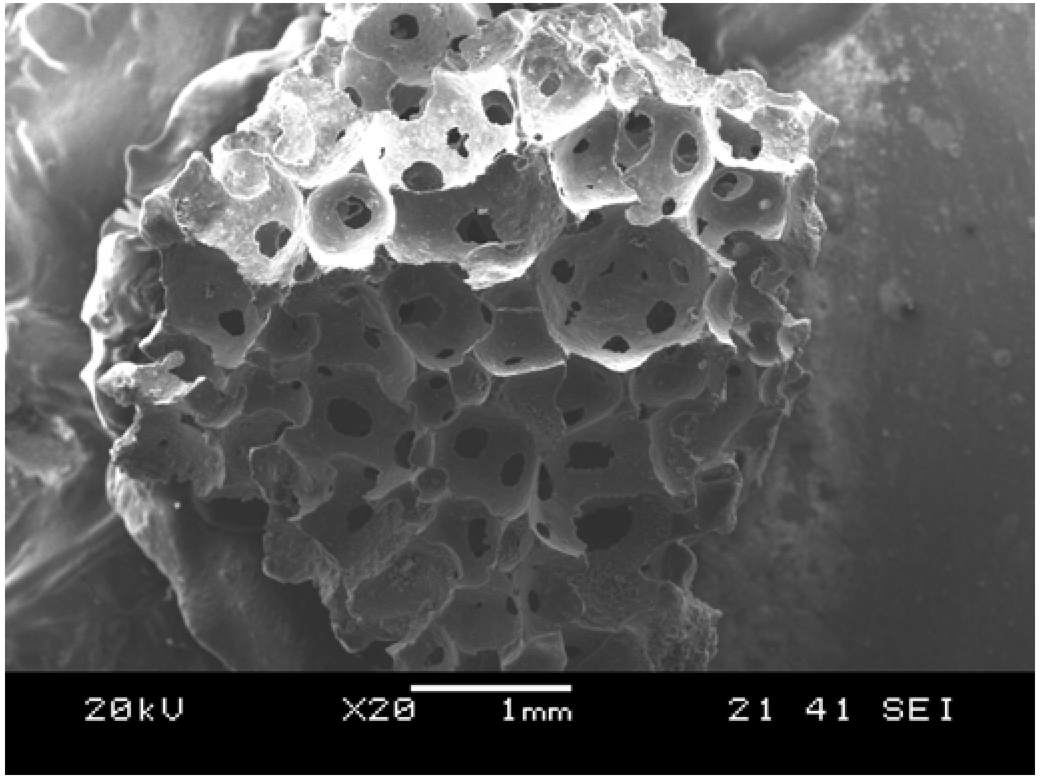
Cellular Solids

- "Cellular solids are nature's equivalent of the I-beam."-M.F. Ashby
- Open cell vs. Closed cell

