OPTIMIZED GRADATION FOR CONCRETE PAVING MIXTURES

BEST PRACTICES WORKSHOP
Outline

• Concrete 101

• Optimized Gradation
  ➢ Why should I care?
  ➢ What is it?

• Historical Perspective

• Best Practices

• Conclusions
Concrete 101

- Typical concrete proportions (by volume) (non-optimized)

- Paste (35%)
  - Air (6%)
  - (16%) Water

- Mortar (61%)
  - Fly Ash (3%)
  - Portland Cement (10%)

- Coarse Aggregate (40%)

- Fine Aggregate (26%)
Concrete 101

• Quality measurements related to optimized gradation
  ➢ Strength
  ➢ Thickness
• Achieving average specified flexural strength is important for a given thickness

Concrete 101

- Quality measurements related to optimized gradation
  - Air content – freeze-thaw resistance
Concrete 101

• Quality measurements related to optimized gradation
  ➢ Permeability - the ease with which fluids can penetrate concrete

• Most durability damage is governed by permeability of the paste
  ➢ Optimize paste volume
  ➢ Use low w/cm
  ➢ Use SCMs
  ➢ Cure
  ➢ Minimize cracking
Optimized Gradation

• What is it?
  ➢ Economically combining aggregate particles to achieve the desired objectives of:
    ➢ Appropriate workability
    ➢ Reduced paste content
    ➢ Required hardened properties
Optimized Gradation

• Why should I care?
  ➢ Durability – long life pavements have high quality and optimized paste contents, which is partially achieved through an optimized gradation approach
Optimized Gradation

• Why should I care?
  ➢ Durability – long life pavements have high quality and optimized paste contents, which is partially achieved through an optimized gradation approach

• Paste quantity
  ➢ Low permeability
    ➢ Optimized gradation requires less paste for a given workability target
Optimized Gradation

• Why should I care?
  ➢ Workable mixture
    ➢ Responds to vibration without segregation
    ➢ Holds an edge
    ➢ Minimal surface voids
Optimized Gradation

• Why should I care?
  ➢ Smoothness
  ➢ Reduced hand finishing
  ➢ Stable edge
  ➢ Uniform response to vibration
Optimized Gradation

• Why should I care?
  ➢ Economics?
  ➢ Lowest material cost?
    – Cementitious content should be reduced, this can offset increased aggregate costs
  ➢ Reduced labor – finishing, re-work and grinding
  ➢ Life-cycle cost
Optimized Gradation

• Why should I care?
  ➢ Sustainability
    ➢ Reduced paste content (cement)
    ➢ Longer life
“We frankly doubt that concrete of the same 28-day strength made with modern materials will always perform as well (as concrete made 15 years ago).”

*Powers, PCA SN 1099, 1934*
• 1960s interstate era – PCC was the predominant paving material
  ➢ Two aggregate system (coarse and fine) - for the most part, uniformly graded
  ➢ Mixed on grade
Optimized Gradation – Historical Perspective

• Post interstate era
  ➢ Intermediate particles (3/8” to #8) scalped for use in other products
  ➢ “Gap graded” mixtures were common
    ➢ Highly responsive to vibration
    ➢ Increased risk of segregation
    ➢ Increased risk of vibrator trails
  ➢ Slipform paving with high energy vibrators became common
Optimized Gradation – Historical Perspective

• Fast forward to late 1980s
  ➢ The PCC paving industry began listening to Jim Shilstone’s approach to combined gradation
  ➢ Coarseness and workability factor
  ➢ Percent retained
  ➢ 0.45 power chart
Optimized Gradation – Historical Perspective

- Coarseness and workability factors

Coarseness Factor = \[
\frac{\% \text{ Retained Above } 3/8'' \text{ Sieve}}{\% \text{ Retained Above } \#8 \text{ Sieve}} \times 100
\]

Workability Factor = \% \text{ Passing } \#8 \text{ (+2.5\% for every 94 lb/yd}^3\text{ over 564 lb/yd}^3\text{)}

![Shilstone Chart](image-url)
Optimized Gradation – Historical Perspective

- Percent retained on individual sieves
Optimized Gradation – Historical Perspective

