Evaluation of Current Wisconsin Mixes Using Performance Engineered Mixture (PEM) Testing Protocols

Project 0092-17-07

Tyler Ley, PhD, PE
Do you have any questions?

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1. Text TYLERLEY390 to +1 (747) 444-3548
2. Text in your message

Total Results: 0
Project Location Overview

1. West Waukesha Bypass (Zignego)
2. Appleton- Oneida St. (Vinton)
3. City of Superior USH 2 (Chippewa Concrete)
4. City of Columbus (Michels)
5. Waukesha- Capitol Drive (Trierweiler)
6. I-39 Rock County (Trierweiler)
7. I-39 Dane County (Trierweiler)
8. I-94 Menomonie (Trierweiler)
STRENGTH RESULTS AND RECOMMENDATIONS
Strength Testing Results: 28-Day Comparison

<table>
<thead>
<tr>
<th>Location</th>
<th>Compressive Strength (PSI)</th>
<th>Modulus of Rupture (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appleton</td>
<td>5,000</td>
<td>812</td>
</tr>
<tr>
<td>Capitol Drive</td>
<td>6,034</td>
<td>842</td>
</tr>
<tr>
<td>Columbus</td>
<td>5,496</td>
<td>743</td>
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<tr>
<td>Superior</td>
<td>5,946</td>
<td>752</td>
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<tr>
<td>W. Waukesha Bypass</td>
<td>4,378</td>
<td>828</td>
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<td>I-39 Rock County</td>
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<td>I-39 Dane County</td>
<td>6,550</td>
<td>807</td>
</tr>
<tr>
<td>Menomone</td>
<td>7,374</td>
<td>680</td>
</tr>
</tbody>
</table>
Strength Testing Results: 28-Day Comparison

Lowest comp
Highest flex
Strength Testing Results: 28-Day Comparison

Highest comp
Lowest flex
Findings

• Higher compressive strength didn’t always correspond to higher flexural strengths.

• Flexural strength is more representative of how a pavement is loaded.

• Flexural strength may provide more insight into the aggregate and paste bond.
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
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
## Box Test Ranking Scale

<table>
<thead>
<tr>
<th>Rank</th>
<th>Overall Surface Voids</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Over 50% overall surface voids.</td>
</tr>
<tr>
<td>3</td>
<td>30-50% overall surface voids.</td>
</tr>
<tr>
<td>2</td>
<td>10-30% overall surface voids.</td>
</tr>
<tr>
<td>1</td>
<td>Less than 10% overall surface voids.</td>
</tr>
</tbody>
</table>
Box Test Ranking Scale

<table>
<thead>
<tr>
<th>4</th>
<th>3</th>
</tr>
</thead>
<tbody>
<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

< 1/4”

Top Edge Slumping

< 1/4”
No Edge Slump

Edge Slump
Workability: Box Test

- 3 locations > 2.0
  - many and/or larger surface voids
  - mixtures may have poor “finishability”
- 5 locations < 2.0
  - mixtures that have small and/or a small number of surface voids
  - good “finishability”
Workability: Box Test (Appleton)

- Look at the Appleton Mixture specifically:
  - Box Test < 2.0
Coarse Sand Limit: ≥15%

Fine Sand Limit: 24-34%

Percent Retained, % Vol

Sieve

Upper Limit

Lower Limit
Coarse Sand Limit: $\geq 15\%$

Fine Sand Limit: 24-34\%

Percent Retained, % Vol
% Retained, Vol

Coarse Sand Limit: ≥15%

Fine Sand Limit: 24-34%

Sieve Numbers:

- #4
- #8
- #16
- #30
- #50
- #100
- #200
Tarantula Curve (Appleton)

• All Tarantula Curve limits within spec except **Coarse Sand Limits**.
• The coarse sand is responsible for cohesion.
• In some box test pictures the corners did not remain in place, likely due to cohesion issues.
• Otherwise good performance with some surface voids and minimal edge slumping.
Workability: Box Test (Rock County)

- Look at the Rock County Mixture specifically:
  - Box Test > 2.0

<table>
<thead>
<tr>
<th>Location</th>
<th>Box Test</th>
</tr>
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<tbody>
<tr>
<td>Appleton</td>
<td>1.3</td>
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<tr>
<td>Capitol Drive</td>
<td>1.8</td>
</tr>
<tr>
<td>Columbus</td>
<td>1.8</td>
</tr>
<tr>
<td>I-39 Dane County</td>
<td>2.3</td>
</tr>
<tr>
<td>I-39 Rock County</td>
<td>2.1</td>
</tr>
<tr>
<td>Menomonie</td>
<td>1.3</td>
</tr>
<tr>
<td>Superior</td>
<td>2.1</td>
</tr>
<tr>
<td>W. Waukesha Bypass</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Average Box Number: 2.8
Coarse Sand Limit: ≥15%