http://www.foardpanel.com

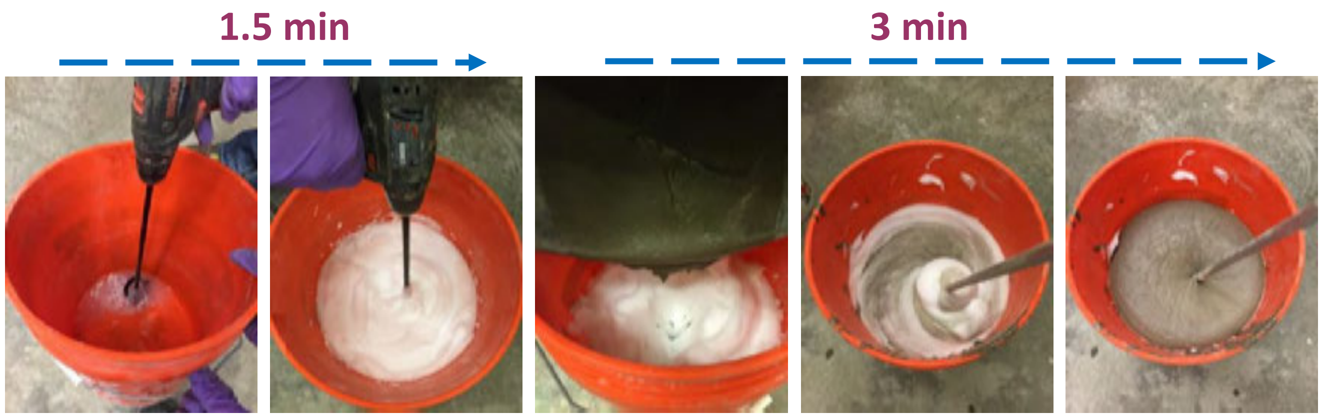


Open-cell (left) and closed-cell (right) foams

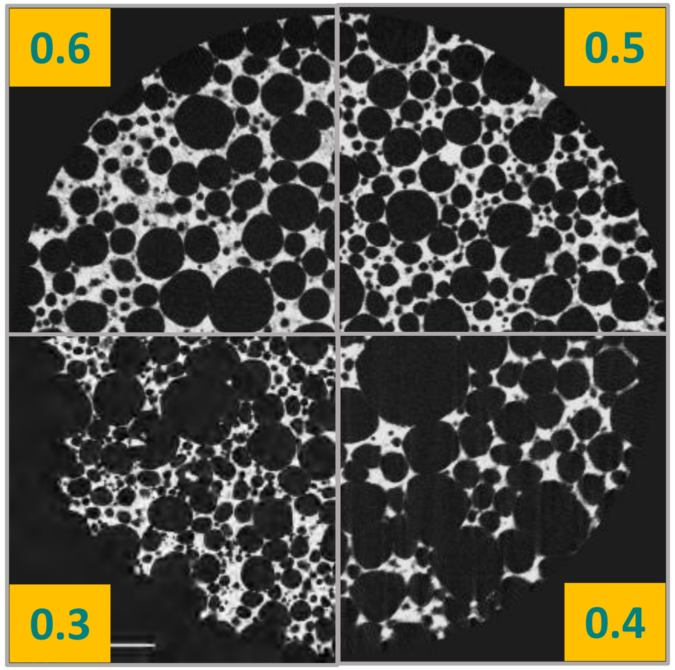


Foam concrete is a mix of open and closed cells

Making foam concrete

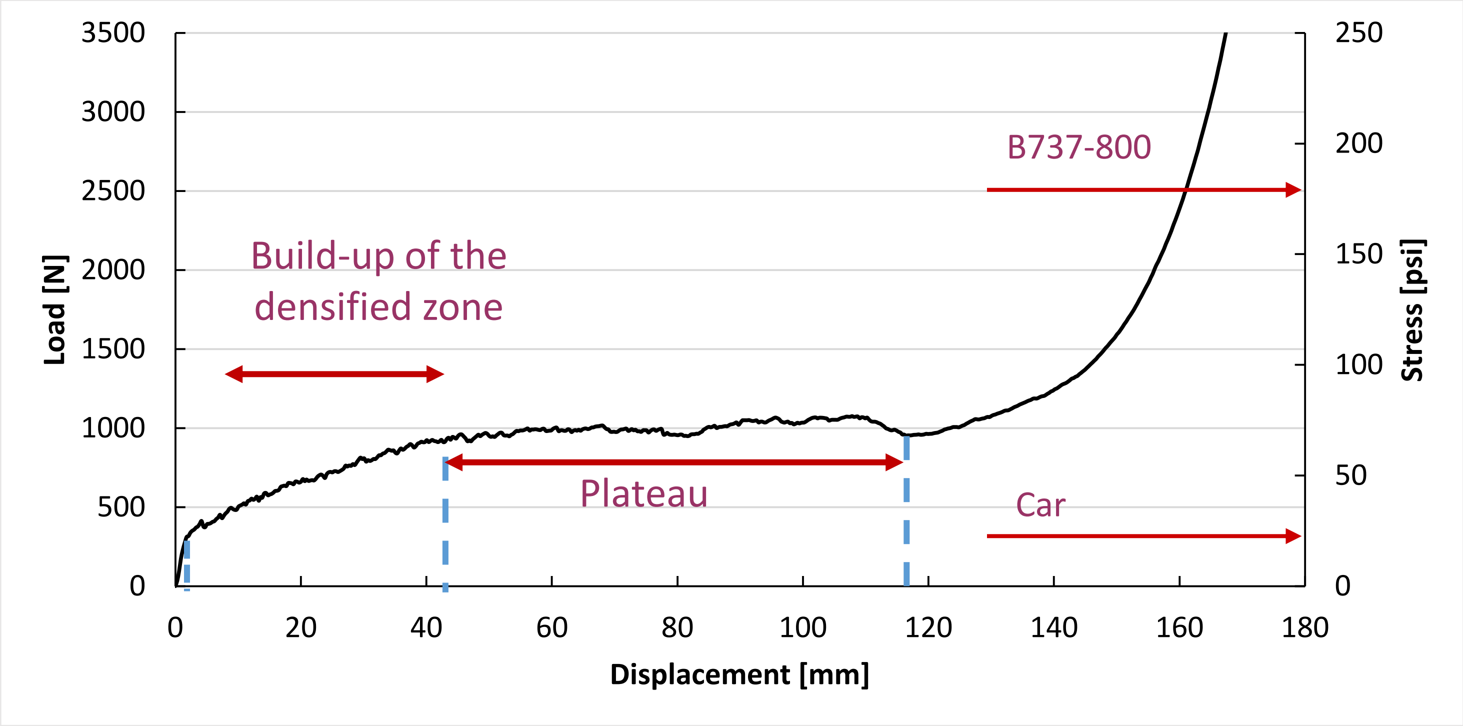


Foam concrete mixing procedures



CT scans of samples of different densities, g/cc

