Control of Entrained Air and Vibration of Concrete for Production of Crossties

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2016 International Crosstie & Fastening System Symposium
16 June 2016

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Background

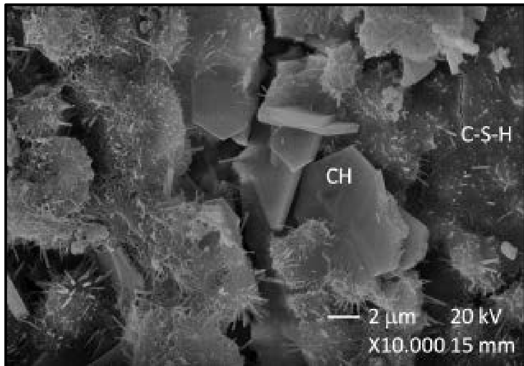
- A partnership with Kyle Riding at Kansas State University under funding from FRA
- Dan Casteneda, Jeremy Koch, Prof. Randy Ewoldt, Yu Song, Ruofei Zuo

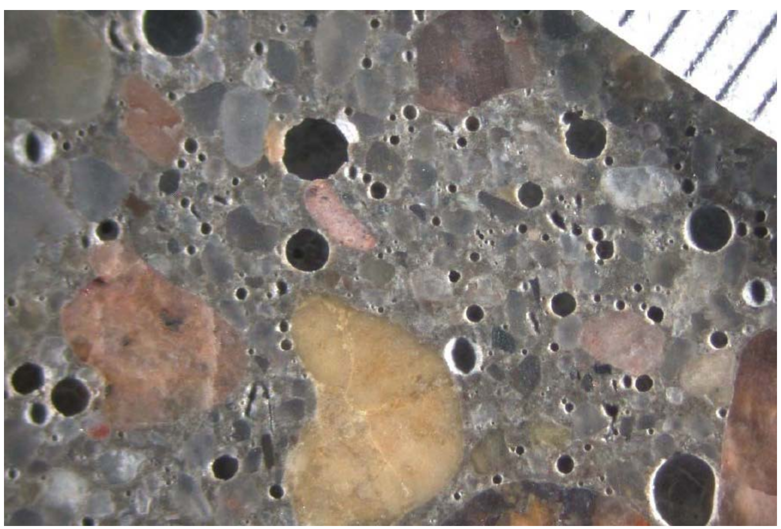
- Project addresses freeze-thaw durability of concrete crossties
- Includes study of vibration and handling of concrete, and impact on entrained air void system

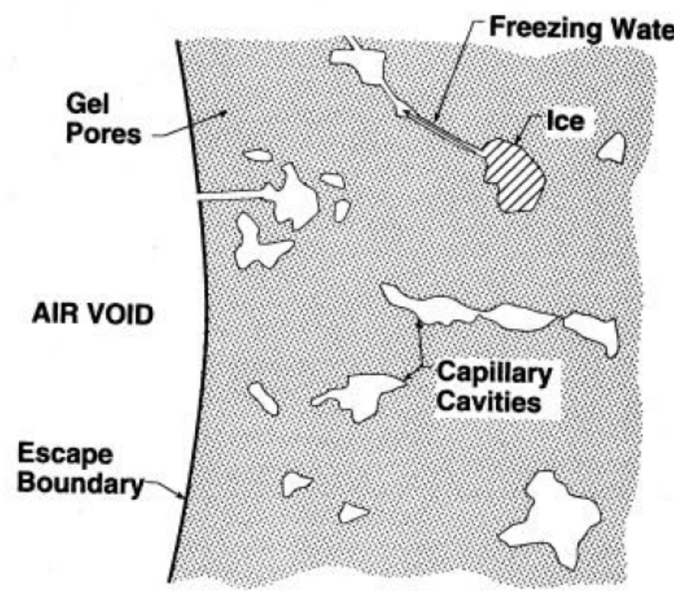
Questions

- How do we ensure sufficient air entrainment to achieve F-T durability?
- How do entrained air bubbles respond to vibration?
- What are actual conditions of crossties in track?

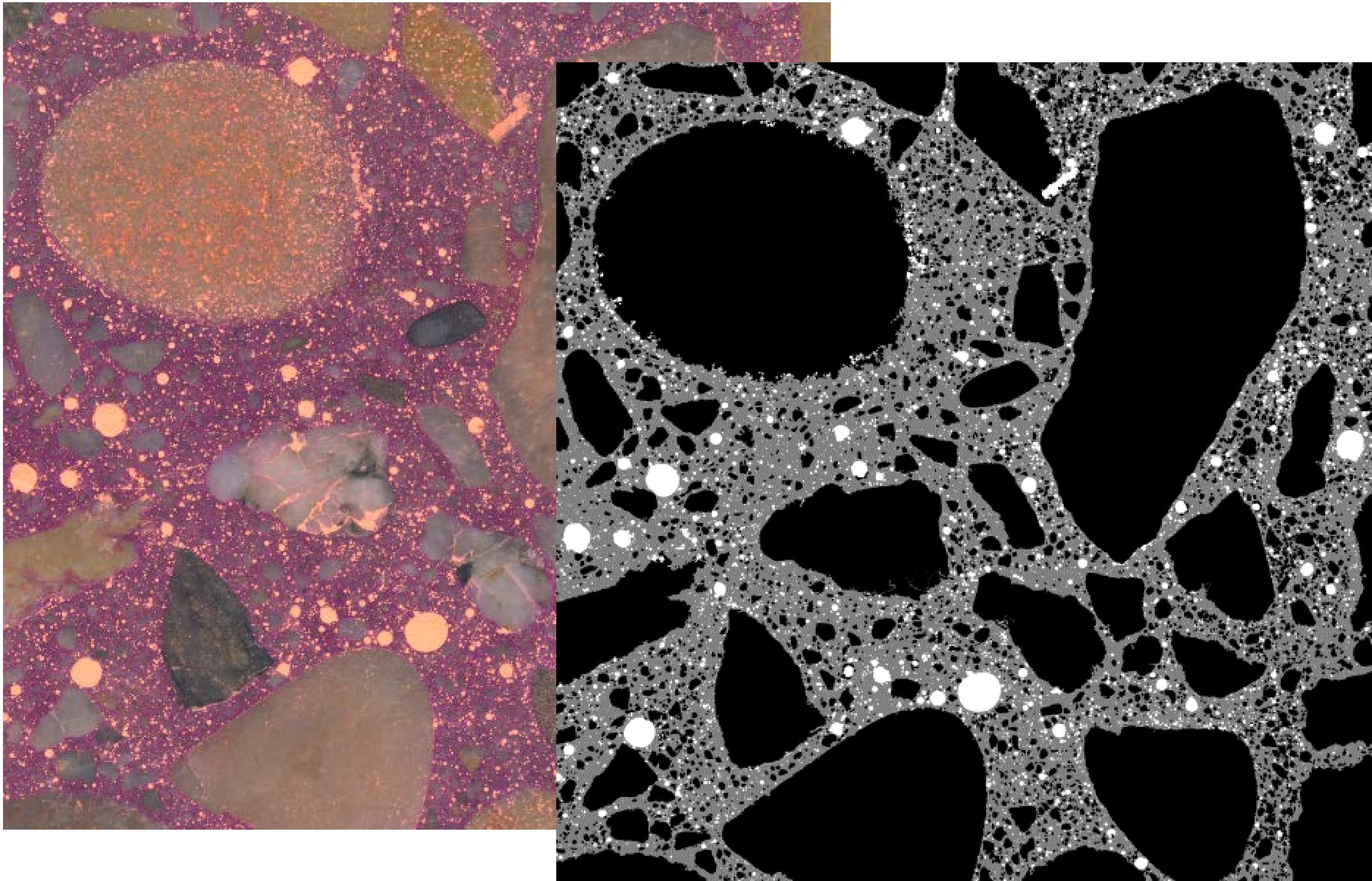
Freeze-Thaw Damage and Air Entraining Admixtures







