PEM and Reduced Cement Paving Mixes in Iowa

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Dan King, P.E., Iowa Concrete Paving Association
Introduction

• Overview of PEM Program
• Iowa Paving Mixes and PEM Interest
• FHWA Trailer Visit
• PEM Shadow Testing 2019
• I-29 Harrison County Project PEM
• Future Outlook for PEM
Performance Engineered Mixtures

• Pooled fund study led by CP Tech Center uniting FHWA, champion state DOTs, and the concrete paving industry

https://cptechcenter.org/performance-engineered-mixtures-pem/
Performance Engineered Mixtures

• Implementing current best practices and new methods for:
  – Designing and specifying concrete pavement mixtures for maximum long-term durability
  – Measuring and relating early age concrete properties to performance
Performance Engineered Mixtures

• Prepare the mixture for the application
  – Use what you need (and no more) from the materials you have
  – Control cementitious content

• Require the things that matter
  – What do we need to design for to maximize durability in our environment?
  – What tests/measurements do we perform to make sure we meet our goals?
What matters to us?

- Cold weather resistance (cold locations)
  - SAM Air Meter, LTDSC- Salt Resistance
- Transport properties/permeability (everywhere)
  - Resistivity/Formation Factor
- Aggregate stability (everywhere)
  - ASR/D-Cracking
- Workability (everywhere)
  - Box Test/V-Kelly
- Strength (everywhere)
  - Flexural or Compressive
- Shrinkage (dry locations)
  - Ring Test
How do we proportion to achieve design goals?

<table>
<thead>
<tr>
<th>Aggregate System</th>
<th>Workability</th>
<th>Transport</th>
<th>Strength</th>
<th>Cold weather</th>
<th>Shrinkage</th>
<th>Aggregate stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate System Type, gradation</td>
<td>✓ ✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Paste quality</td>
<td>Air, w/cm, SCM type and dose</td>
<td>✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Paste quantity</td>
<td>Vp/Vv</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>✓ ✓</td>
<td>-</td>
</tr>
</tbody>
</table>
Controlled mixtures

- Control the cementitious content
  - Excess has a:
    • Negative effect on permeability, shrinkage, cost
    • Small negative effect on strength
  - “Optimum” depends on:
    • Aggregate type
    • Gradation
    • Aggregate shape
Super Air Meter (SAM)

- Test at 14.5, 30 & 45 psi
  - Release and repeat
- Air content & SAM number
- SAM number correlates to spacing factor => F/T Test
- Mix Design SAM # <0.20
- Field SAM # <0.30 & Air>6%
Workability

- Slump Test
  - Uniformity Test tells nothing about response to vibration
- Box Test and V-Kelly
  - Response to Vibration
- Factors in Workability
  - Aggregate Gradation
  - Paste Content
  - Admixtures
Workability - Box Test

- Fill box to 9.5 inches
- Insert vibrator 12,500 vpms
  - 3 seconds to bottom
  - 3 seconds out
- Edges of box are removed and inspected
- PEM Limits <30% Voids or Rating of 2 or less
Transport Properties - Resistivity

- Cast Two Cylinders
- Place in bucket with (Ca, Na, K) hydroxide solution
- Test Resistivity at 3, 7, 28, 56 and 91 days
Calcium Oxychloride Potential

- Salts can cause chemical attack
  - Reaction between Ca(OH)$_2$ & CaCl$_2$ or MgCl$_2$ expands ~30% & forms above 32F

- Low temperature differential scanning calorimetry (LT-DSC)
  - 10 gms hydrated paste ground, mix w 10 mg 20% CaCl2 solution, low temperature cycling

- Limit the CaOXY formation to < 0.15 (g/100g) reduces oxychloride formation
- Potential reduced by use of SCMs
Iowa Paving Specifications

- In many ways, the goals and ideas of the PEM program are familiar to Iowa
- In recent decades, we’ve seen the introduction of QMC and C-SUD paving mixes
Development of QMC Specification

- 1997 First (QMC) project
  - Incentive Compressive Strength
- 1998 - 1999 12 projects
  - Incentive Third Point flexural
- No Correlation of Strength to Durability
- Minimal Mix Improvement
Development of QMC Specification