Testing a crushable material

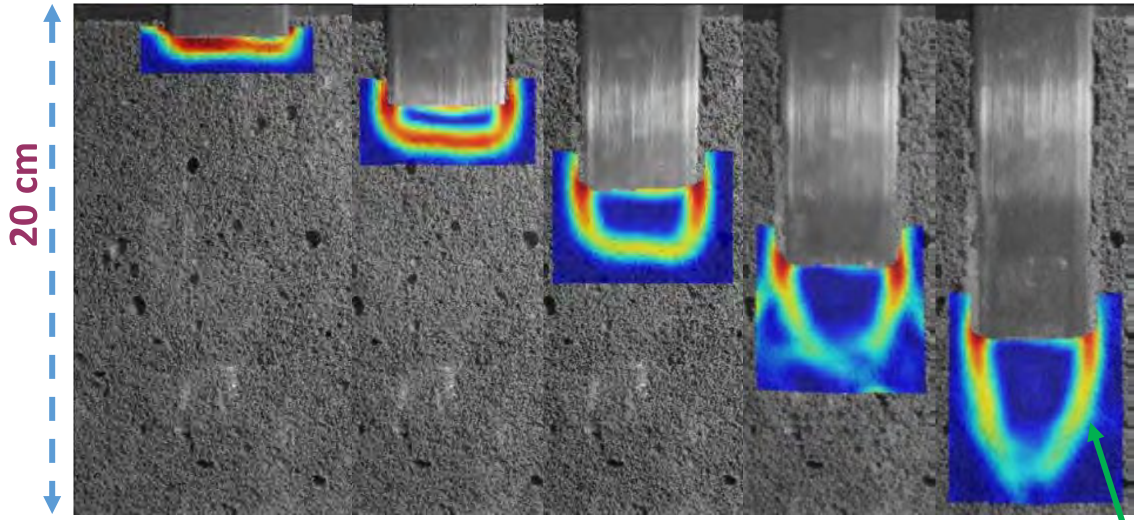


Penetration test

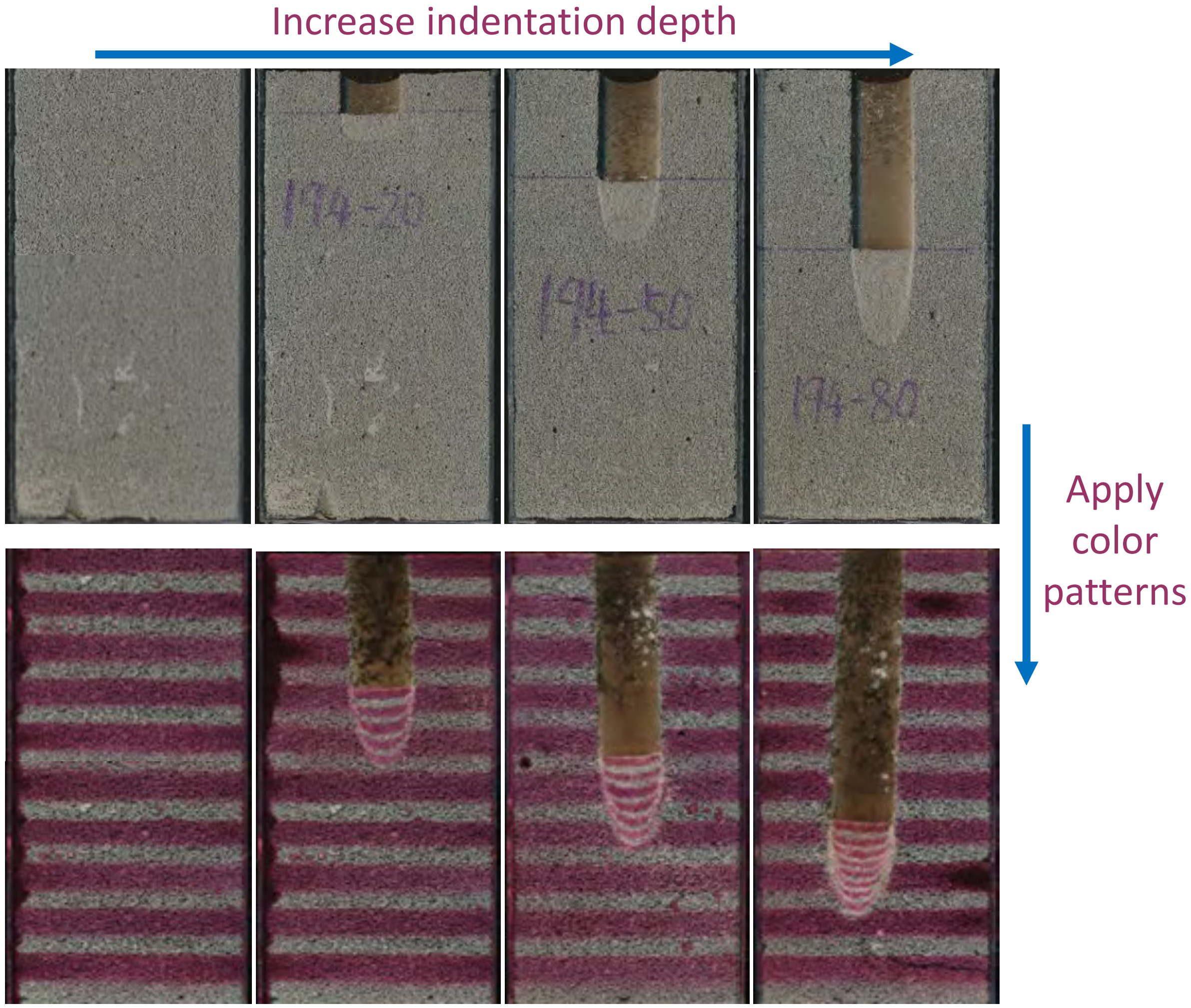
Tested specimens (half and top view)

Densification

- Novel experiments
- Digital image correlation (DIC)
- Deformation analysis:
  - Cut by half and sprayed with color
  - Tie back together for the penetration test