- 0.45 power chart

![0.45 Power Curve](image)
Optimized Gradation – Historical Perspective

- Shilstone’s approach has been an improvement, but …
  - Focuses on 3/8” to #8
  - Aimed at preventing segregation
  - Lack of definitive rules for interpreting the graphical output
  - Some mixtures that plot in zone 2 have still been problematic
Optimized Gradation – Best Practices

- The “Tarantula” curve, the latest development in optimized grading for slipformed concrete pavements
- Developed by Dr. Tyler Ley and others

Cook, Ghaeezadah, Ley
Optimized Gradation – Best Practices

• Remember the purpose of optimized gradation:
  ➢ Economically combining aggregate particles to achieve the desired objectives of:
    ➢ Reduced paste content
    ➢ Desired workability
    ➢ Required hardened properties
• The Tarantula curve was developed concurrently with a lab test that evaluates a concrete mixture’s response to vibration

Following slides from Tyler Ley, Oklahoma State University
Optimized Gradation – Best Practices

• Needed 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 an edge (cohesiveness)
• The box test was born out of this need

Optimized Gradation – Best Practices

• 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 sides of the box are then removed and inspected for honeycombing or edge slumping
Optimized Gradation – Best Practices

- Visual rating of surface voids and edge slumping
  - A rating of 3 or 4 is considered undesirable
  - Excessive edge slumping with any rating is considered undesirable
  - The box test evaluates the response of a concrete mixture to vibration and its ability to hold an edge
  - It has compared well with field performance

<table>
<thead>
<tr>
<th>Rating</th>
<th>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>
Optimized Gradation – Best Practices

- Low amounts of water reducer indicate a good mixture
- High amounts indicate an undesirable combined gradation
- Quantify how WRA dosage demand varies with changes in the combined gradation
Optimized Gradation – Best Practices

• In the beginning, ...
  ➢ Lab evaluation of multiple mixtures
  ➢ Focused first on Zone II of the coarseness factor chart
Optimized Gradation – Best Practices

• Typical mixture used in the laboratory studies
  ➢ 0.45 w/cm
  ➢ 5 sacks total cementitious
  ➢ 20% fly ash
  ➢ Single sand source
  ➢ 3 crushed limestones
    ➢ Limestone A
    ➢ Limestone B
    ➢ Limestone C
Optimized Gradation – Best Practices

- Limestone A

![Graph showing gradation analysis for Limestone A with various sieves and percentage retained.

Key points:
- Middle of Shilstone
- Bottom of Shilstone
- 60%CA, 40%FA
- Left of Shilstone
- Min Boundary
- Max Boundary

Notations:
- 17.1
- 12.7
- 16.1
- 8.3 oz/cwt

WR dosage to pass the box test

Sieve No.:
- #200
- #100
- #50
- #30
- #16
- #8
- #4
- 3/8"
- 1/2"
- 3/4"
- 1"
- 1.5"

% Retained:
- 35%
- 30%
- 25%
- 20%
- 15%
- 10%
- 5%
- 0%
Optimized Gradation – Best Practices

- Box test results vary significantly for mixtures that plot in the same area of the coarseness factor chart.
- The coarseness factor chart is not a reliable indicator of response to vibration and ability to hold an edge.
• What about the Haystack?
• Box test results are no better than for a typical mixture
Optimized Gradation – Best Practices

- Focus on the combined percent retained chart
Optimized Gradation – Best Practices

• Sieve limestone A to match the gradation of limestone C
• The percent retained on each sieve chart provides improved feedback over the coarseness factor chart
Optimized Gradation – Best Practices

- What about fine aggregate?
Optimized Gradation – Best Practices

• And coarse aggregate?
Optimized Gradation – Best Practices

• Defining coarse sand (between the #4 and #30) and fine sand (finer than the #30)
• ACI 302.1R-04 recommends the sum of material retained on the #8 and #16 sieves should be a minimum of 13% to avoid edge slumping
• Determine how fine aggregate gradation impacts the box test:
  ➢ Remove all coarse sand (#30 to #4)
  ➢ Test multiple mixtures
    ➢ All fine sand
    ➢ Multiple mixtures with slowly increasing amounts of coarse sand
Optimized Gradation – Best Practices

• Fine aggregate impacts
  ➢ #8 and #16 tend to cling to coarse aggregate particles, improving cohesion and stability of the mixture
  ➢ Reduced edge slumping
  ➢ Improved response to vibration
Optimized Gradation – Best Practices