• In 2000, Incentive based on Shilstone Gradation Chart
• Variations of incentive boxes
• 2016 Incentive removed
  – Provide proportions in Zone II
• Minimal workability issues past 20 years
  – Aggregate Shape Effect
QMC – Aggregate Shape

- US 75 Woodbury Co. 2000
- Quartzite CA & IA
  - 45.5% CA/ 19.5% IA/ 35% FA
- Very Coarse w Angular Aggregates
  - Finishing difficulties
  - edge tear
  - slow production rates
QMC 20 Years Lessons Learned

• Partnership with contractors expedited changes
• Placement impacts durability
• Excessive handling with soft aggregates affect strength
• Well graded aggregates improve placement
• Aggregate shape and texture affect placement
• Slag and fly ash reduce permeability
• Optimized gradation allows for reduction in cementitious content and w/cm
C-SUD Paving Mixes

• While QMC was implemented by the DOT, local agencies in Iowa also needed to adapt their mixes to new trends – Greater de-icing demands, impacting long-term durability
C-SUD Paving Mixes

• The C-SUD specification allows local agencies to optimize the gradation according to the QMC specification

• Plus additional options:
  – Greater allowable fly ash & SCM substitution rates (35-40%)
    • Additional protection against CaOXY formation from de-icing salts
  – Further lowering of maximum w/cm (0.42)
    • This lower w/cm was adopted for QMC a few years ago, too
How does QMC mix compare with PEM?
2018 PEM Pooled Fund Research Project

- Shadow projects
- Investigate ruggedness of test methods
- Develop specification limits
- Collect data for modelling
- Contractor QC Testing
- FHWA Mobile Concrete Trailer
Iowa PEM Shadow Project

- Cedar Valley Corp volunteered
- US 20 Woodbury Co. 2018
- Comprehensive QC Plan
  - Control Charts
  - Air PWL
    - SAM Test
    - Box Test
    - Resistivity/Formation Factor
    - Calcium Oxychloride Potential
    - Trial batch mix design reduced cement
S.A.M. Number
Before Paver
Box Test Ranking

Bar graph showing Box Test Rank by date.

Y-axis: Box Test Rank

Key dates with higher Box Test Rank:
- 7/11/2018
- 7/16/2018
- 7/18/2018
- 7/24/2018
- 7/31/2018

Incorporating a photograph of a concrete block in the upper right corner.
Combined Aggregate Gradation

Tarantula Curve Combined Aggregate Gradation, % Retained

![Graph of Combined Aggregate Gradation](image_url)
Calcium Oxychloride Potential

- Limiting CaOXY formation to less than 0.15 (g/100g)
- 20% Class C fly ash replacement met the limit
- Higher percent slag/fly ash replacement will further reduce potential
Dr. Taylor estimated cement content based on dry rodded unit weight of combined aggregate.

**PEM Mix Design w Lower Cement Content**

- Investigate lower cement mix on shoulders
  - 4 ft. by 6 in. thick
- Validate mix using PEM tests

<table>
<thead>
<tr>
<th>A-2-C20 Mix</th>
<th>Abs. Vol.</th>
<th>lbs/CY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT:</td>
<td>0.083</td>
<td>440</td>
</tr>
<tr>
<td>FLY ASH:</td>
<td>0.025</td>
<td>110</td>
</tr>
<tr>
<td>WATER: w/c=0.474</td>
<td>0.155</td>
<td>261</td>
</tr>
<tr>
<td>FINE AGGREGATE:</td>
<td>0.305</td>
<td>1357</td>
</tr>
<tr>
<td>COARSE AGGREGATE:</td>
<td>0.372</td>
<td>1680</td>
</tr>
<tr>
<td>INTERMEDIATE AGG.:</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AIR:</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