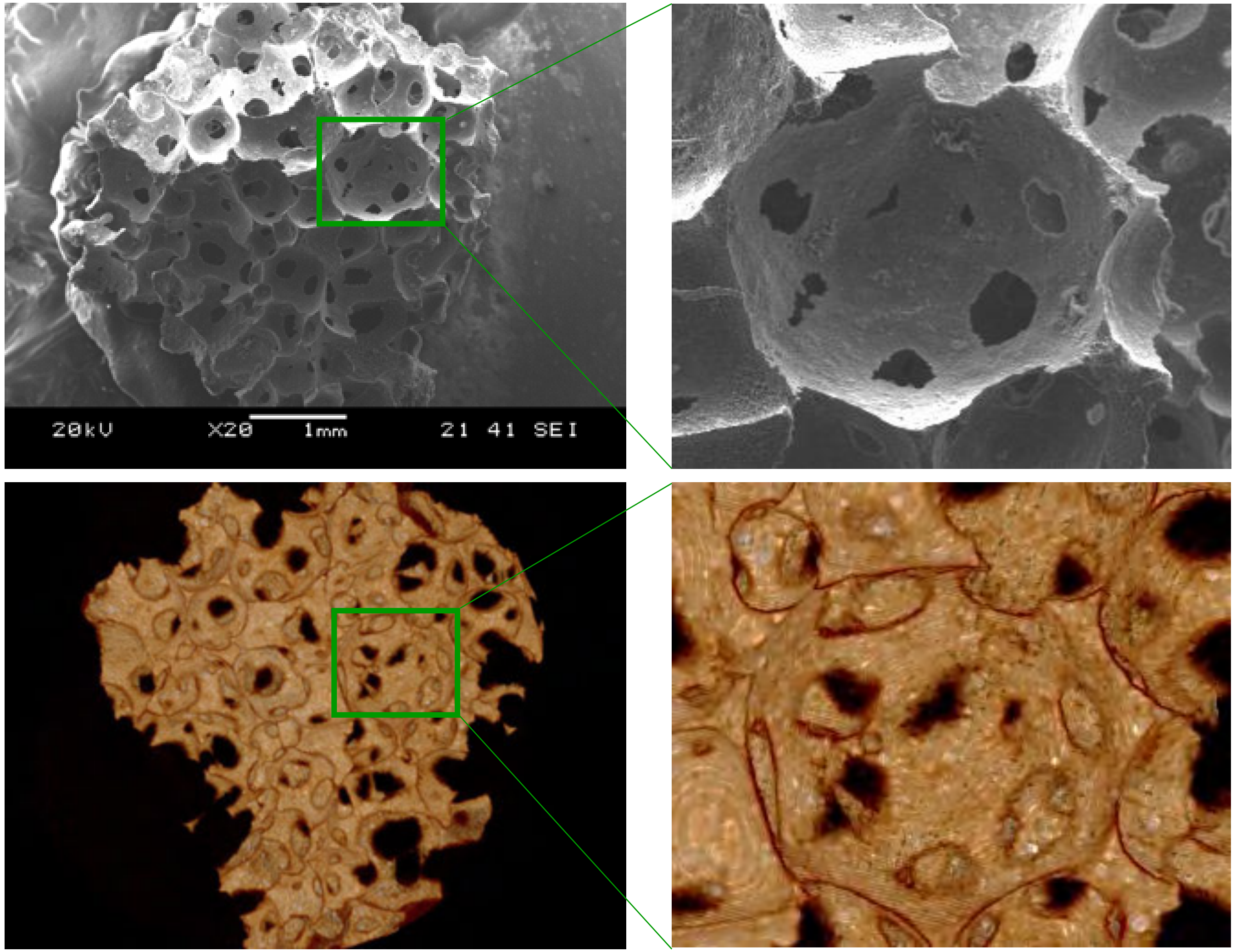


A DIC analysis: Stress distribution under the penetration



Densifications under the indenter
(0.4 g/cc, w/c=0.5)

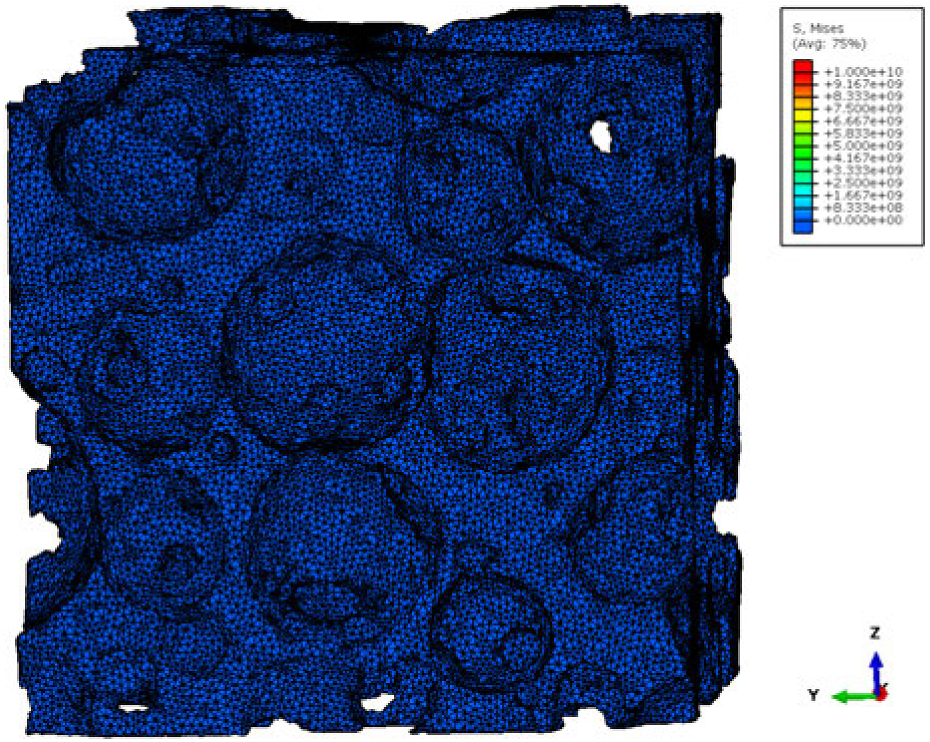
X-ray computed tomography

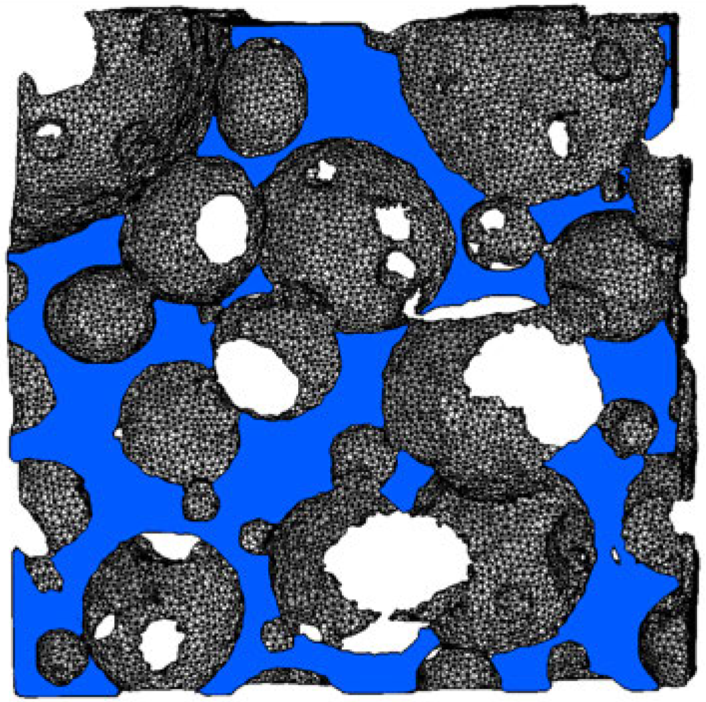


SEM vs. CT rendering (same perspective)

