“Freeze-Thaw Durability of Concrete Crossties”

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Date: Friday, March 04, 2016
Time: Seminar Begins 12:20 pm
Location: Newmark Lab, Yeh Center, Room 2311
University of Illinois at Urbana-Champaign

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University of Illinois at Urbana-Champaign
Freeze-Thaw Durability of Concrete Crossties

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William W. Hay Railroad Engineering Seminar
March 4, 2016
FRA BAA Project
Prof. Kyle Riding, Kansas State
Prof. David Lange, UIUC
and Prof. Randy Ewoldt, UIUC
2012-2015

Final Project Presentation was on Jan 28, 2016
Freeze-thaw durability

- Damage requires near-saturated conditions
  - Can a crosstie be critically saturated in well draining ballast?
- Damage requires many freeze-thaw cycles
  - Midwest climate is more severe than the arctic!
What about air entrainment?

- Air entraining admixtures
Goals: Improve understanding of…

- How air bubbles respond to vibration.
- Actual conditions of crossties in track.
- How to produce ties with better freeze-thaw resistance.
- New testing methods to assess freeze-thaw performance.
Report contents

- Chapter 1: Introduction
- Chapter 2: Bubble Mechanics Theory
- Chapter 3: Bubble Mechanics Validation
- Chapter 4: Role of Aggregates During Vibration
- Chapter 5: Vibration-Rheology-Material Interplay
- Chapter 6: Concrete Railroad Tie Fabrication
- Chapter 7: Tie Field Temperature & Humidity
- Chapter 8: Degree of Saturation Determination
- Chapter 9: Freeze-Thaw Potential in Track
- Chapter 10: Freeze-Thaw Sample Preparation
Rheology of Concrete

• Concrete exhibits a yield stress at rest
• Vibration defeats yield stress
Rheology of Concrete

- **Concrete**
  - Stress (Pa)
  - Shear rate (1/s)

- Equation: $y = 4475 + 1356 \times x$
  - Yield Stress: 4475 Pa
  - Plastic Visc: 1356 Pa.s
Theory for bubble rise

- 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:

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

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

So, very small bubbles are relatively stable
Vibration with air entrainment

• Vibrate fresh materials and measure fresh air content
• Air loss is prominent when aggregates are present
Rheology during vibration

- Simple yield stress fluids (Bingham) with aggregates
- Shows influence of vibration

Dim symbols: No vibration
Solid symbols: Sample is vibrated
Granular Physics

- Roscoe’s Equation predicts the viscosity increase when particles are added to a fluid. From paste to concrete:

\[
\mu_{\text{mortar}} = \mu_{\text{paste}} \left(1 - \frac{1}{r} V_{\text{sand}}\right)^{0.89m-9.31} \quad \mu_{\text{conc}} = \mu_{\text{mortar}} \left(1 - \frac{1}{r} V_{\text{coarse}}\right)^{0.57m-3.40}
\]

- Vibrated granular constitutive model predictions:

  \[
  \sigma = G\gamma_c + \eta_H \dot{\gamma}
  \]

  Bingham

  \[
  \sigma = \left[\frac{G}{f_b} + \eta_H\right] \dot{\gamma}
  \]

  Newtonian!

Practical Implication: “Cone of Action”

- A consequence of depth-dependent rheology: failure angle
- Theoretical prediction:
  \[ \theta_f = \frac{\pi}{4} + \frac{\alpha}{2} \]
  \( \alpha = \) angle of repose
- Consequence: effect of vibration is not uniform, leading to inhomogeneous air distribution
Air Content under Vibration

- Vibrated concrete is quasi-Newtonian
- Model explains experimental observations
- We can predict air bubble size distribution:

![Graph showing air bubble size distribution with and without vibration](image-url)
Bubble Rise simulations

• Large bubbles rise and leave quickly
• Small bubbles endure due to $D^2$ law

• Model explains how VISCOSITY under VIBRATION controls AIR LOSS
• DURATION of vibration is key
• Suggests: There exists an ideal viscosity for maintaining air distribution
• And we control viscosity via concrete mix design
How is vibration damped?

• Vibration of beam samples
• Accelerometers measure vibration energy

Table 4.5 Bingham parameters of fresh concrete, mortar, and paste with varying aggregate content

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Yield Stress (Pa)</th>
<th>Plastic Viscosity (Pa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar – 0% FA; 100% CP</td>
<td>164.2</td>
<td>31.8</td>
</tr>
<tr>
<td>Mortar – 20% FA; 80% CP</td>
<td>114.2</td>
<td>49.1</td>
</tr>
<tr>
<td>Mortar – 40% FA; 60% CP</td>
<td>90.1</td>
<td>68.3</td>
</tr>
<tr>
<td>Mortar – 60% FA; 40% CP</td>
<td>276.6</td>
<td>423.7</td>
</tr>
<tr>
<td>Concrete – 0% CA; 40% FA; 60% CP</td>
<td>207.3</td>
<td>10.5</td>
</tr>
<tr>
<td>Concrete – 22% CA; 40% FA; 38% CP</td>
<td>130.1</td>
<td>22.8</td>
</tr>
<tr>
<td>Concrete – 33% CA; 34% FA; 33% CP</td>
<td>208.5</td>
<td>33.5</td>
</tr>
<tr>
<td>Concrete – 45% CA; 28% FA; 27% CP</td>
<td>467.3</td>
<td>101.1</td>
</tr>
</tbody>
</table>
Loss of Air due to Vibration

- Paste shows no air loss
- Concrete has high air loss

Blue dot – no vibration
Red square – after vibration

Paste samples

Concrete samples
Plant Testing

• Three plants visits. (1 month stays for 2 plants; 4 days for 3rd plant)
• Testing in these plants included:
  • Slump
  • Fresh and hardened air content
  • Unit weight
  • Temperature
  • Rheology
  • Vibration
Plants Vibration

- Three plants visits. (1 month stays for 2 plants; 4 days for 3rd plant)
- Testing in these plants included rheology and vibration

Plant A
vibration rods attached to the casting machine.

Plant B
vibrator under forms

Plant C
used handheld vibrator
Plants Vibration

- The accelerometers used to measure vibrations.
Confirmed:
Handling & vibration drives air from concrete

- Average hardened air content:

<table>
<thead>
<tr>
<th>Location in the Manufacturing Process</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer (M)</td>
<td>9.2</td>
<td>8.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Before Vibration (BV)</td>
<td>8.0</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>After Vibration (AV)</td>
<td>6.0</td>
<td>5.5</td>
<td>5.3</td>
</tr>
</tbody>
</table>
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

Lytton, BC
Installing instrumented crossties
Model to predict temp/RH history on basis of local weather station data

- 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
How should we test crossties?
How should samples be taken?
Extensive FT testing

Full ties
FT tests
Half ties
Excised prisms
Cast prisms
Sawcut ties perform poorly

- Large samples (half-ties) vs. excised samples from the same ties
Summary

• We developed new models for vibration and air
• We documented true field conditions of crossties
• We proposed new guidelines for making durable concrete
• We proposed new approaches for production specification language
• We recommended quality control approaches

• Better understanding of distress mechanisms leads us to improve product performance!