Fine Sand Limit: 24-34%
VKelly

• Kelly ball test
  – Developed in the 1950s in US
  – Standardized in California DOT test
  – Comparable to slump test
    • 1.1 to 2.0 times the Kelly ball reading
VKelly

- Measure initial slump (initial penetration)
- Start vibrator for 36 seconds at 8000 vpm
- Record depth every 6 seconds
- Repeat
- Plot on root time
- Calculate slope = VKelly Index
Workability: V-Kelly - Average

IDEAL ZONE

Average V-Kelly Index [in/sqrt(s)]

- Waukesha: 0.72
- Appleton: 0.89
- Superior: 0.71
- Columbus: 0.51
- Capitol Drive: 0.80
- I-39 Rock County: 0.53
- I-39 Dane County: 0.70
- Menomonie: 0.70
Workability: Box Test vs. V-Kelly

$R^2 = 0.36$
Workability: Recommendations

- **Box Test**: Do not require as a design specification, but this test may be valuable to contractors during mix design.

- **V-Kelly**: 0.8 to 1.2 in/sqrt(s) was recommended\(^1\) but the data in this study showed good box values can be achieved with V-Kelly values as low as 0.7 in/sqrt(s).

- Consider implementation of a warning band on the Tarantula Curve to account for variability during production.
DURABILITY RESULTS AND RECOMMENDATIONS
Super Air Meter
AASHTO TP 118

Gives you air volume and SAM Number

digital gauge

six clamps!
Discussion

• If SAM < 0.30 at the plant
  • then minimal change of SAM Number after the paver.

• If SAM > 0.30
  • then significant change in SAM Number after the paver.

• Observed air loss did not decrease the quality of the air void system when the SAM Numbers were < 0.30.
SAM Variability

- Bat. Vibe shown in **BLUE**
- Rodding shown in **GREEN**

### SAM Value

- **I-39 Dane County**
- **I-39 Rock County**
- **Menomonie**

- Bat. Vibe Average of Plant
- Bat. Vibe Average of Before Paver
- Bat. Vibe Average of After Paver
- Rod Average of Plant
- Rod Average of Before Paver
- Rod Average of After Paver
Discussion

• Bat. Vibe showed more variability and inconsistency.
• Rodding was more consistent with lower variability.
Proceq Resipod

Inner probes

Outer probes
Surface Resistivity Reading (kΩ-cm)

7-DAY  14-DAY  28-DAY  56-DAY  90-DAY

VERY LOW
LOW
MODERATE
HIGH
Durability: Recommendations

- **SAM and Air Content**: Recommended 0.20 design limit and 0.30 field limit with air content > 4%. Another option would be to have an action limit where the contractor would be required to take action if the SAM Number is between 0.25 and 0.30. This would likely be done by increasing the air content in their mixture.

- **Surface Resistivity**: Consider as a informational parameter and collect data for future consideration of implementation.
Summary

- Mixtures showed improvement with Aggregate Optimization
- Consistently found good Box Test, V-Kelly, SAM, and resistivity values in the field
What is next for the Wisconsin PEM?
Percent Retained, % Vol

Coarse Sand Limit: ≥15%

Fine Sand Limit: 24-34%

Upper Limit

Lower Limit
Coarse Sand Limit: \( \geq 15\% \)

Fine Sand Limit: 24-34%
Is this the right limit???
What are the benefits in using 1.5” dia. stone?
Can we reduce variability of SAM?

• The research team developed a miniature vibrating table.

• This is a base that uses the Bat. Vibe to power it. It is lightweight and allows users to get much lower variability by using a Bat. Vibe.

• It is called the MinT or Miniature Table.
MinT – Top View

Restraint Clamp

Unit weight goes here
MinT – Bottom View

Vibrator goes here

Restraint bolts
MinT – Assembly / Operation

Fill in two layers with 55 s of vibration for each layer.
What is next for the US PEM?
A new fresh property test that accurately predicts the strength and permeability of concrete in 12 mins.
No anxious waiting for strength breaks or worrying about sample handling.
No anxious waiting for strength breaks or worrying about sample handling.