Detailed comparison

Finite element modeling using CT data for mesh





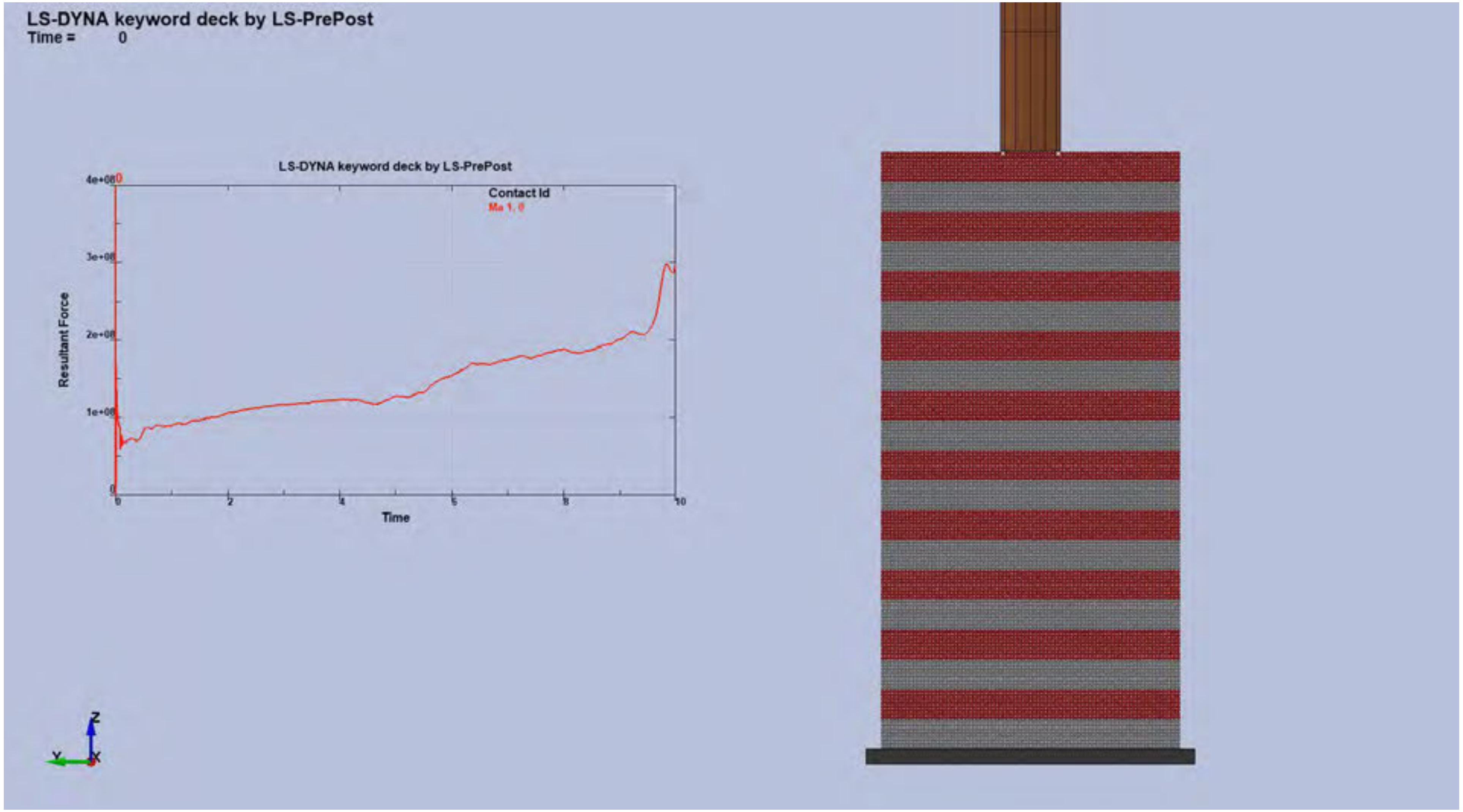
Uniaxial compression of a 1-mm foam concrete cube: whole (left) and slice (right)

Modeling crushing process

- Use LS-DYNA to simulate the dynamic crushing process
  - Use SPH elements to handle large deformation

- Details for the simulation
  - 3D model
  - Same aspect ratio as the physical penetration test
  - Material inputs
    1) foam concrete density √
    2) Load-displacement curve √
    3) Young's modulus √

3D model of the penetration test (unloaded)



