Rethinking Testing for Concrete Pavements

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Tyler Ley, P.E., Ph.D.
Acknowledgements

- Oklahoma DOT
- FHWA
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- Minnesota DOT
- Idaho DOT
- North Dakota DOT
- Pennsylvania DOT
- Connecticut DOT
- Illinois DOT
- Indiana DOT
- Michigan DOT
- Wisconsin DOT
- New Jersey DOT
- RMC Foundation
Outline

• Introduction
• Box Test
• Super Air Meter
• The Phoenix!
The Big Picture

We need our materials to last as long as possible with little to no maintenance

We need tools to help us achieve this economically and without impacting our productivity

We need to take action!
What do we need from our concrete?

- Workable
- Durable
- Economical
- Strength

- Every project has a different set of requirements!!!
What do we need from our concrete?

- **Workable**
- Durable
- Economical
- Strength

- Every project has a different set of requirements!!!
How do we determine if a concrete mixture has the right workability for a concrete pavement?
What part of a paver is the most critical for concrete consolidation?
We want a test that is simple and can examine:

- Response to vibration
- Filling ability of the grout (avoid internal voids)
- Ability of the slip formed concrete to hold a sharp edge (cohesiveness)

The slump test can not tell us this!
Box Test

Add 9.5” of unconsolidated concrete to the box

A 1” diameter stinger vibrator is inserted into the center of the box over a three count and then removed over a three count

The edges of the box are then removed and inspected for honey combing or edge slumping
<table>
<thead>
<tr>
<th>Box Test Ranking Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4</strong></td>
</tr>
<tr>
<td>Over 50% overall surface voids.</td>
</tr>
<tr>
<td><strong>3</strong></td>
</tr>
<tr>
<td>30-50% overall surface voids.</td>
</tr>
<tr>
<td><strong>2</strong></td>
</tr>
<tr>
<td>10-30% overall surface voids.</td>
</tr>
<tr>
<td><strong>1</strong></td>
</tr>
<tr>
<td>Less than 10% overall surface voids.</td>
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</tbody>
</table>
Box Test Ranking Scale

<table>
<thead>
<tr>
<th>4</th>
<th>3</th>
</tr>
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<tr>
<td>Over 50% overall surface voids.</td>
<td>30-50% overall surface voids.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-30% overall surface voids.</td>
<td>Less than 10% overall surface voids.</td>
</tr>
</tbody>
</table>
Edge Slumping

Bottom Edge Slumping

< \( \frac{1}{4} \)"

Top Edge Slumping

< \( \frac{1}{4} \)"
Edge Slump

No Edge Slump
Summary

The Box Test examines the window of workability for concrete pavement mixtures

This is helpful when:
– mixtures are designed in the lab
– trial batching in the field
– troubleshooting field problems
– measuring variation in production

It is like having a miniature paver!!!
The TARANTULA curve!

**Fine sand sum of #30 through #200**
Between 24 to 34% for slip formed
Between 25 to 40% for flowable

**Coarse sand sum of #8 through #30 greater than 20%**

- Increases cohesion
- Decreases workability and promotes segregation
- Creates surface finishing problems
- Not in Scope of work

% Retained

Sieve No.

#200 #100 #50 #30 #16 #8 #4 0.375 0.5 0.75 1 1.5
Use in the field

Minnesota
1996-1998

Data from Maria Masten
Minnesota 2009
87% of mixtures met the sand criteria

Data from Maria Masten
Minnesota
2010
98% of mixtures met the sand criteria

Data from Maria Masten
Minnesota Pavement Mixtures from 1996 - 2011

% within the Tarantula limits

Smoothness

20 point change

Alturki and Ley 2017
Field Concrete

- The Minnesota contractors are producing gradations that fit within the Tarantula and having good success with them
- They are doing this with trial and error and no knowledge of the Tarantula Curve
- Similar data is available for Iowa and Michigan.
Box Test

AASHTO TP ??

www.tarantulacurve.com
What do we need from our concrete?

- Workable
- **Durable**
- Economical
- Strength

- Every project has a different set of requirements!!!
Today’s topics!

- air
- water to cement ratio
Why Do We Add Air to Concrete?

