Aggregate Optimization

Quality Assurance Workshop
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Outline

• Background on Aggregate Optimization
• Utilization of Optimized Aggregate Mixes
• PennDOT Pro Team Study
• Field Data
• Specification
Background

Evaluating the overall particle size distribution of a concrete mix.

Aggregate optimization really gained traction in the 1980’s when Shilstone developed various metrics to evaluate the optimal aggregate curves.

Coarseness Factor Chart
Power 45 Curve
Combined % Retained
Updated Tarantula Curve
Control Charts

- Graphic Illustrations that track aggregate gradation
- Used to control blends
- Visually optimizing aggregate proportions within a mix design
Power 45 Chart

Cumulative % Passing (y-axis) vs. Sieve Sizes ^0.45 (x-axis)

Maximum Density Line = (individual sieve size / nominal maximum sieve size) ^0.45
Coarseness Factor

Coarseness Factor = (cumulative % retained 3/8” sieve / cumulative % retained on #8 sieve)

Workability Factor = cumulative combined % passing #8 sieve +/- 2.5% for every 94 lbs/cyd cement above or below 564 lbs/cyd
Combined Percent Retained

Sum of the % Retained on adjacent sieves, excluding the first and last sieve.
Combined Percent Retained – Tarantula Curve

Sum of the % Retained on adjacent sieves, excluding the first and last sieve.

Adjustments made in the combined % retained tolerances.
Utilization of Charts in DESIGN

• Designing a mix to utilize optimum aggregate blend

• Charts provide graphic illustration of blend.

• MANY other variables and considerations during mix design development.

• Changes in aggregate blends & proportions change other aspects of a design and should be considered.
  
  • Coarse aggregate volume (pumping or paving)

  • Paste volume

  • Aggregate surface area

  • Paste to sand ratio (mortar fraction)

  • Overall mix rheology
Utilization of Charts in PRODUCTION

- Provide quick indication as to how well the mix is blended based on design.

- Chart and track gradation blends.

- Minor adjustments to blends as gradations fluctuate before production.
Benefits of Aggregate Optimization

- Improved Workability
  - Water Reduction
  - Improved Consolidation
  - Reduction in Vibration Effort
- Reduced Paste Content
  - Reduction in Shrinkage & Propensity to Crack
  - Reduction in Permeability
  - Reduction in Heat of Hydration
- Increase in compressive strength
  - Paste efficiency by increased surface area
Water Demand with Aggregate Optimization

- Basic study by adding a % of #8s
- Total Cementitious Constant
- W/C Ratio Constant
- Coarse Agg Volume Constant
- Increased % of #8 Gravel, reducing #67 Gravel volume
- Slump increased until optimum concentration reached, then dropped.
- Compressive strengths improved slightly.
- Result - Increased slump by 1" without the addition of water, only the addition of 20% #8 Gravel.
Aggregate Gradations – 20% Shot Gravel

- Taking the mix that gave us the best water reduction

- We can see it falls in the well graded side of the coarseness factor chart

- Falls inside of the Tarantula Curve
Compressive Strength with Aggregate Optimization

• Using the same study...

• Target consistent slump by reducing water content.

• Reducing W/C Ratio

• Thus increasing compressive strength accordingly.
Commercial Applications

• Warehouse floors

• Driveways

• Standard for majority of flatwork

• Compressive strength ranges 3,000psi and up
PennDOT Pro-Team

- To determine the cause of cracking through the investigation of concrete bridge deck…

- DESIGN
- CONSTRUCTION
- MATERIALS
Bridge Deck Cracking

- Pro-Team comprised of Pennsylvania Aggregate and Concrete Association (PACA) Technical Committee Members

- Pro-Team to continue the developments set forth with AAAP and determine additional design considerations to improve the performance of the materials

- Main focus was Aggregate Optimization
Aggregate Blending

Develop a mix utilizing the optimum particle size distribution for various aggregate sizes.

Adjust weights and blends to fit targeted control charts.

Test several mixes and blends.

Also run high cement mixes to compare shrinkage improvements.
ASTM C 1581

Restrained Ring Test
ASTM C 1581 - Restrained Ring Test

- Test method is used for determining the crack potential of concrete mixtures with aggregate under $\frac{1}{2}$” in size.