Entrained air in concrete

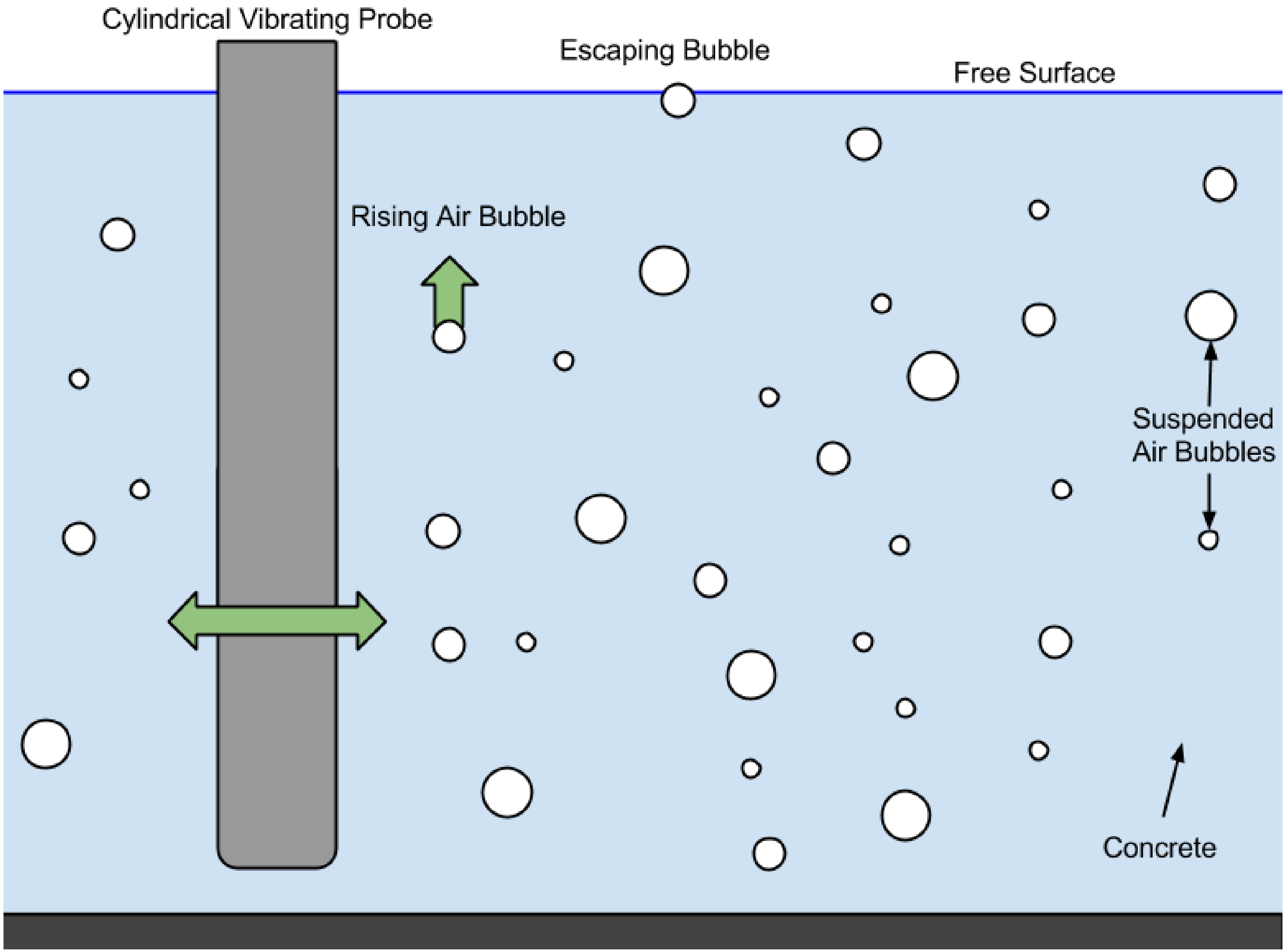


VIBRATION --

handling, placement, compaction

Q: How does vibration effect entrained air bubbles? Is vibration reducing the freeze/thaw resistance of concrete?

Vibration of Fresh Concrete



Rise of Spherical Particles

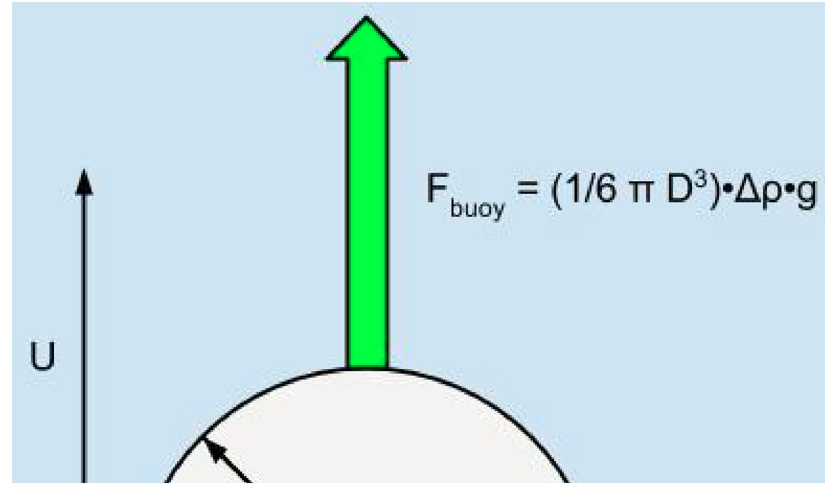
- All bubbles are stable when concrete has yield stress is at rest
- Bubbles rise under buoyant forces in a viscous fluid with no yield stress
- Vibration defeats yield stress

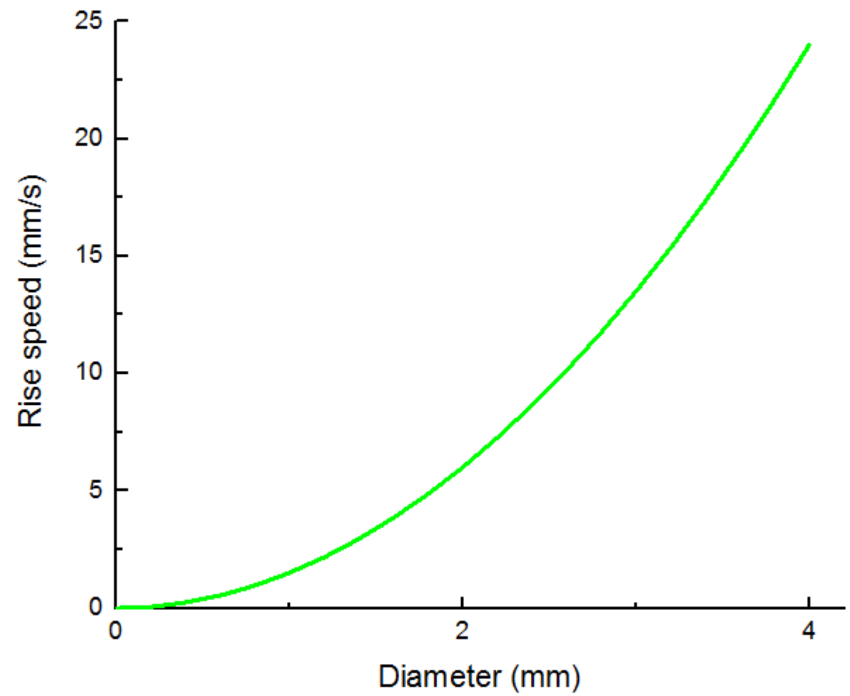
- Terminal velocity of a hard sphere:

Buoyant Force vs. Stokes' Drag Force

$$\frac{1}{6}\pi\Delta\rho g D^3 \quad = \quad 3\pi\mu U D$$

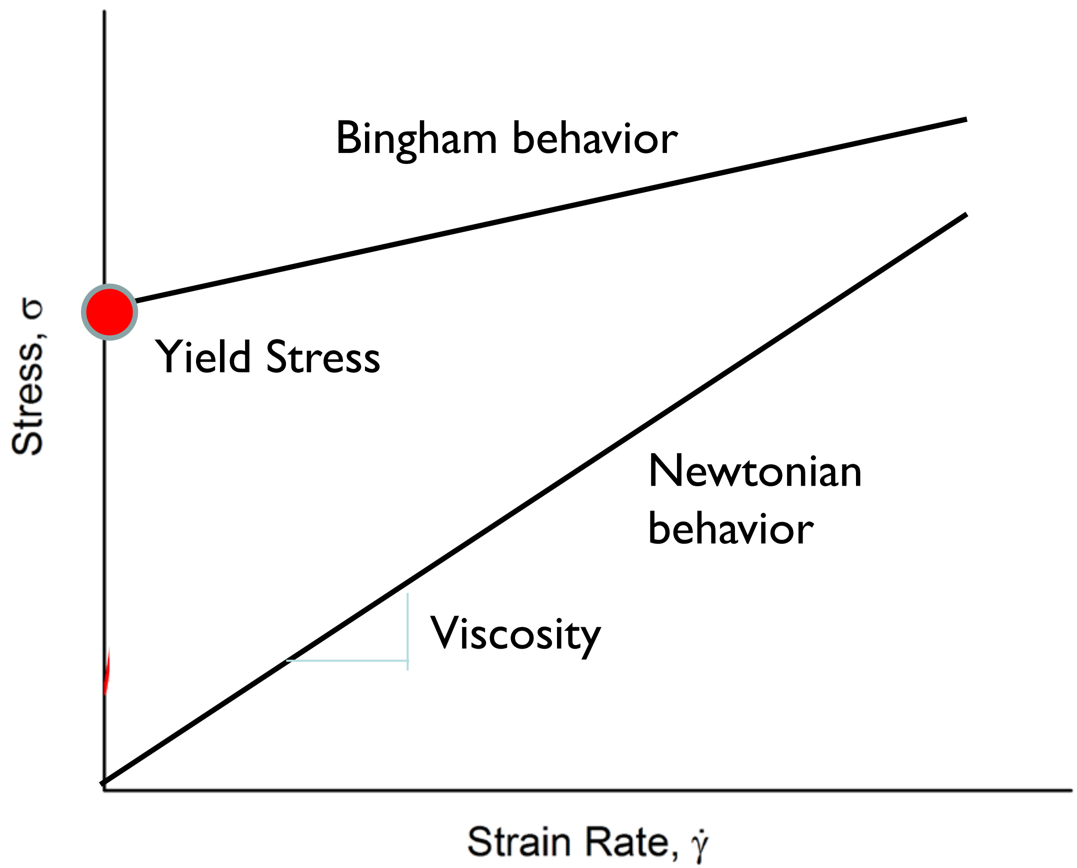
$$U = \frac{1}{12}\frac{\Delta\rho g D^2}{\mu}$$