Simulation of crushing process

Simulation vs. experiment


60 mm


60 mm

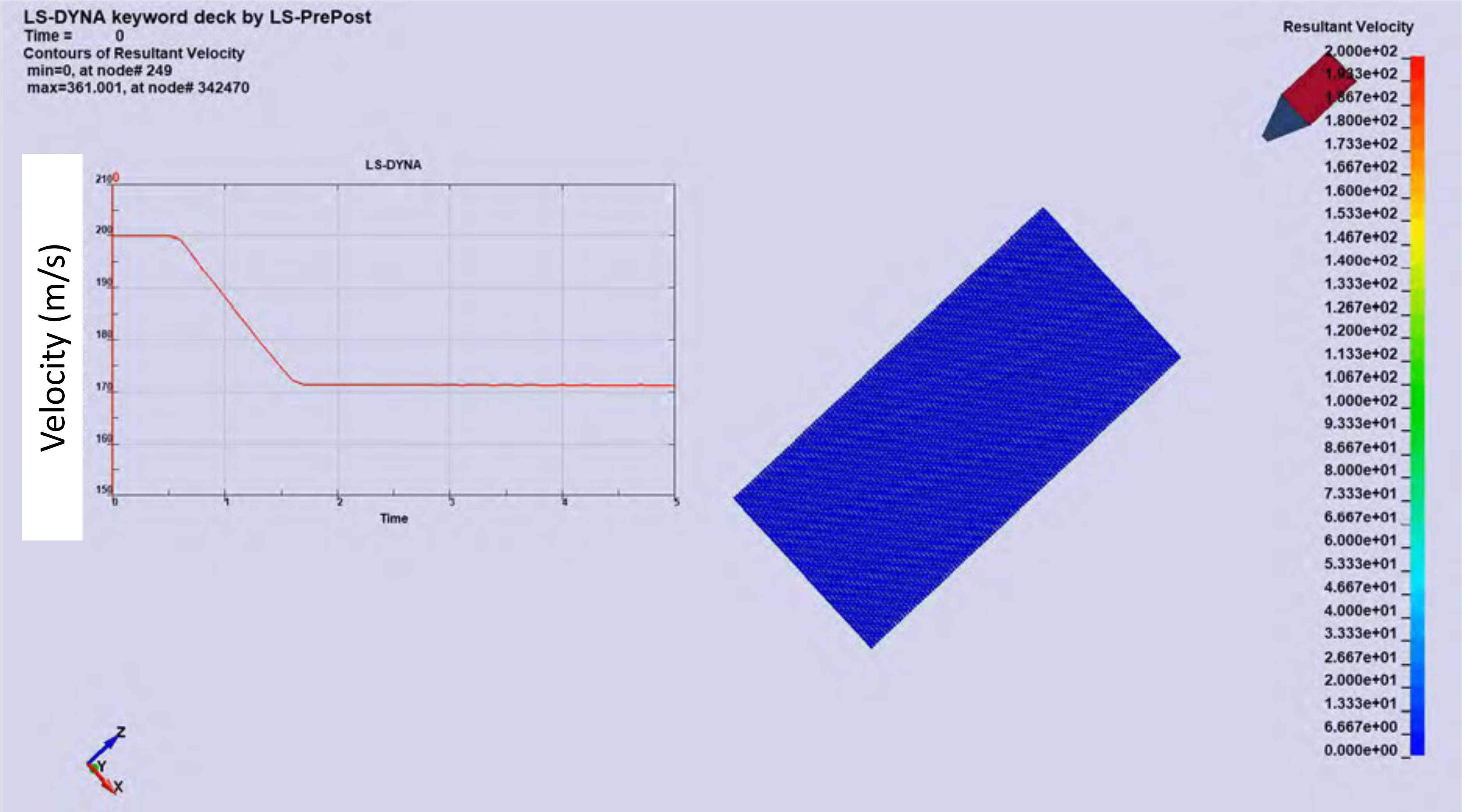

90 mm


90 mm


120 mm

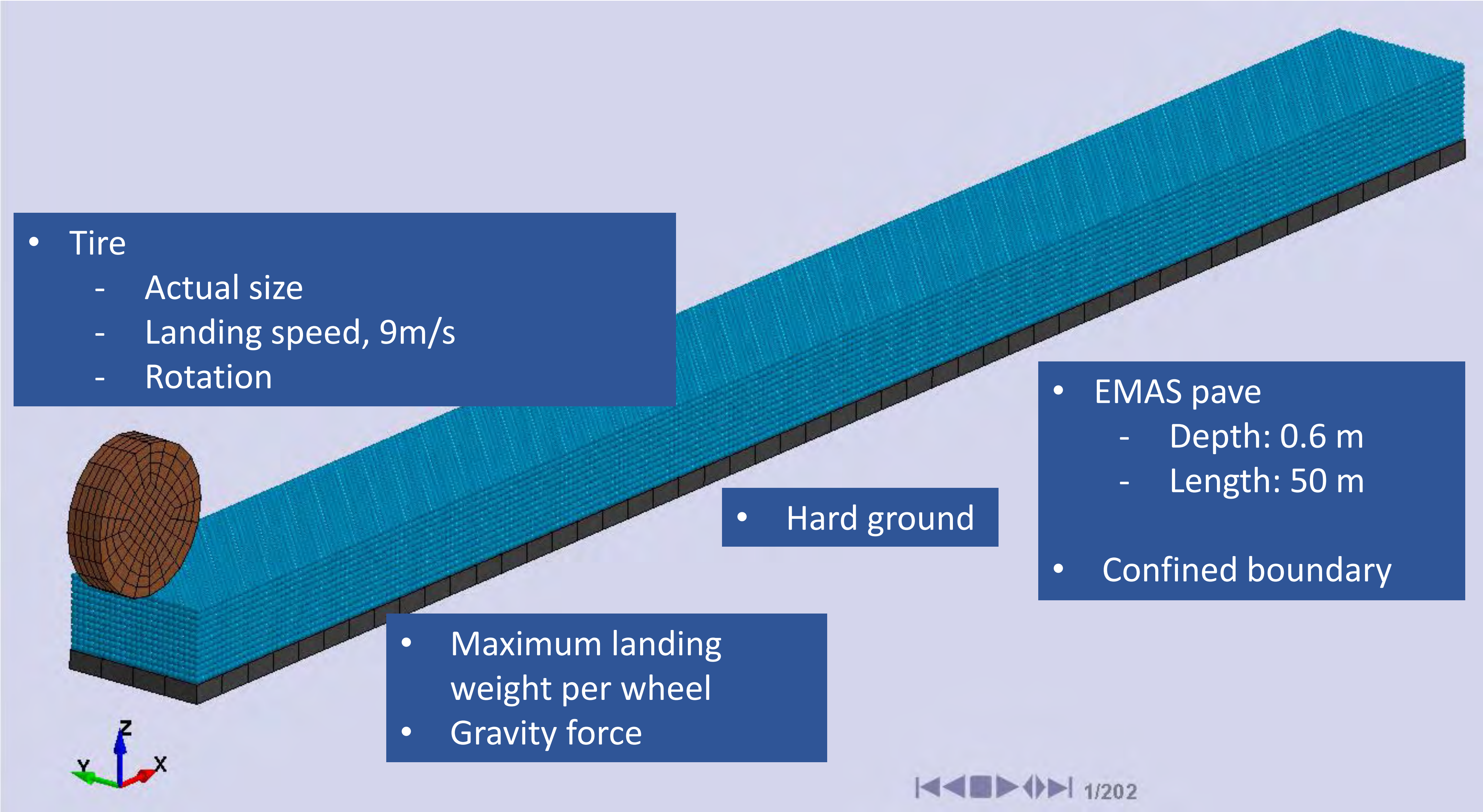

120 mm

Case 1: projectile impact (200 m/s)



Velocity of the projectile (left) and velocity of the material (right)