No 90 day wait for permeability results.
No anxious waiting for strength breaks or worrying about sample handling.

No 90 day wait for permeability results.

Have confidence that you are getting the concrete that you want before it hits the grade.
We can do all of this if we can measure the water to cement ratio in fresh concrete.
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 after 12 min
- Weigh pan
Items needed...

Batch and agg info

Cylinder and a scale

Pans
Awesome kiln!!!

1500 °F (max temp)
Change in weight over time

Remaining Weight (%)

Time (minutes)

Fresh concrete is added here

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

ALL Water is gone!
How do you get w/cm?

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

• Calculate how much water will be in aggregate after reaching SSD and remove that from the total water

• Use batch ticket to find the cement content in the cylinder.
There is an app for that!!!
Lab Data

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

Line of equality

Measured w/cm

Batched w/cm

(+0.02 w/cm)

(-0.02 w/cm)

27 Tests
23 Tests
23 Tests
130 Tests
31 Tests
Field Data

32 Tests
88% w/in 0.01 w/cm
COV = 3%
Discussion

• The Phoenix can measure the w/cm within 0.01 in 12 mins with fresh concrete in the field.

• The test can also do moisture corrections of the aggregates.
Discussion

• If we know our w/cm is right then we should be confident that we will get the strength and permeability of our hardened concrete.

• Accurately measuring fresh concrete is more powerful than measuring hardened concrete.
• We are creating a small run of these kilns to get feedback, build data for ASTM, and create interest.

• We already have lots of DOTs involved.

• We would love to find some interested contractors or producers that would like to participate.
Thank You!
Any Questions?

Tyler Ley
www.tylerley.com
www.youtube.com/tylerley

Facebook and Instagram:
Concrete.tyler

Tyler.ley@okstate.edu
Summary of Recommendations

• Strength
  – No direct correlation between compressive and flexural strength in this dataset.
  – Flexural strength could indicate other qualities of interest. More research is necessary but is outside the scope of this project.

• Workability
  – OAG: Consider implementation of a warning band to account for producer variability during production.
  – Box Test: Do not require as a design specification, but this test may be valuable to contractors during mix design.
  – V-Kelly: 0.8 to 1.2 in/sqrt(s) was recommended¹ but the data in this study showed good box values can be achieved with V-Kelly values as low as 0.7 in/sqrt(s).
Summary of Recommendations

• Durability
  – **SAM and Air**: Recommended 0.20 design limit and 0.30 field limit with air content > 4%. Another option would be to have an action limit where the contractor would be required to take action if the SAM Number is between 0.25 and 0.30. This would likely be done by increasing the air content in their mixture.
  – **Surface Resistivity**: Consider as a design parameter and collect data for future consideration of implementation.
  – **CTE**: Consider as a design parameter and collect data for future consideration of implementation.
Citations

1) Taylor, Peter; Wang, Xuhao; and Wang, Xin, "Concrete Pavement Mixture Design and Analysis (MDA): Development and Evaluation of Vibrating Kelly Ball Test (VKelly Test) for the Workability of Concrete" (2015). InTrans Project Reports. 105.
Results

- The Vibration Table and MinT had similar standard deviations for the SAM Number.

- The rodding and stinger vibrator had 2x higher variability.

- The variability for the air content were all similar.

<table>
<thead>
<tr>
<th>SAM Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consolidation Method</strong></td>
</tr>
<tr>
<td>Rodding</td>
</tr>
<tr>
<td>Vibration Table</td>
</tr>
<tr>
<td>Mini-Table (MinT)</td>
</tr>
<tr>
<td>Stinger</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Air Statistics</th>
</tr>
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<td>Mini-Table (MinT)</td>
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<tr>
<td>Stinger</td>
</tr>
</tbody>
</table>
Suggested Binder Content for Different Parts of the Tarantula Curve

**Coarse Sand Limit:** \( \geq 15\% \)

**Fine Sand Limit:** 24-34%

- **Upper Limit:** 450 lbs
- **Lower Limit:** 550 lbs

*Max W/C: 0.43*
Suggested Binder Content for Different Parts of the Tarantula Curve

Percent Retained, % Vol

Sieve

Upper Limit

Coarse Sand Limit: ≥15%

Fine Sand Limit: 24-34%

Lower Limit

450 lbs

500 lbs

550 lbs

*Max W/C: 0.43
Suggested Binder Content for Different Parts of the Tarantula Curve