Rheology basics

- Concrete exhibits a yield stress at rest
- Vibration defeats yield stress

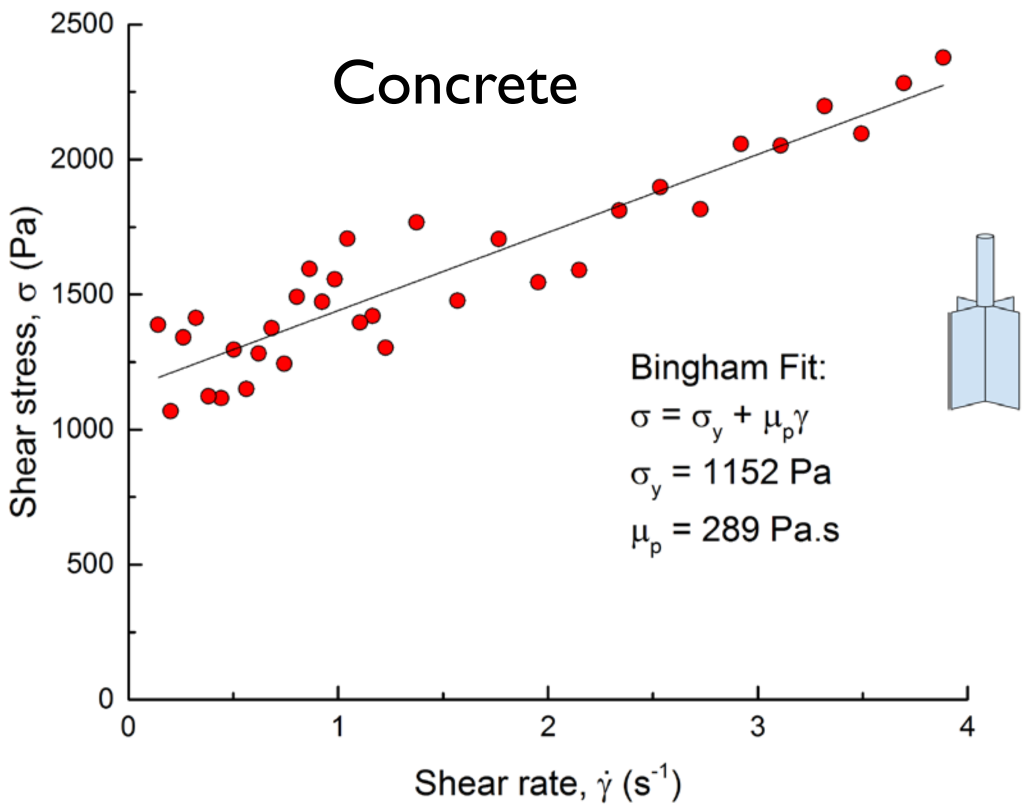


Experimental Setups: Two Rheological tests

- Two rheometer – small scale and large scale for concrete
- Considered rheology for materials UNDER VIBRATION

Rheology of concrete -- at rest

Concrete/mortar/cement are yield-stress fluids



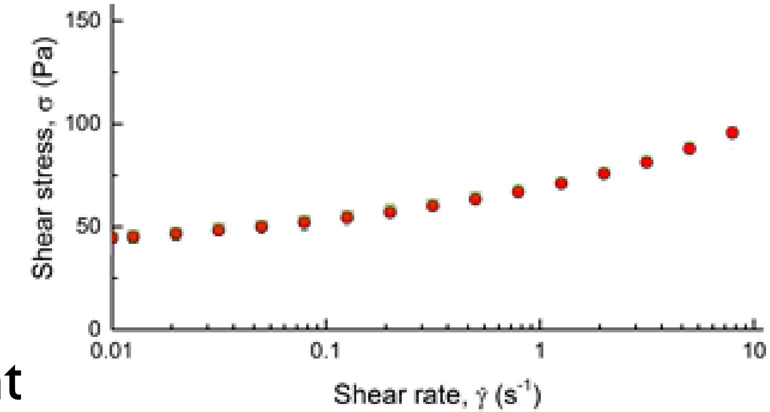
Yield-stress fluids are capable of arresting sufficiently small particles (such as bubbles). Roughly when $D < \frac{21\sigma_y}{g\Delta\rho}$

Beris, A. N., et al. "Creeping motion of a sphere through a Bingham plastic." *Journal of Fluid Mechanics* 158 (1985): 219-244.

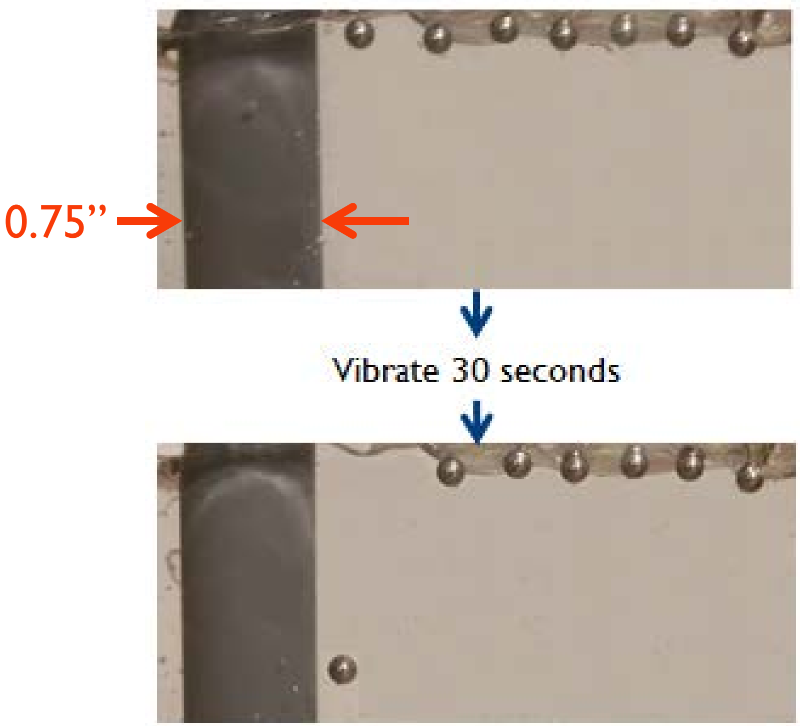
Bingham Fluids and Vibration Propagation

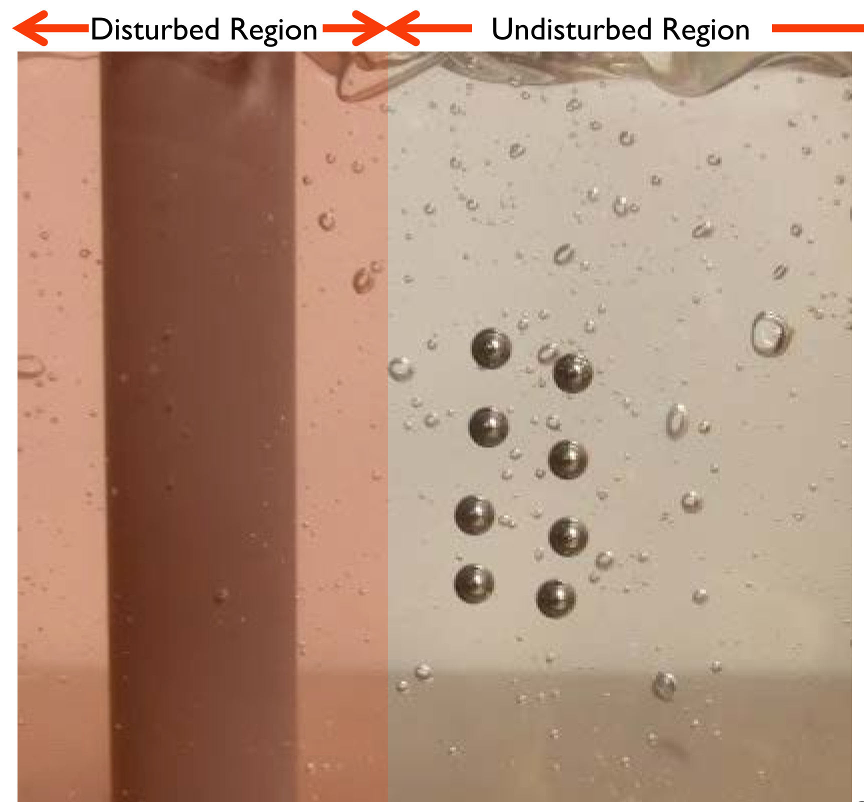
Water + Carbopol (0.30wt%) is a simple yield-stress fluid

(Bonus: transparent!)