• Air-entrained bubbles are a key to the freeze-thaw resistance of concrete

Air volume ≠ freeze-thaw performance

• Smaller bubbles are more effective in providing freeze-thaw resistance and have less of an impact on our concrete than larger bubbles
If \( f'c > 5,000 \) psi then these recommendations can be reduced by 1%.

ACI 318
If $f'_c > 5,000$ psi then these recommendations can be reduced by 1%

ACI 318
What Do You Want in an Air-Void System?

- Volume of air provided is the same for both.
- Case B has a better air void distribution.
What Do You Want in an Air-Void System?

• Volume of air provided is the same for both.
• Case B has a better air void distribution.
What causes large bubbles?

- Admixture incompatibility
- Admixture/cement incompatibility
- Sand gradation
- Inadequate mixing
- Alkali content of binder
- Cement grinding aids
- Changes in temperature
How do you measure this?
Hardened Air Void Analysis

From Hover
Hardened Air Void Analysis

From Hover
Freeman et al., 2012

Chord Size, microns

WROS Only
PC1 + WROS
The graph illustrates the frequency distribution of chord sizes (in microns) for different types of mixtures. The x-axis represents the chord size, and the y-axis represents the frequency. Two types of mixtures are shown:

- **WROS Only** (green line)
- **PC1 + WROS** (blue line)

The graph is labeled as follows:

- **Mixture with small bubbles**
- **Mixture with large bubbles**

The legend indicates that the data is from Freeman et al., 2012.
• Spacing Factor – $\frac{1}{2}$ of the average distance of an average sized void uniformly distributed in the paste

• **Desired Value < 0.008 in (ACI 201)**
Low spacing factor

High spacing factor

WROS Only

PC1 + WROS

Freeman et al., 2012
ASTM C 457 Spacing Factor, in
Air %
WROS .45
ACI 201.2R

Small bubbles
Yes!
No!

ACI 201.2R

Small bubbles
Yes!
No!
You can’t tell the size of the bubbles by looking at the volume!!!

ASTM C 457 Spacing Factor, in
Air %
WROS .45
WROS .45 + PC1
ACI 201.2R

You can’t tell the size of the bubbles by looking at the volume!!!

You can’t tell the size of the bubbles by looking at the volume!!!

Large bubbles

Small bubbles

Yes!

No!
Durability Factor vs. Fresh Air %

- Recommended
- Not Recommended

- WROS .40
- WROS + PC1 .40

Ley et al., 2017

Small bubbles
Large bubbles
Mixtures with small bubbles

Freeman et al., 2012
Mixtures with large bubbles

Open symbols failed ASTM C666

Yes!

No!

Freeman et al., 2012
Mixtures with large bubbles

Freeman et al., 2012
Summary

• We need to know the size of bubbles within the concrete

• *The volume of air does not tell you anything about bubble size*

• Although a hardened air void analysis can measure this, it is not practical to run regularly
Super Air Meter (SAM)

• We have modified a typical ASTM C 231 pressure meter so that it can hold larger pressures
• We have replaced the dial gage with a digital one
digital gauge

six clamps!
Air content given here
Pressure (psi) vs. Time

- Top Chamber, $P_c$
- Bottom Chamber, $P_b$
- Equilibrium Pressure

Diagram showing the pressure over time for different chambers.
Pressure (psi)

Time

Top Chamber, P_c
Bottom Chamber, P_a
Equilibrium Pressure

release pressure in both chambers
Pressure (psi) vs. Time

- Top Chamber, Pc
- Bottom Chamber, P
- Equilibrium Pressure

Air content and SAM number given here.
Why is the SAM number useful?

digital gauge

six clamps!
Durability Factor
Fresh Air %
WROS .40
WROS + PC1 .40
Recommended
Not Recommended
Ley et al., 2017
Small bubbles
Large bubbles
Recommended
Not Recommended

Ley et al., 2017

Large bubbles
Small bubbles

SAM Number

Durability Factor

WROS .40
WROS + PC1 .40

0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
0.00 0.10 0.20 0.30 0.40 0.50 0.60

SAM Number
Over 227 lab mixtures from two different research groups
88% agreement

Ley et al., 2017
Durability Factor % vs. SAM Number

98 mixtures
91% agreement

Cliff of Doom

Recommended
Not Recommended

Recommended
Not Recommended
Discussion

The SAM Number does a better job correlating with spacing factor and freeze thaw performance than total air volume.