Case 2: B-737 landing gear crushing



- Tire
  - Actual size
  - Landing speed, 9m/s
  - Rotation

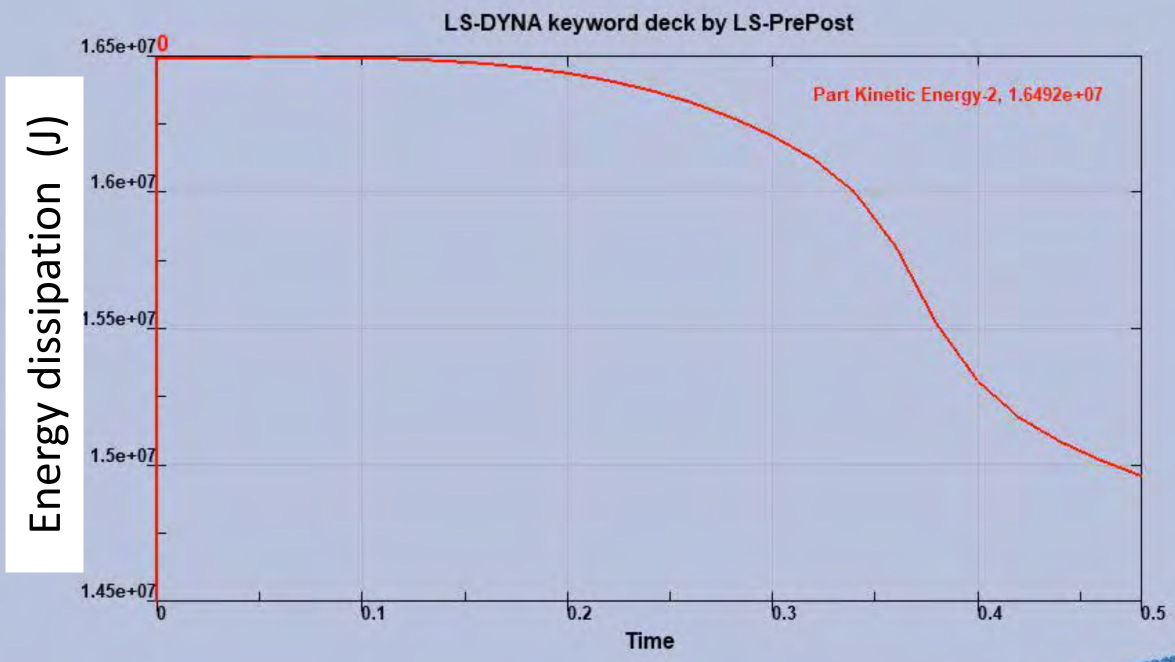
- EMAS pave
  - Depth: 0.6 m
  - Length: 50 m
- Confined boundary