But in a lab-scale vibration environment vibration doesn’t propagate into fluid





Early Finding

- Simple yield-stress fluids (like carbopol) do not behave like fresh concrete during vibration.
- What explains how vibration propagates?

Granular Hypothesis

Experiment: measure the air content vs. vibration time

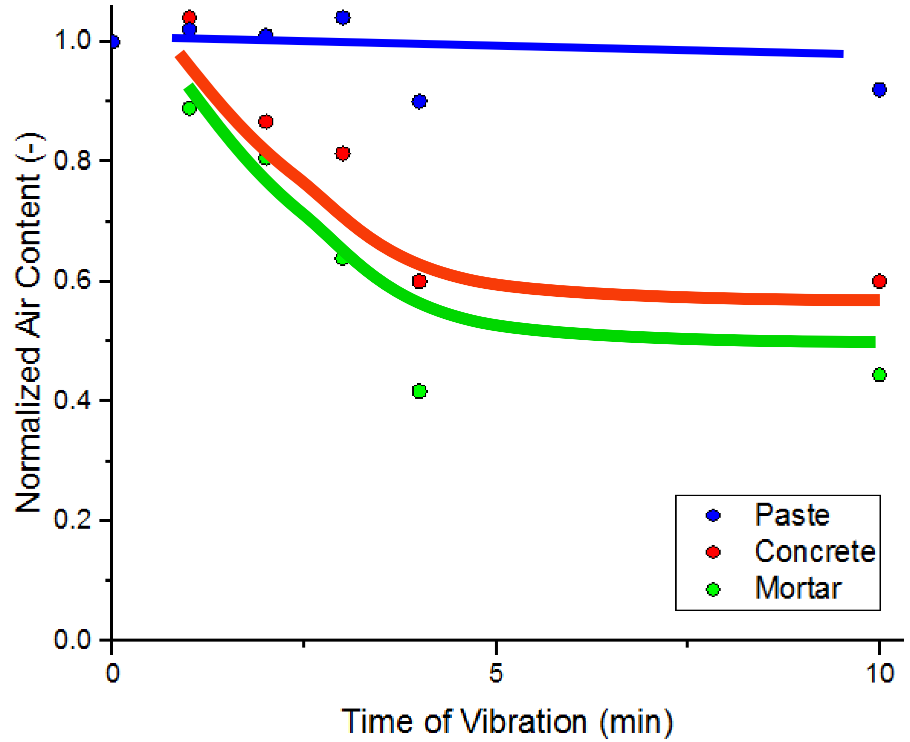
After 10 minutes of vibration, air content drops by:

40% for concrete

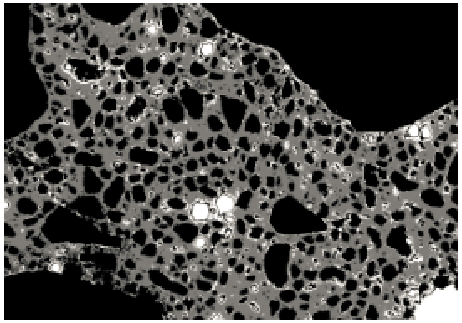
55% for mortar

8% for cement paste

Why is air more readily removed in concrete and mortar?



Key point:
Concrete and mortar are granular



Experiment Strategy

Use surrogate materials…

(simple yield stress) 0.30wt% carbopol in water
(granular) 1 mm glass beads in 100 cSt silicone oil

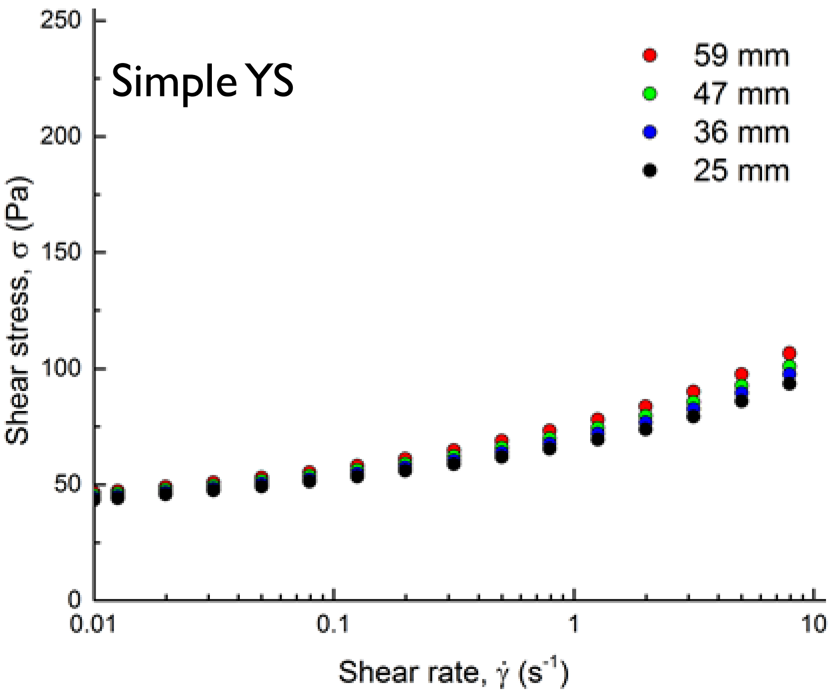
…to demonstrate the rheological responses of simple materials in two environments…

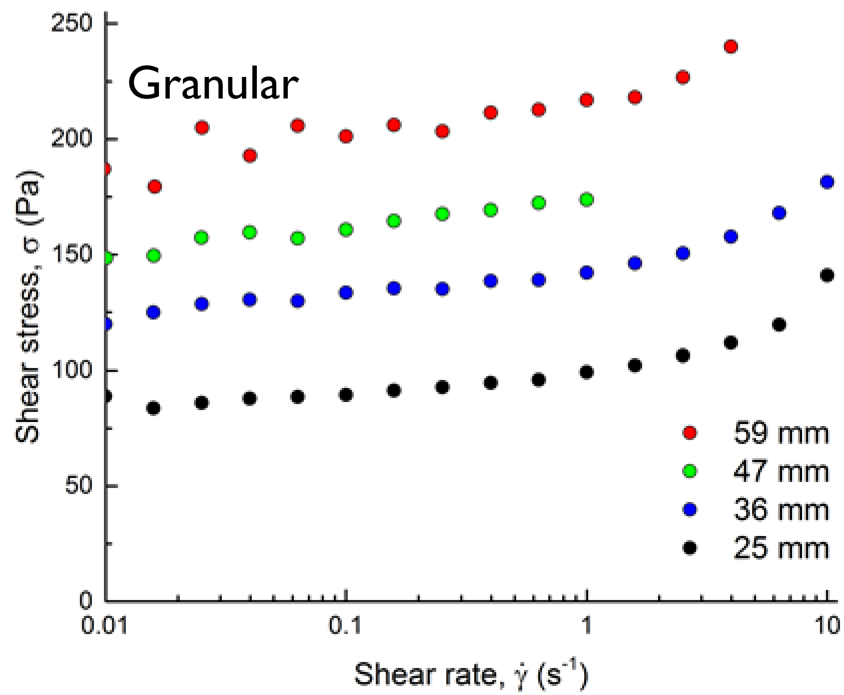
varied depth

applied vibration

…and compare these signatures to concrete and mortar

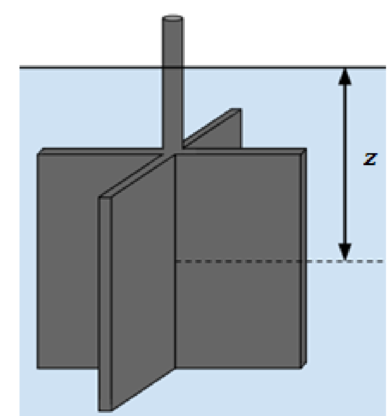
Surrogate Material Rheology – Depth Dependence