The test can be completed in fresh concrete!!!
21 State DOTs + 1 Canadian Province helped analyze **231 concrete mixtures from 110 different projects**

More than: 15 different SAMs and operators, 62 different aggregates, 19 cement sources, 20 different fly ashes, 39 different admixtures

60% pavements, 20% bridge decks, and 20% other self-consolidating, precast, ready mix, and central mix concrete

Thank you to all that helped!
Low quality air void system

High quality air void system

231 field mixes

25% in the low quality quadrant!!!

70% agreement

SAM Number

Spacing Factor (μm)
Discussion

The SAM Number correlates to performance in rapid freeze thaw testing.

A SAM Number of 0.20 correlates to a spacing factor of 0.008” for 458 concrete mixtures completed by 22 different DOTs and two research groups.

88% agreement in lab
70% agreement in the field
Why is this useful?

• The SAM can tell us about the quality (size and spacing) of our air void system before the concrete sets.

• It can help us design concrete mixtures that have more reliable and stable air void systems.

• It can better ensure freeze thaw durability.
Challenges with the SAM

The SAM looks like a normal air meter but it is more complicated.

You must ensure the concrete is properly consolidated and the meter does not leak!

Some users require specialized training.
Why is the w/cm important?

- This lowers your strength and increases your permeability.

- We need a reliable field test to measure this.
We call this test “The Phoenix”!!!
Steps

• Record batch ticket and aggregate properties
• Make and weigh 4x8 cylinder
• Dump cylinder into pan and weigh
• Start test
• Come back when finished
• Weigh pan
Heating element

Cooktop

30 min test
Dry concrete
Change in mass over time

Fresh concrete is added here

ALL Water is gone
Change in mass over time

Fresh concrete is added here

The test removes the water from the paste and aggregate!!!!

ALL Water is gone
The Phoenix removes all the water!!!

- If we know the absorption capacity of the aggregate then we can remove this from the total water content and get the w/cm.

- During mixing the moisture content of the aggregate will become SSD.
How do you get w/cm?

- The change in mass before and after cooking = amount of water in the cylinder

- Use the batch ticket information to find the amount of binder within the cylinder
How do you get w/cm?

- Assume aggregate at SSD and remove the water in the aggregate from the total

- Make a correction based on the measured cylinder unit weight versus the unit weight from the batch ticket - this corrects for air
How can we test in the lab?

• Make mixtures in the lab where we carefully control the moisture contents and batch weights.

• We should know the w/cm very accurately.

• Measure the w/cm with the Phoenix and compare.
Mix Information

• 9 Sources of Coarse Aggregate
  – Granites and Limestones

• 3 Sources of Fine Aggregate
  – Natural sands and Manufactured sand

• Specific Gravities: 2.42-2.75

• Absorptions (%): 0.46-4.69

• Five different w/cm

• Different paste contents
Lab Data

9 Coarse Agg
3 Fine Agg
5 Different w/cm
228 Tests
COV < 3%
9 Coarse Agg
3 Fine Agg
5 Different w/cm
228 Tests
COV < 3%

Lab Data

- 9 Coarse Agg
- 3 Fine Agg
- 5 Different w/cm
- 228 Tests
- COV < 3%

Graph showing measured w/cm versus design w/cm for different aggregates (Granite 1, 2, 3, 4, Limestone 1, 2, 3, River Rock 1, 2) with ideal expected values and COV < 3%.
Discussion

• All lab mixes are within +/- 0.02 w/cm with most of them within +/- 0.01 w/cm.

• The COV is < 3%!!!

• What about the field?
Field Unit

Protective Cage

3ft
How can we test in the field?

- Use the batch ticket information to determine design w/cm
- Measure w/cm with the Phoenix
- All testing was done at the batch plant
- Four different projects 27 different mixtures
- Paving, bridge decks, substructure
Field Data

27 mixtures investigated
15% with w/cm > 0.02 than design
Discussion

• The Phoenix data looks promising

• 15% of mixtures had a w/cm > 0.02 than what was reported on the batch ticket.

• We are sampling at the batch plant and everyone knows that we are watching.
How can this group help?

Taking the industry from a horse and buggy to an engine is not easy.