- Difficult to find testing equipment.

- Only evaluate concrete with $\frac{1}{2}$” and smaller aggregate.

- We decided to build the ring molds at our machine shop per ASTM material Standards.

- Needed to make testing modifications to accommodate larger aggregate sizes.
Modification to ASTM C 1581

The outside ring diameter per the specifications is 16 +/- 0.12 inches which matches 80-16 PVC Pipe

The ASTM specifies that the largest aggregate to be used with the test method is 1/2”

We decided to increase the outer ring diameter to 20” to accommodate standard #57 aggregate (provided 3” annular space).

Also added “control” joints to increase the rings propensity to crack.

We initially found it was taking too long to crack and we weren’t able to get enough data in a reasonable amount of time.
ASTM C 1581 - Restrained Ring Test

CURING MODIFICATION:

- Moist cured in molds for 24 hours (burlap & plastic)
- Remove outer ring after 24 hours
- Seal top surface with foil tape or wax
- Cure in environmentally controlled room
  
  73.5 +/- 3.5 degrees F

  50 +/- 4% relative humidity
ASTM C 1581 - Restrained Ring Test

Strain gauges are attached to inside of steel ring.

Monitor strain in the steel caused by shrinkage of concrete.

Strain reading normalized at start of test.

Heat of hydration causes steel to expand showing positive strain.

Then compresses as concrete shrinks

Until cracking occurs.
Ring Testing - Humidity Controlled Room
Data Acquisition

Strain gauges and thermocouples attached to interior of steel ring

Data transmitted through 9-pin jack to data logger to be stored
Data Acquisition

Data transmitted through 9-pin jack to data logger to be stored

Downloaded into spreadsheet at set intervals
Mix Designs
Induced drying in humidity controlled room after 24 hours.
ASTM C 1581 - Restrained Ring Test

Results Gathered:

Age at Cracking – Day at which cracking occurs, TOC (day)
Initial Strain – Initial strain reading when drying begins, $\mu \varepsilon$
Maximum Strain – Strain when concrete cracks, $\mu \varepsilon_{\text{max}}$
Net Strain, $\varepsilon_{\text{net}}$ – Difference between strain at time t and initial strain
Strain Rate Factor, $\alpha$ = Rate of strain (in/in)/day
Stress rate, $q$ – Stress rate at cracking (psi/day)
ASTM C 1581 -
Restrained Ring Test

Strain development over time
ASTM C 1581 -
Restrained Ring Test

Strain Rate Factor

\[ \alpha = \text{Rate of strain} = \mu \varepsilon_{\text{net}} \text{ (in/in)/day} \]

Calculated by \[ \varepsilon_{\text{net}} = \alpha \sqrt{t} + k \]

Linear regression analysis of net strain vs. square root of elapsed time.

\[ S = \sum \left( y_i^{\text{th}}(a,b) - y_i^{\text{obs}}(a,b) \right)^2 \]
\[ S = \sum (a + bx_i - y_i)^2 \]

Least squares curve fit is defined as the process of obtaining the best description of data in terms of some theory, involving parameters or variables that are initially unknown.
ASTM C 1581 - Restrained Ring Test

Results:

Time of Crack (TOC, hours or days)

Stress rate, \( q \) – Stress rate at cracking.

\[
q = \frac{G |\alpha_{\text{avg}}|}{2 \sqrt{t_r}}
\]

- \( q \) = stress rate (psi/day)
- \( G \) (constant) = 10.47 x 10^6 psi
- \( |\alpha_{\text{avg}}| \) = absolute value of avg strain rate factor (in/in)/ day
- \( t_r \) = elapsed time at cracking (day)
Results