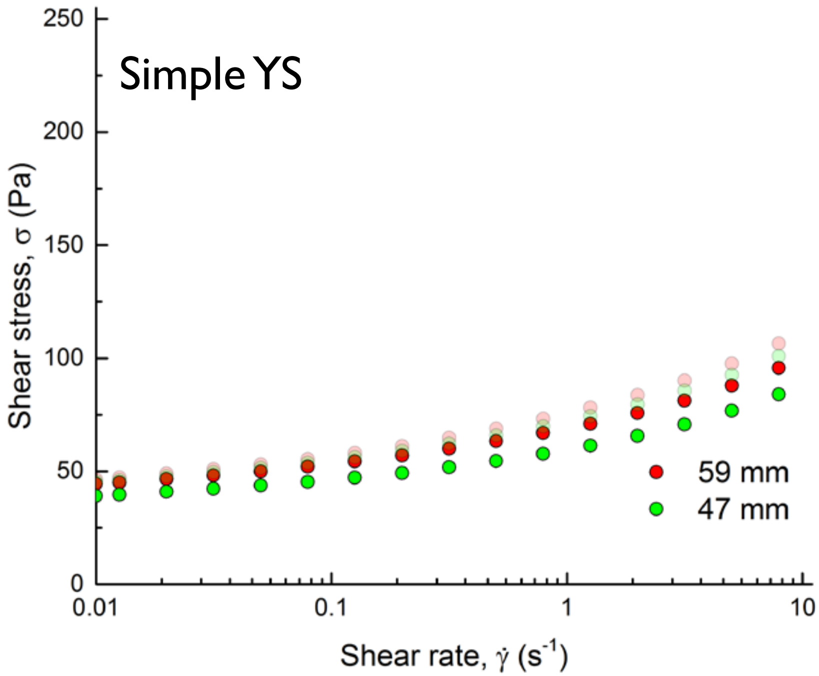


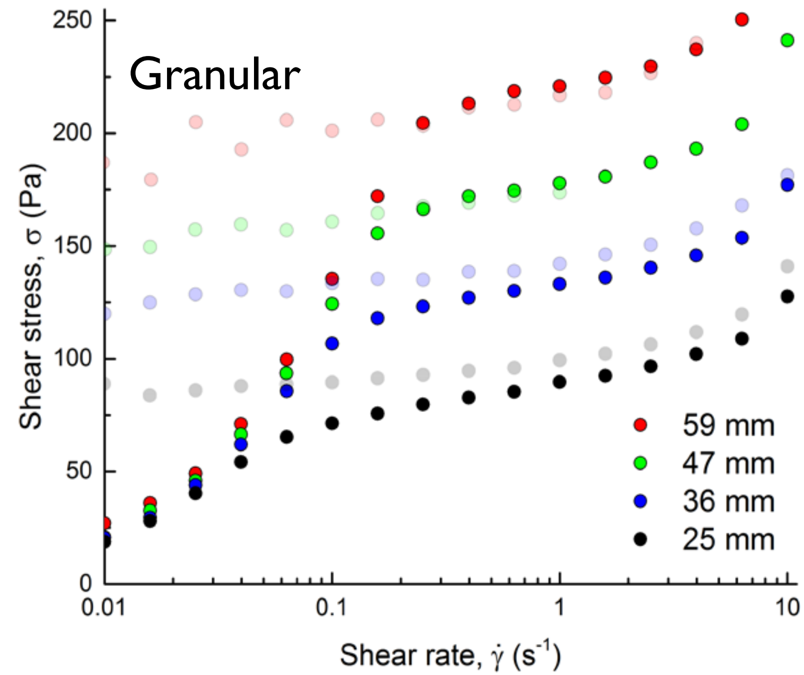
Rheology vs. Depth:

- Simple YS fluids: Stress does *not* change with depth
- Granular fluids: Stress *increases* with depth



Surrogate Material Rheology – Effect of Vibration





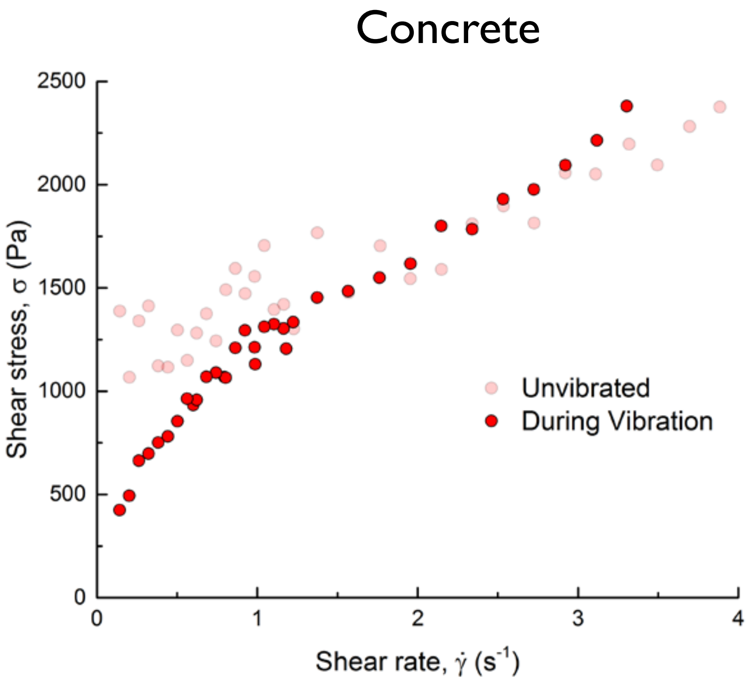
Rheology during Vibration (with Depth Variation):

- Simple YS fluids: Vibration has *no* effect
- Granular fluids: Vibration *eliminated* yield stress and depth-dependent effect, high strain rate behavior is relatively unchanged

Tests on concrete showed this same behavior

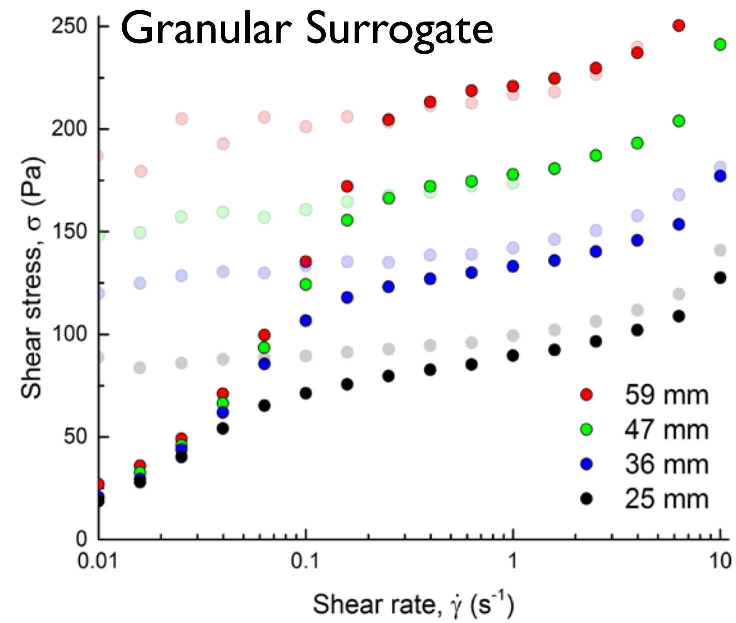
During Vibration

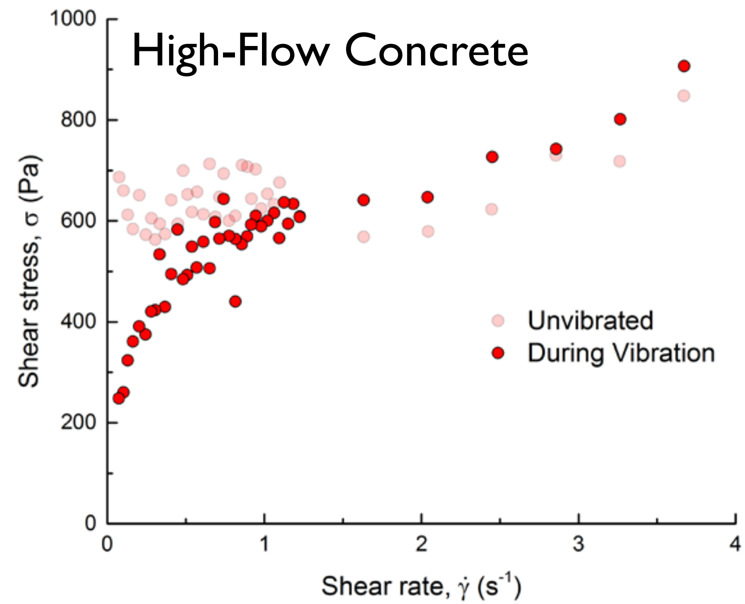
- Yield stress is dramatically reduced/eliminated
- High strain rate behavior is unchanged
- Granular signature!