Paste Content, % 26.3

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT:</td>
<td>0.078</td>
<td>412</td>
</tr>
<tr>
<td>FLY ASH:</td>
<td>0.024</td>
<td>103</td>
</tr>
<tr>
<td>WATER: w/c=0.40</td>
<td>0.122</td>
<td>206</td>
</tr>
<tr>
<td>FINE AGGREGATE (44%):</td>
<td>0.315</td>
<td>1401</td>
</tr>
<tr>
<td>COARSE AGGREGATE (44%):</td>
<td>0.315</td>
<td>1422</td>
</tr>
<tr>
<td>INTERMEDIATE AGG. (12%):</td>
<td>0.086</td>
<td>387</td>
</tr>
<tr>
<td>AIR:</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

Paste Content, % 22.4

550 lbs

515 lbs
PEM Mix Design

• Some concerns lowering cement content of standard A mix for shoulder
  – Used QMC proportions
• Performed trial batch
  – Box Test
• Placement went very well
• Average w/c 0.42
PEM Mix Design
Iowa DOT Current Practices QMC

- Strength – avg 640 PSI Flexural
- Volume of Paste = 24.3%
- w/c Ratio = 0.42 max.
- Air Content 6 to 10%
- SAM Results all below 0.30
- Ca Oxychloride Limit = 0.15 g/100g
- Formation Factor ~ 1000
  - 20% C ash
- Aggregates – Iowa DOT Methods
- Workability Good
  - Combined Aggregate Grading
QMC vs PEM - What We Learned

- FHWA Mobile Concrete Lab closeout session
- Current QMC practices pretty good
- Possibly add resistivity testing
- Investigate Reduced Cement Mixes
### 2019 PROJECT AVERAGES

<table>
<thead>
<tr>
<th>Location</th>
<th>SAM #</th>
<th>BOX #</th>
<th>W/C</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polk I35</td>
<td>0.23</td>
<td>1.2</td>
<td>0.39</td>
<td>11.89</td>
</tr>
<tr>
<td>Harrison I29</td>
<td>0.22</td>
<td>1.1</td>
<td>0.40</td>
<td>15.67</td>
</tr>
<tr>
<td>Black Hawk US 20</td>
<td>0.18</td>
<td>1.4</td>
<td>0.40</td>
<td>7.15*</td>
</tr>
<tr>
<td>Plymouth US 75</td>
<td>0.20</td>
<td>1.3</td>
<td>0.40</td>
<td>12.64</td>
</tr>
</tbody>
</table>

*Aggregates with high absorption affect results*
2019 I-29 Harrison County

- With success of reduced cement mix in 2018
- Trial reduced cement mix on I-29 outside shoulder
  - 10ft wide, 11 inch thick
  - Mainline 24’ & Inside 6’
  - Shoulder paved integral
- Trial Batch
  - Box Test & SAM Test
# 2019 I-29 Harrison County Shoulders

## A-6-C20 Mix

<table>
<thead>
<tr>
<th>Component</th>
<th>Abs. Vol.</th>
<th>lbs/CY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT</td>
<td>0.092</td>
<td>463</td>
</tr>
<tr>
<td>FLY ASH</td>
<td>0.027</td>
<td>116</td>
</tr>
<tr>
<td>WATER: w/c=0.474</td>
<td>0.163</td>
<td>274</td>
</tr>
<tr>
<td>FINE AGGREGATE:</td>
<td>0.395</td>
<td>1744</td>
</tr>
<tr>
<td>COARSE AGGREGATE:</td>
<td>0.263</td>
<td>1188</td>
</tr>
<tr>
<td>INTERMEDIATE AGG.:</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AIR:</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

Paste Content, %: 28.2

## PEM Mix – I-29 Shoulders

<table>
<thead>
<tr>
<th>Component</th>
<th>Abs. Vol.</th>
<th>lbs/CY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT</td>
<td>0.077</td>
<td>387</td>
</tr>
<tr>
<td>FLY ASH</td>
<td>0.022</td>
<td>97</td>
</tr>
<tr>
<td>WATER: w/c=0.419</td>
<td>0.120</td>
<td>203</td>
</tr>
<tr>
<td>CI. V AGGREGATE (55%):</td>
<td>0.399</td>
<td>1761</td>
</tr>
<tr>
<td>COARSE AGGREGATE (45%):</td>
<td>0.327</td>
<td>1476</td>
</tr>
<tr>
<td>INTERMEDIATE AGG.:</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AIR:</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