Mix Designs & Data
### Mix Designs

<table>
<thead>
<tr>
<th>Mix Name</th>
<th>Cement (lbs)</th>
<th>GGBFS (lbs)</th>
<th>#57 CA (lbs)</th>
<th>#8 CA (lbs)</th>
<th>CA Volume (cf)</th>
<th>W/C Ratio</th>
<th>28 Day (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAAP Std</td>
<td>390</td>
<td>210</td>
<td>1769</td>
<td>0</td>
<td>10.50</td>
<td>0.45</td>
<td>6,750</td>
</tr>
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<td>AAA Blend</td>
<td>390</td>
<td>210</td>
<td>1598</td>
<td>167</td>
<td>10.50</td>
<td>0.45</td>
<td>7,110</td>
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<tr>
<td>AAAP Opt</td>
<td>390</td>
<td>210</td>
<td>1691</td>
<td>200</td>
<td>11.25</td>
<td>0.45</td>
<td>7,310</td>
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<tr>
<td>AAAP Max</td>
<td>690</td>
<td>0</td>
<td>1769</td>
<td>0</td>
<td>10.50</td>
<td>0.45</td>
<td>6,440</td>
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<tr>
<td>AAAP High</td>
<td>800</td>
<td>0</td>
<td>1769</td>
<td>0</td>
<td>10.50</td>
<td>0.45</td>
<td>7,010</td>
</tr>
</tbody>
</table>
Restrained Shrinkage

High Cement Mixes

- AAAP High Cement 800#
- AAAP Max Cement 630#
- AAAP
Free Shrinkage

Free Shrinkage - ASTM C 157
High Cement Mix Designs
(Modified Curing)

- AAAP Standard
- AAAP Max Cement
- AAAP High Cement
- Maximum

Free Shrinkage (micro-strain)

Time (days)
Restrained Shrinkage
Free Shrinkage - ASTM C 157
Aggregate Optimized Mix Designs
(Modified Curing)

Free Shrinkage (micro-strain) vs. Time (days)

- AAAP Standard
- Poly. (AAAP Standard)
- AAAP Blend
- Poly. (AAAP Blend)
- AAAP Optimized
- Poly. (AAAP Optimized)

- Maximum
PennDOT Deck Survey

Bridge Deck Crack Performance
PennDOT Bridge Deck Survey

Measure:

Weighted crack spacing based on total deck area and total crack length.. (YDS / SY)

Average spacing between cracks (YDS)
## PennDOT Bridge Deck Survey – Preliminary Results

Simple Span Decks – Averaging 64 feet

<table>
<thead>
<tr>
<th>Location</th>
<th>Mix Design Specification</th>
<th>Initial Cracking Metric</th>
<th>One Year Cracking Metric</th>
<th>Avg. Crack Spacing</th>
<th>One Year Avg. Crack Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statewide</td>
<td>AAA</td>
<td>0.200</td>
<td>0.087</td>
<td>5</td>
<td>11</td>
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<tr>
<td>Statewide</td>
<td>AAAP</td>
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<td>25</td>
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<tr>
<td>Statewide</td>
<td>SSP-1</td>
<td>0.0028</td>
<td>NA</td>
<td>356</td>
<td>NA</td>
</tr>
<tr>
<td>Statewide</td>
<td>SSP-2</td>
<td>0.000</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
### PennDOT Bridge Deck Survey – Preliminary Results

**Continuous Span Decks – Averaging 164 feet**

<table>
<thead>
<tr>
<th>Location</th>
<th>Mix Design Specification</th>
<th>Initial Cracking Metric</th>
<th>One Year Cracking Metric</th>
<th>Avg. Crack Spacing</th>
<th>One Year Avg. Crack Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statewide</td>
<td>AAA</td>
<td>0.054</td>
<td>0.200</td>
<td>19</td>
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<td>NA</td>
<td>356</td>
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<tr>
<td>Statewide</td>
<td>SSP-2</td>
<td>0.000</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
AAA to AAAP

Improvements over AAA Concrete

- Reduced total Cementitious
- Required the use of a pozzolan
- Reduced Permeability
- 14 day Wet Cure

Improvements over AAAP Concrete

- Utilized Aggregate Optimization
Improving AAAP with Aggregate Optimization

Improvements over AAAP Concrete

- Utilizing control charts to optimize aggregate blend
- 500 micro strain Free Shrinkage limit
- Should see better workability in the field
- Should see better consolidation in the field.
Specifying Aggregate Optimization

The aggregate optimization charts should be used as targets.

Aggregates based on locally available materials.

Balanced with job applications, pumping/paving.

Cost components.
Moving Forward…

Continue to investigate concrete properties and their effects on shrinkage.

Evaluate curing practices in relation to shrinkage and long term durability.

PennDOT continue to monitor in place decks.

Continue to monitor the deck placements with new specification statewide.
QUESTIONS