Experiment Conclusions:

- Granular nature of concrete is key
- Vibration causes a reduction/elimination of yield stress in granular materials, which will allow air voids to rise
- Rheology is depth dependent in undisturbed granular materials, but depth dependence disappears (at low shear rates) during vibration



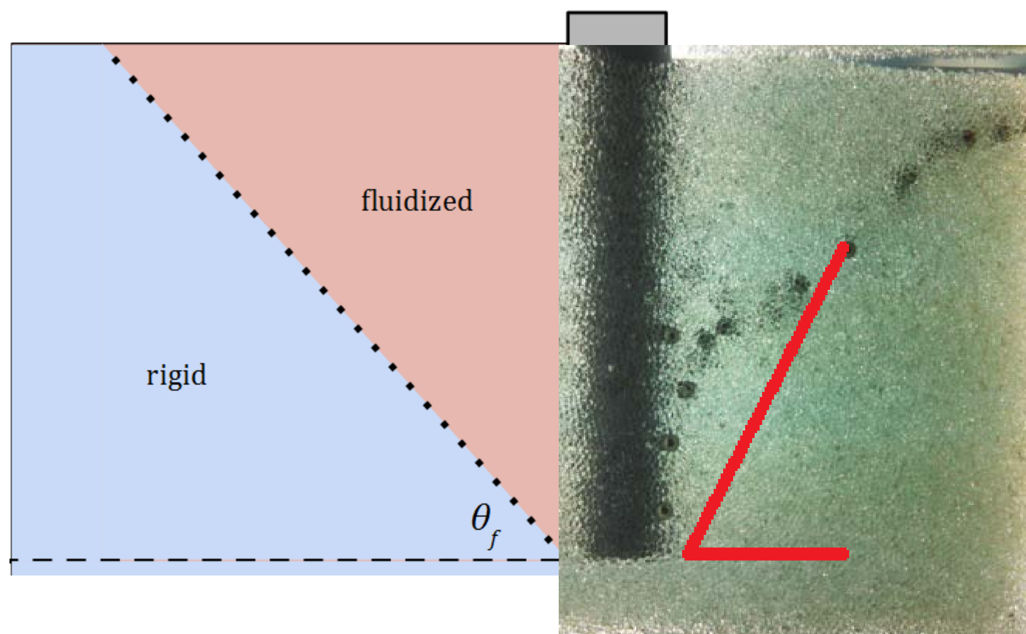


A practical implication: “Cone of Action”

- Previous results obtained in a uniform, vertically vibrating environment.
- Another option: probe vibration.
- Granular failure angle: $\theta_f = \frac{\pi}{4} + \frac{\alpha}{2}$ α = angle of repose

- Predicted “Cone of Action” goes against conventional wisdom of a “Radius of Action” (cylinder)

- Consequence:
effect of probe vibration is not uniform, current practices lead to inhomogeneous air distribution/compaction

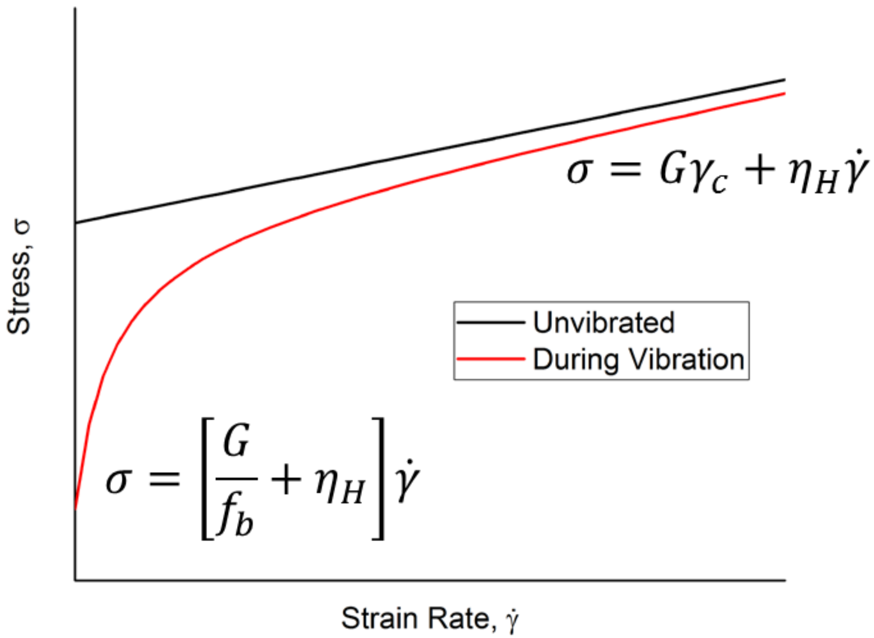


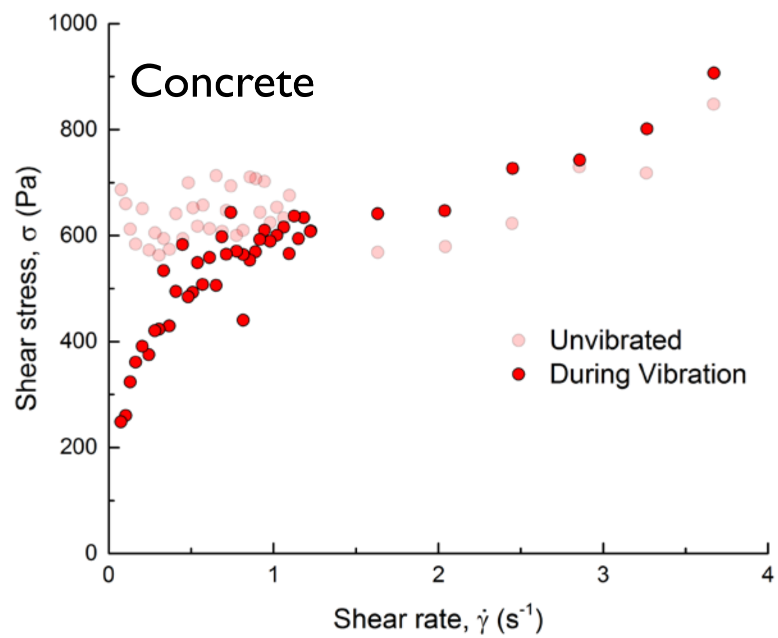
Application: Bubble Rise Model Development 1/2

- Vibrated granular constitutive model:

$$\dot{\sigma}(t)+\left[\frac{\dot{\gamma}(t)}{\gamma_c}+f_b\right]\sigma(t)=[G+\eta_H f_b]\dot{\gamma}(t)+\eta_H\frac{[\dot{\gamma}(t)]^2}{\gamma_c}+\eta_H\ddot{\gamma}(t)$$

- Predictions: compare favorably to Experiment:

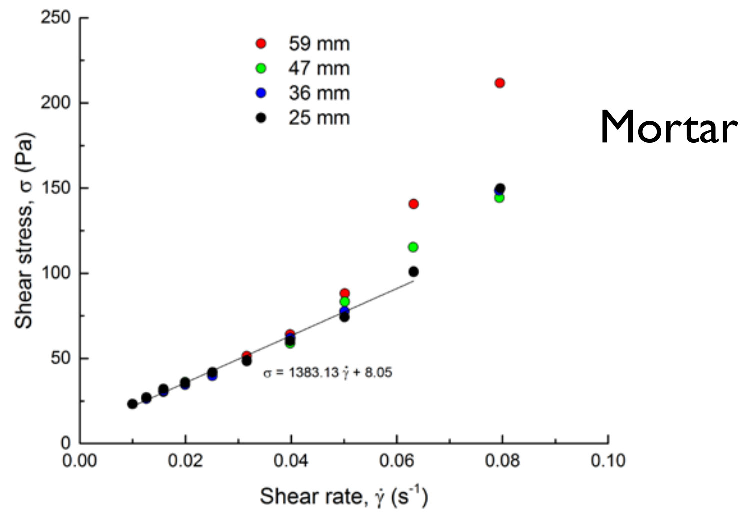




Hanotin, C., et al. "Viscoelasticity of vibrated granular suspensions." *Journal of Rheology,* 59.1 (2015): 253-273.

Application: Bubble Rise Model Development 2/2

- Model predicts Newtonian behavior at low strain rates: $\sigma = \left[\frac{G}{f_b} + \eta_H\right]\dot{\gamma}$

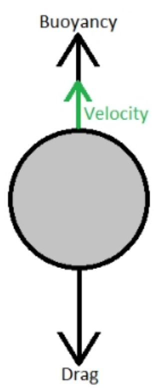


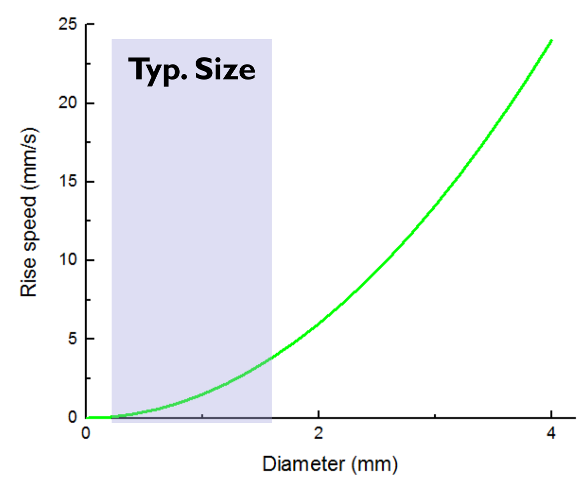
- Depth-dependent rheology not a factor during vibration
- Bubbles are spherical:

$$Ca = \frac{\mu\dot{\gamma}}{2\Gamma/D} = \frac{\sigma}{2\Gamma/D} \approx 0.04 \ll 1$$

- Rise Speed Equation:

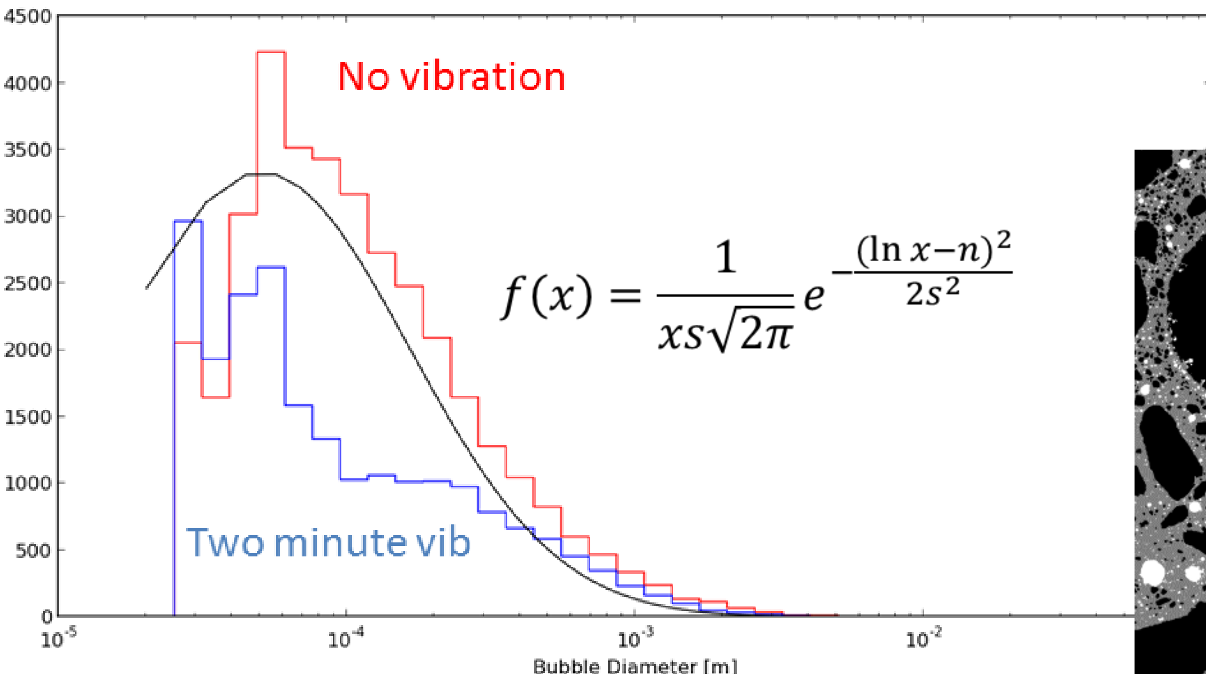
$$U = \frac{1}{12}\frac{\Delta\rho g D^2}{B\mu_{conc}}$$



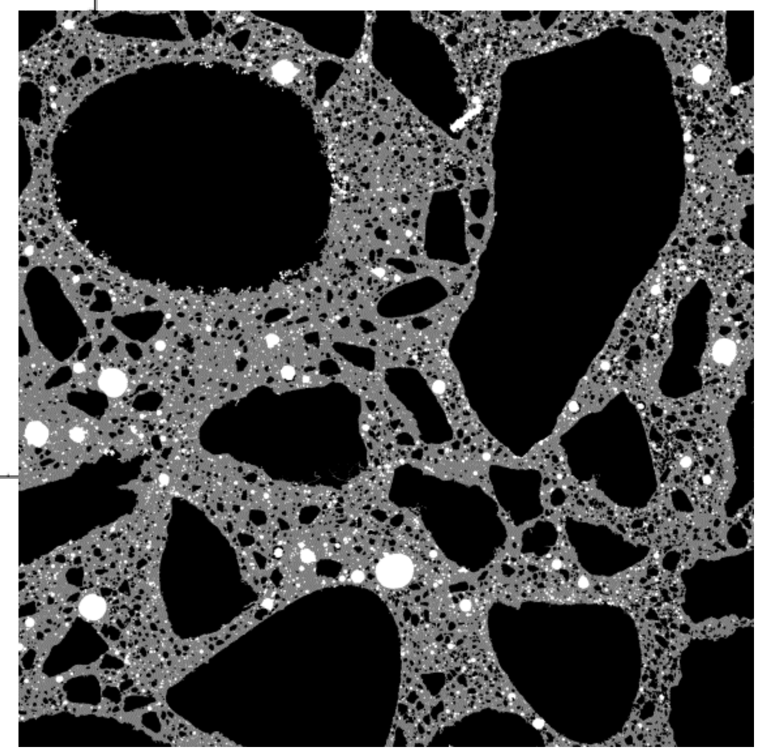


Bubble Rise Model: Initial Air Distribution

- From polished samples:



$$f(x) = \frac{1}{xs\sqrt{2\pi}} e^{-\frac{(\ln x - n)^2}{2s^2}}$$

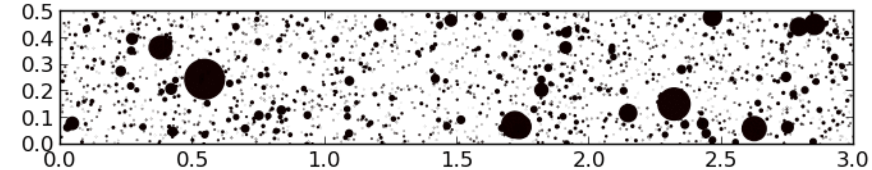


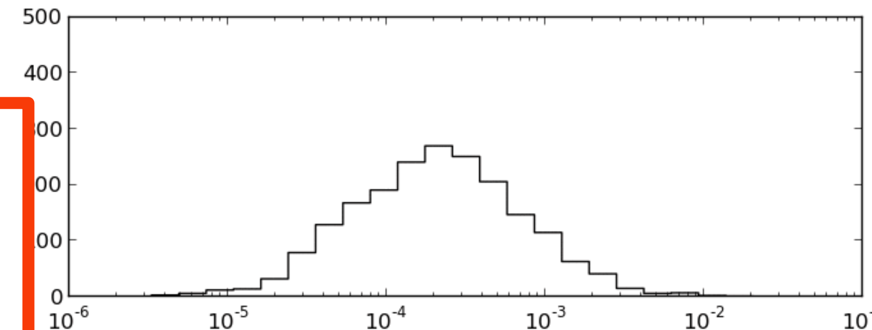
Bubble Rise Model: Predictions from Simulations

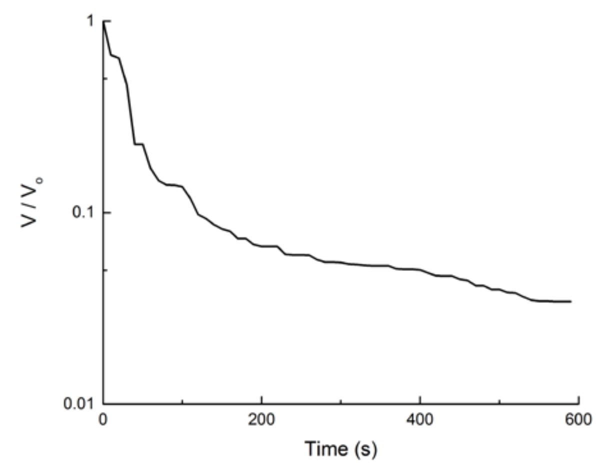
Starting with experimentally-determined initial distribution, yield stress, and plastic viscosity, simulations demonstrate…

- Rapid removal of large air voids within first minute
- Vibration does not eliminate small air bubble population
- Vibrating concrete does not necessarily interfere with freeze/thaw resistance
- Problems with EA lead us to focus on mixing and initial bubble size distribution

Diameter x10







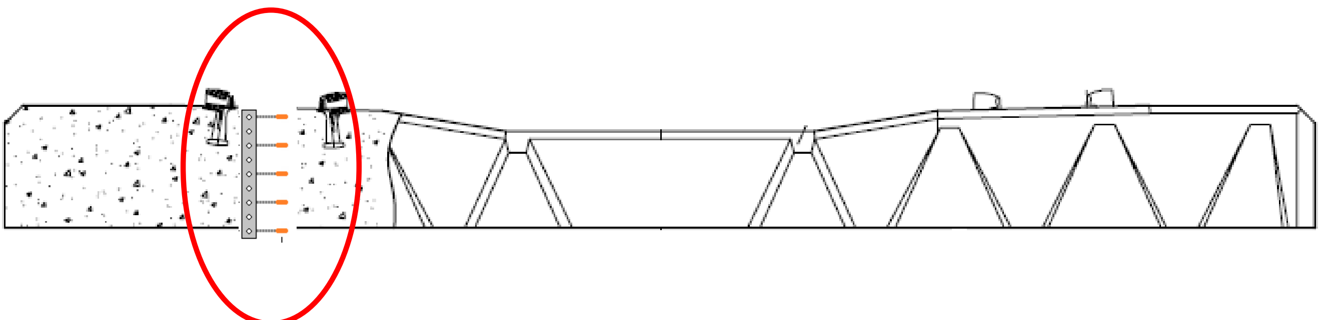
WHAT ARE FIELD CONDITIONS OF CONCRETE CROSSTIES?