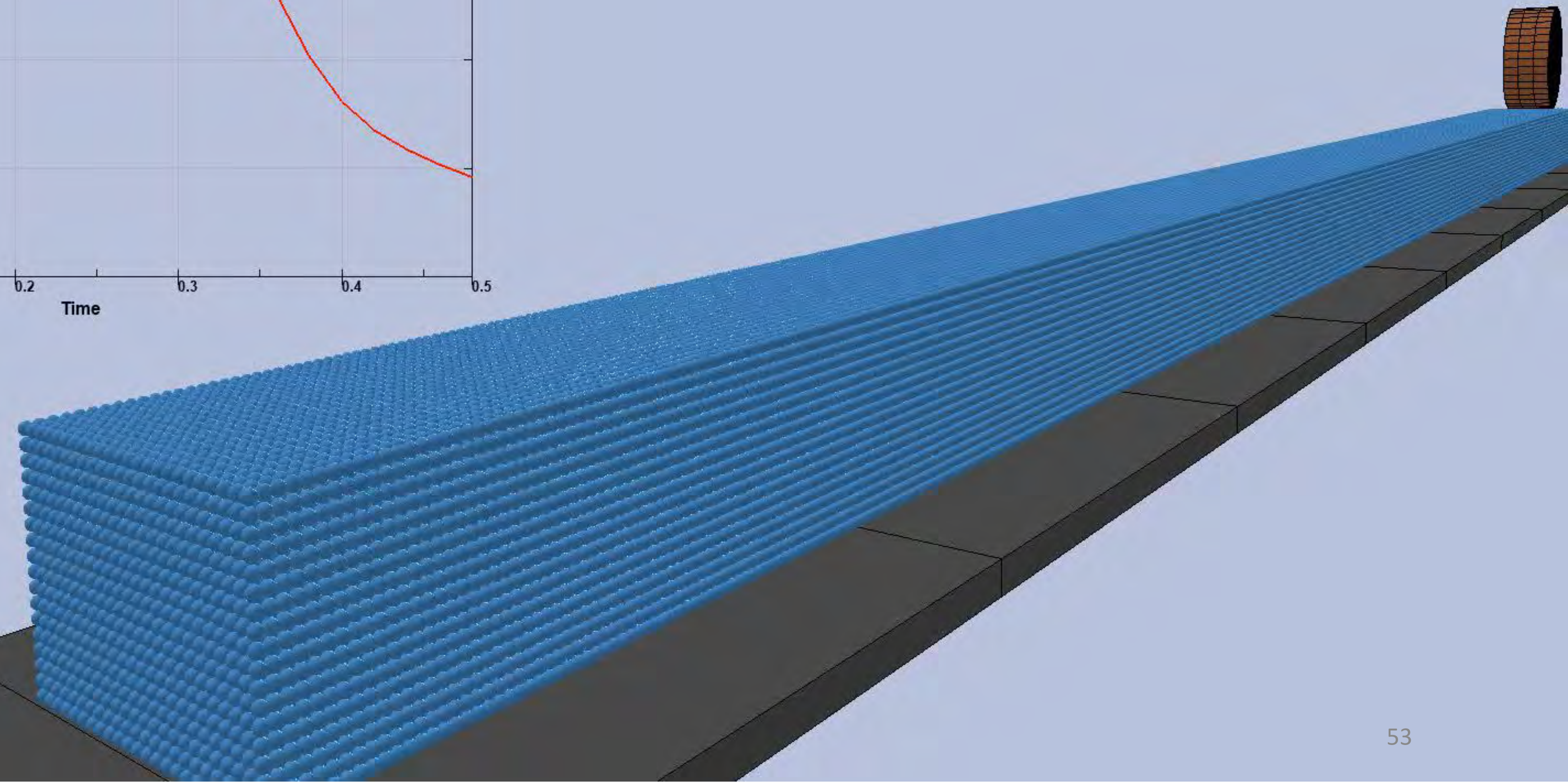
- Hard ground

- Maximum landing weight per wheel
- Gravity force

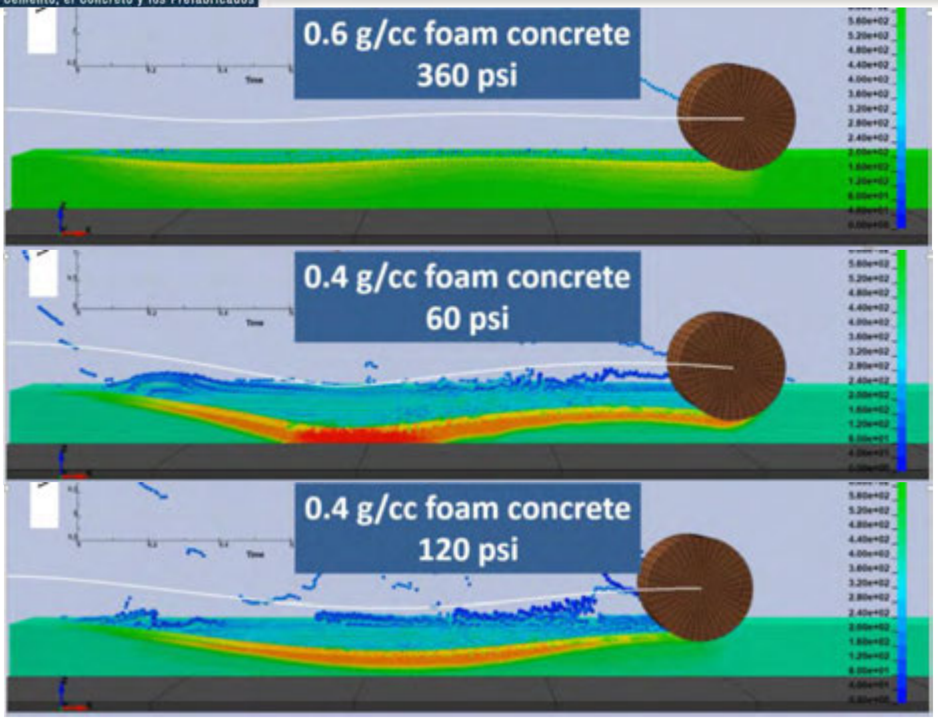
- 3D view

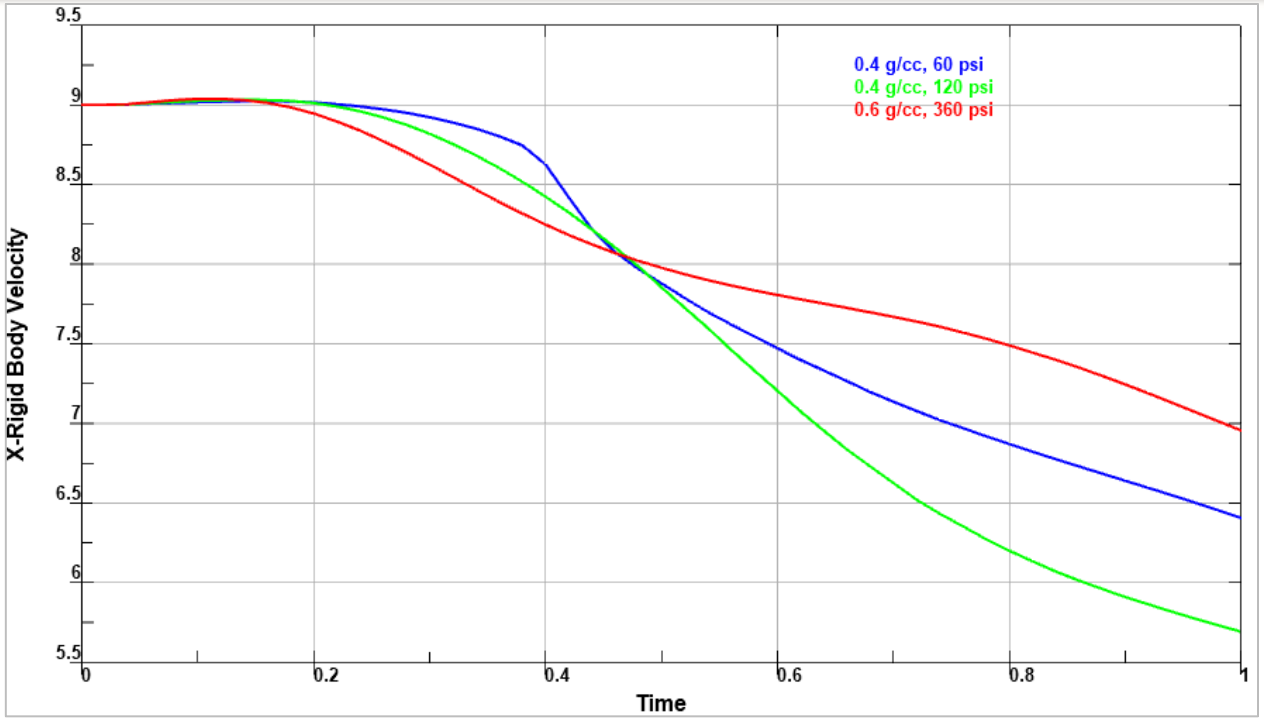
0.4 g/cc foam concrete, 30 psi





Result comparison





Comparison of speed reduction with different foam concrete designs

- Various output parameters
  - Speed reduction, energy dissipation, crushing density, …

Important insights for real applications!

- Influencing factors observed from simulation
  - Material density, strength, wheel rebound…

3D printing – research needs

- Materials research: Rheology, flow, placement, set, green strength
- Options for reinforcing steel
  - Co-extrusion of reinforcing bars and meshes – high modulus polymers
  - Use of fiber reinforcement in concrete
- Shrinkage cracking control
  - Most research is on pastes and mortars – shrinkage is too high
- Architectural expression
  - How to best use construction that can be “non-linear”

3D printing – Market potential

- What does 3D printing do well?
  - Curved shapes
  - Customized shapes
  - Continuous construction – e.g. wind turbine towers
- What technology competes?
  - Shotcrete can produce organic shapes
  - Tilt-up or pre-fabricated construction can be very rapid
  - Etc. Etc.... 3D printing is not a perfect solution for construction!

Summary

- 3D-printed concrete has great potential
- Control of rheology is a key, and vibration can be used to control flow
- Computer modeling is powerful for material design
- The future of 3D printing requires more research
- 3D printing will succeed in specific market niches

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