Paste Content, %: 21.9

579 lbs vs. 484 lbs
2019 I-29 Harrison County Shoulders

A-6-C20
- 579 lbs/cy
- Avg w/c ratio = 0.392

PEM
- 484 lbs/cy
- Avg w/c ratio = 0.413

- Mainline 2020 decided to increase cement content due to w/c ratio
  - Later, found out a water reducer was not included in the mix.
# I-29 Harrison QMC vs PEM

<table>
<thead>
<tr>
<th></th>
<th>QMC Mix Design 2019</th>
<th>Weight (lbs/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash Grove IP Cement</td>
<td></td>
<td>426</td>
</tr>
<tr>
<td>Nebraska City Fly Ash (20%)</td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>Weeping Water CA (45%)</td>
<td></td>
<td>1427</td>
</tr>
<tr>
<td>N. Valley Cl. V. Aggregate (55%)</td>
<td></td>
<td>1708</td>
</tr>
<tr>
<td>Water (basic w/c=0.40) 0.42 max</td>
<td></td>
<td>213</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>PEM Mix Design 2020</th>
<th>Weight (lbs/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash Grove IP Cement</td>
<td></td>
<td>399</td>
</tr>
<tr>
<td>Nebraska City Fly Ash (20%)</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Ft. Calhoun CA (45%)</td>
<td></td>
<td>1441</td>
</tr>
<tr>
<td>N. Valley Cl. V. Aggregate (55%)</td>
<td></td>
<td>1752</td>
</tr>
<tr>
<td>Water (basic w/c 0.40, 0.42 max)</td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

533 lbs vs 499 lbs
I-29 Harrison QMC vs PEM

- Trail batch 2020 mix for mainline
- Mixed at plant and hauled to grade
- Paving began after trial batch
- 2019 – wet conditions
- 2020 – hot, dry
I-29 Harrison QMC vs PEM

Average Project Workability Factor VS Coarseness Factor

QMC 2019

Average Project Workability Factor VS Coarseness Factor

PEM 2020

ZONE PAY: REFER TO SUPPLEMENTAL SPECIFICATION
I-29 Harrison QMC vs PEM

Tarantula Curve Combined Aggregate Gradation, % Retained
QMC 2019

Tarantula Curve Combined Aggregate Gradation, % Retained
PEM 2020
I-29 Harrison QMC vs PEM

Control Chart for Water to Cementitious Ratio
QMC Harrison I-29

Control Chart for Water to Cementitious Ratio
PEM Harrison I-29
I-29 Harrison QMC vs PEM
I-29 Harrison QMC vs PEM
I-29 Harrison QMC vs PEM

Iowa PEM Resistivity - Harrison I-29 QMC 2019

Iowa PEM Resistivity - Harrison I-29 PEM 2020

>20.7 Very Low
I-29 Harrison QMC – PEM Summary

• Average w/c ratio
  – QMC 2019 = 0.396
  – PEM 2020 = 0.390.

• Smoothness-Zero Band
  – QMC 2019 24.87 in/mi
    • 58.4% Max possible Incentive
  – PEM 2020 19.26 in/mi
    • 72.7% Max possible Incentive
Summary

• Iowa QMC Mixes comparable with PEM Mix
• PEM testing helped validate reduced cement content QMC mixes (QMPEM)
  – 0.099 Abs Vol Cement – (1\textsuperscript{st} Iteration)
    • 524 lbs/cy Type I/II
    • 517 lbs/cy Type IS(20)
    • 499 lbs/cy Type IP(25)
  – Trial Mix Design - SAM Air Test and Box Test
  – \textbf{QC} Testing - SAM Meter 1/day, Box Test – 1/day, Resistivity if available
• Influence of Aggregate Shape on cement content
Influence of Aggregate Shape

US 20 Project

I-29 Project

???
PEM - Future

- Continue gather data on SAM testing, workability, resistivity, etc.
- Get a SAM Meter and practice using
  - Purchase
  - FHWA or ICPA equipment loan
- Box Test – Build box
  - Vibrator requirements
- Investigate lower cement mix with other aggregate combinations
- Eventually, modify QMC DS
Thank You!