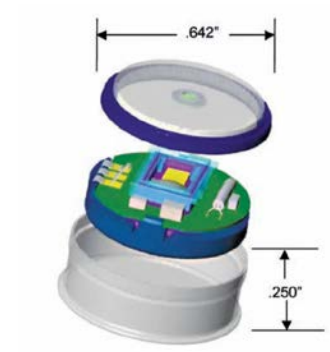
Field testing

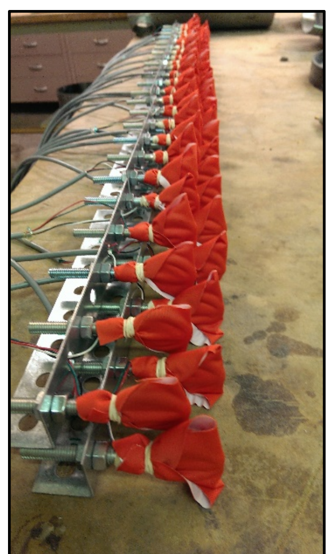
- ***Locations:***
  - ***Lytton, British Columbia***
  - ***Rantoul, IL***
- ***Parameters***
  - ***Temperature***
  - ***Internal relative humidity***

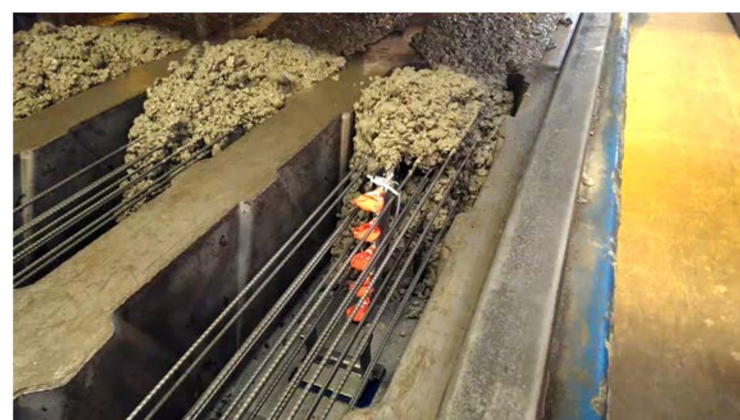
Instrumentation

- Install **humidity & temperature** sensors inside crosstie at rail seat area during manufacturing

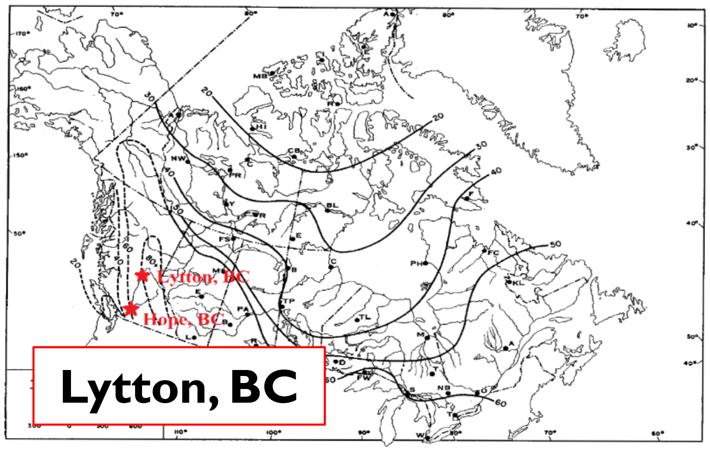








Installing instrumented crossties



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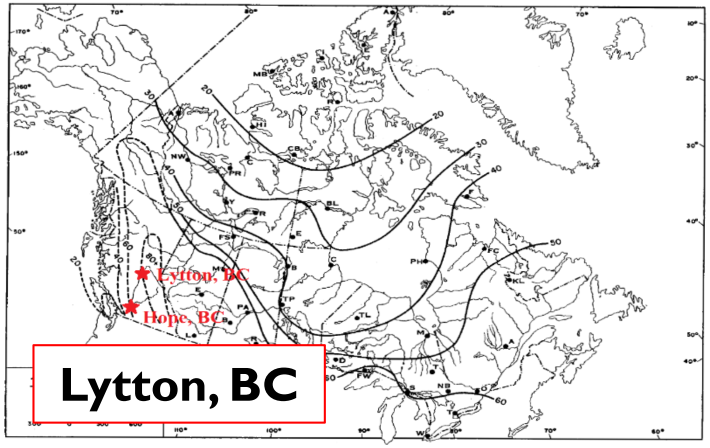
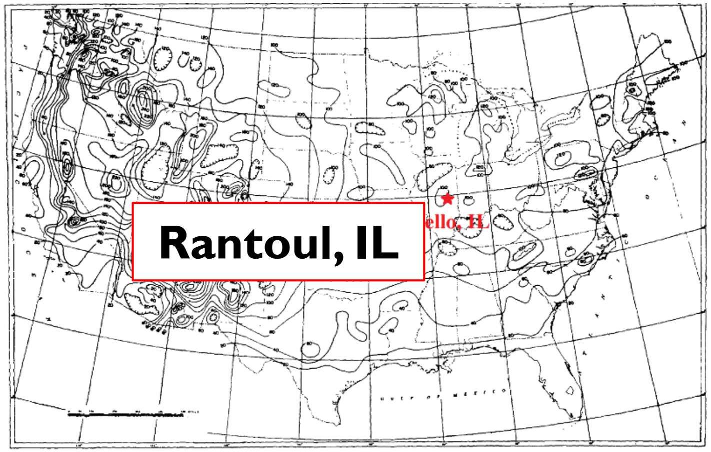
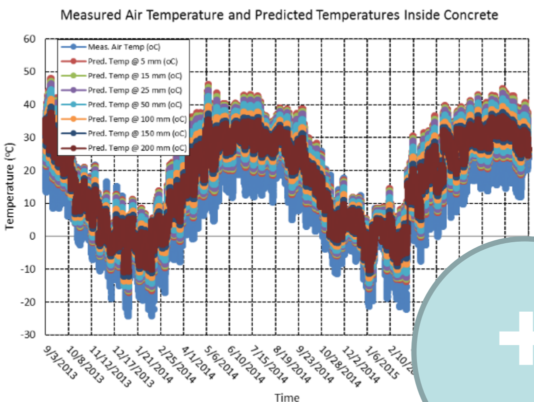
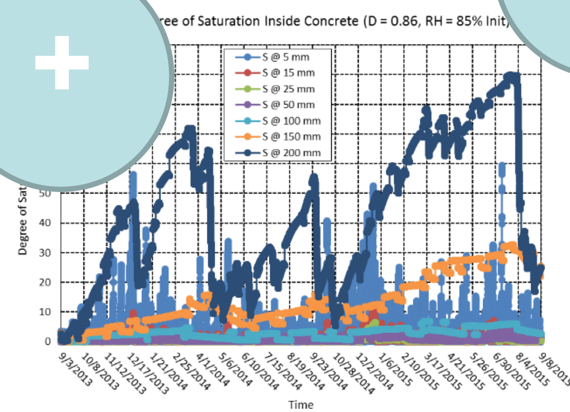




Model to predict temp/RH history on basis of local weather station data





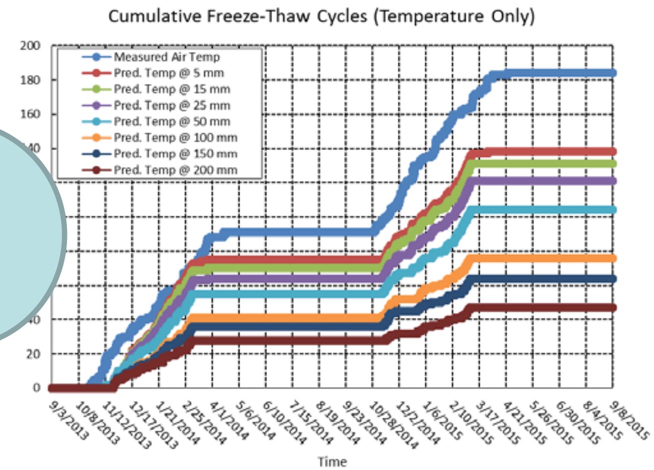


Fig. 2. Mean annual frequency (days) of freeze-thaw cycles.

- Key findings:
  - Concrete is persistently high moisture in winter
  - Concrete temps DO experience significant cycling
  - Concrete FT cycles ~ 0.7X ambient weather
  - Crossties received 70 FT cycles/yr

Conclusions

- Key to understanding propagation of vibration
  - Concrete and mortar are **granular** materials.
- Implications of granularity
  - Yield stress of concrete is eliminated during vibration
  - Static yield stress of concrete is depth dependent
  - "Cone of action"
- Smallest air bubbles are stable even under vibration
  - The smallest bubbles do persist, so if a concrete exhibits FT durability problems, investigate your mixing and AEA effectiveness.

Conclusions

- Concrete in the field
  - Harsh climates in North America get 100+ FT cycles per year
    - Concrete FT cycles ~ 0.7X ambient weather
    - Crossties receive 70 FT cycles/yr
  - Surface is most vulnerable
    - Concrete outer surface can be assumed to be saturated in winter conditions.
    - Freeze-thaw damage is primarily at surface until cracking opens material for greater water access

Acknowledgements

- Project funding from Federal Railroad Administration
- Ties with embedded sensors manufactured by CXT
- Assistance with field data collection by University of British Columbia