Ask questions!

Share what you learn here with others
Help others become experts with these new tests
Conclusion

• The Box Test is designed to measure the window of workability required for concrete pavements.

• The SAM can measure the volume and size distribution of the bubbles in fresh concrete and ensure freeze-thaw durability.

• The Phoenix can accurately measure the w/cm in fresh concrete in both the lab and the field.
www.youtube.com/tylerley
Questions???

www.tylerley.com

www.youtube.com/tylerley
<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Size</th>
<th>SpG</th>
<th>Abs (%)</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite 1</td>
<td>Coarse</td>
<td>2.75</td>
<td>0.46</td>
<td>OK</td>
</tr>
<tr>
<td>Granite 2</td>
<td>Coarse</td>
<td>2.75</td>
<td>0.51</td>
<td>GA</td>
</tr>
<tr>
<td>Granite 3</td>
<td>Coarse</td>
<td>2.59</td>
<td>1.06</td>
<td>MN</td>
</tr>
<tr>
<td>Granite 4</td>
<td>Coarse</td>
<td>2.66</td>
<td>0.66</td>
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<td>Coarse</td>
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<tr>
<td>Limestone 3</td>
<td>Coarse</td>
<td>2.67</td>
<td>0.64</td>
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<tr>
<td>River Rock 1</td>
<td>Coarse</td>
<td>2.67</td>
<td>1.52</td>
<td>MN</td>
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<tr>
<td>River Rock 2</td>
<td>Coarse</td>
<td>2.68</td>
<td>0.81</td>
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<td>Natural Sand 1</td>
<td>Fine</td>
<td>2.62</td>
<td>0.64</td>
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<tr>
<td>Natural Sand 2</td>
<td>Fine</td>
<td>2.61</td>
<td>0.20</td>
<td>OK</td>
</tr>
<tr>
<td>Man Sand</td>
<td>Fine</td>
<td>2.76</td>
<td>1.05</td>
<td>OK</td>
</tr>
</tbody>
</table>
States that have plans to shadow specify the SAM

- Michigan
- Minnesota
- Idaho
- Oklahoma
- Colorado
- Wisconsin
- New York
- Kansas
How long does it take?

With just the SAM
Inexperienced user – 10 min to 12 min
Experienced user – 7 min to 9 min

With the CAPE
Inexperienced user – 7 min to 9 min
Experienced user – 4.5 min to 6.5 min

Test must be completed within 12 min
**Controlled Air Pressure Extender** aka CAPE

- **Step 1**: (14.5 psi)
- **Step 2**: (30 psi)
- **Step 3**: (45 psi)
What air content do you use?

Air content between 3.75% and 7.75% for 0.008” spacing factor
What air content do you use?
What air content do you use?

Efficient

Inefficient

![Graph showing air content and durability factor.](image-url)
Air content between 3.75% and 7.75% for 0.008" spacing factor

231 field mixes

Efficient

Inefficient

Spacing Factor (μm)

Air Content %
How variable is the test?

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Parameter</th>
<th>COV</th>
<th>Time to complete the test</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAM</td>
<td>SAM Number(^1)</td>
<td>15.2%</td>
<td>10 min</td>
</tr>
<tr>
<td>ASTM C457</td>
<td>Spacing Factor(^2)</td>
<td>20.1%</td>
<td>7 days</td>
</tr>
<tr>
<td>ASTM C666</td>
<td>Durability Factor(^3)</td>
<td>22.7%</td>
<td>3.5 months</td>
</tr>
</tbody>
</table>

\(^1\) Assumes a SAM Number of 0.32 and a standard deviation of 0.049 from this paper

\(^2\) From ASTM C457

\(^3\) From ASTM C666 with a durability factor of 75 and Method B

170 SAM comparisons were used to determine this.
Why are they different?

If the producer designs the SAM Number to be 0.20 at their working air content then they will have $< 2\%$ chance of getting a failing test in the field.

The rejection limit is determined by freeze thaw testing (ASTM C 666).
Why are they different?

Mix Design: 0.20
Acceptance: 0.30

SAM Number:

0.20
0.30
AASHTO PP84-19 Specification

Mixture Design
SAM < 0.20 and Air > 4%

Field
SAM < 0.30 and Air > 4%