- **Upper Limit**
- **Lower Limit**
- **Coarse Sand Limit:** ≥15%
- **Fine Sand Limit:** 24-34%

*Max W/C: 0.43*
Suggested Binder Content for Different Parts of the Tarantula Curve

- Coarse Sand Limit: ≥15%
- Fine Sand Limit: 24-34%

*Max W/C: 0.43
Recommendations

- #200 Sieve limit in the Tarantula Curve – Change limit to 2%.
- 1.5” sieve limit in the Tarantula Curve – Limit based on WisDOT experience and more research is needed.
- Removal of the Uncompacted Voids Content from WisDOT spreadsheet and specification.
  - Instead use the Tarantula Curve with binder modifications for different zones.
Water Reducer Needed to Pass the Box Test

Cook and Ley 2017
Water Reducer Needed to Pass the Box Test

- Drastically different performance and the same voids content

Cook and Ley 2017

WR (mL/100kg)

Void Content (%)
Water Reducer Needed to Pass the Box Test

Similar performance but different voids content

Great workability

Poor workability

Cook and Ley 2017

WR (mL/100kg)

Void Content (%)
Recommendations for future research

- Investigate the use of the Miniature Table – MinT in the field.
- Another option would be to have an action limit where the contractor would be required to take action if the SAM Number is between 0.25 and 0.30. This would likely be done by increasing the air content in their mixture.
- If the SAM Number is < 0.30 then consolidation from the paver is not expected to change the quality of the air void system and so testing is not required after the concrete paver.
Strength Testing Results

Compressive Strength

Days After Casting

Appleton  | Capitol Drive  | Columbus  | Superior  
---------|----------------|-----------|-----------
I39 Rock County | I39 Dane County | Menomonie |

Flexural Strength

Days After Casting

Appleton  | Capitol Drive  | Columbus  | Superior  
---------|----------------|-----------|-----------
I39 Rock County | I39 Dane County | Menomonie |
# Workability: Mix Design Summary

## General Design

<table>
<thead>
<tr>
<th>Location</th>
<th>Appleton</th>
<th>Capitol Drive</th>
<th>Columbus</th>
<th>Superior</th>
<th>W. Waukesha Bypass</th>
<th>I-39 Rock County</th>
<th>I-39 Dane County</th>
<th>Menomonie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Sand Spec: ≥ 15%</td>
<td>13.6%</td>
<td>18.1%</td>
<td>18.4%</td>
<td>25.7%</td>
<td>24.7%</td>
<td>24.3%</td>
<td>19.0%</td>
<td>24.2%</td>
</tr>
<tr>
<td>Fine Sand Spec: 24-34%</td>
<td>28.3%</td>
<td>30.0%</td>
<td>24.7%</td>
<td>25.0%</td>
<td>23.1%</td>
<td>30.2%</td>
<td>29.9%</td>
<td>32.4%</td>
</tr>
<tr>
<td>Total Cementitious</td>
<td>565 lbs</td>
<td>565 lbs</td>
<td>565 lbs</td>
<td>530 lbs</td>
<td>565 lbs</td>
<td>565 lbs</td>
<td>520 lbs</td>
<td>520 lbs</td>
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<tr>
<td>W/C</td>
<td>0.41</td>
<td>0.37</td>
<td>0.39</td>
<td>0.42</td>
<td>0.41</td>
<td>0.40</td>
<td>0.40</td>
<td>0.38</td>
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## Tarantula Curve

<table>
<thead>
<tr>
<th></th>
<th>Appleton</th>
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<th>I-39 Dane County</th>
<th>Menomonie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warning Band Exceeded?</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Out of Specification?</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>

## Workability

<table>
<thead>
<tr>
<th></th>
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<th>I-39 Dane County</th>
<th>Menomonie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box Test</td>
<td>1.3 (0.3)</td>
<td>1.8 (0.3)</td>
<td>1.8 (0.3)</td>
<td>2.1 (0.3)</td>
<td>1.9 (0.3)</td>
<td>2.1 (0.3)</td>
<td>2.3 (0.3)</td>
<td>1.3 (0.4)</td>
</tr>
<tr>
<td>V-Kelly</td>
<td>0.89 (0.10)</td>
<td>0.80 (0.13)</td>
<td>0.51 (0.15)</td>
<td>0.71 (0.11)</td>
<td>0.72 (0.12)</td>
<td>0.62 (0.08)</td>
<td>0.55 (0.21)</td>
<td>0.70 (0.11)</td>
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</table>