• Given that coarse sand (#30 to #4) improves the mixture, how much is enough?
  ➢ A minimum of 15% cumulative retained on the #8-#30 sieve sizes is suggested
  ➢ The #8 and #16 should be limited to 12% to minimize finishing issues
Optimized Gradation – Best Practices

- Determine how fine aggregate gradation impacts the box test:
  - Keep the ratio of coarse and fine sand constant
  - Vary the gradation of the fine sand

![Graph showing aggregate gradation](image-url)
• Determine how fine aggregate gradation impacts the box test:
  ➢ Vary the fine sand (#30 to #200) while holding the #16 through 1” constant
Optimized Gradation – Best Practices

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Optimized Gradation – Best Practices

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  - Vary the fine sand (#30 to #200) while holding the #16 through 1” constant
Optimized Gradation – Best Practices

• The distribution of fine sand can vary largely without affecting the workability.
• An aggregate volume between 24% to 34% is recommended for #30 - #200.
• This range was similar for multiple gradations and aggregate sources
• More than 20% retained on the #30 sieve size created finishing issues
Optimized Gradation – Best Practices

• The Tarantula curve

Excessive amount that decreases workability and promotes segregation and edge slumping.

Not in Scope of work

Excessive amount creates workability issues.

Creates surface finishability problems normally associated with manufactured sands.

Greater than 15% on the sum of #8, #16, and #30
24-34% of fine sand (#30-200)

Sieve No.

#200 #100 #50 #30 #16 #8 #4 0.375 0.5 0.75 1 1.5
• Tarantula Curve validation
  ➢ MNDOT implements a combined gradation specification in the late 1990s (incentive for Zone II) (data from Maria Masten)
Optimized Gradation – Best Practices

• Tarantula Curve validation
  ➢ Through trial and error, contractors independently validated the Tarantula curve by honing in on mixtures that fit within the recommended limits (data from Maria Masten)

Minnesota 2009
87% of mixtures met the sand criteria
Optimized Gradation – Best Practices

• With added experience, the field mixtures continue to be refined and further reflect the Tarantula curve recommendations.
Concrete 101

• Typical concrete proportions (by volume)
**Aggregate System**

- 50/50 – void ratio 27.1%
- Tarantula – void ratio 25.3%
Proposed Mixture Proportioning Procedure

Put it all together

<table>
<thead>
<tr>
<th></th>
<th>Tarantula</th>
<th>50/50</th>
<th>50/50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void ratio</td>
<td>125</td>
<td>150</td>
<td>125</td>
</tr>
<tr>
<td>Cementitious</td>
<td>427</td>
<td>505</td>
<td>424</td>
</tr>
</tbody>
</table>

![Graph showing V Kelly vs. Vp/Vv]
Optimized Gradation – Best Practices

• Strength will not be adversely affected
  ➢ 338 lb/yd³ of portland cement
  ➢ 85 lb/yd³ of fly ash

• Still have to do trial batches

<table>
<thead>
<tr>
<th>Source</th>
<th>7 Day Strength</th>
<th>28 Day Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min-Max (psi)</td>
<td>Average (psi)</td>
</tr>
<tr>
<td>Limestone A</td>
<td>4000-6320</td>
<td>5180</td>
</tr>
<tr>
<td>Limestone B</td>
<td>4990-5270</td>
<td>5130</td>
</tr>
<tr>
<td>River Rock</td>
<td>3990-4850</td>
<td>4440</td>
</tr>
</tbody>
</table>
Optimized Gradation – Best Practices

• Putting optimized gradation into practice
  ➢ Specifications
    ➢ Aggregate grading – modify as needed to allow use of the Tarantula curve
    ➢ Control paste volume
      – Cementitious content
      – Maximum w/cm = 0.42
Optimized Gradation – Best Practices

• Putting this into practice
  ➢ Plant production
  ➢ Stockpile management – minimize segregation
  ➢ Aggregate stockpile moisture content
  ➢ Multiple aggregate bins
  ➢ Thorough mixing
Optimized Gradation – Best Practices

• Conclusions
  ➢ Optimized gradation is one tool helping to produce durable concrete
    ➢ Reduced paste content
    ➢ Improved workability
  ➢ The box test evaluates a mixtures response to vibration and ability to hold an edge
  ➢ The Tarantula curve was developed in parallel with the box test
  ➢ The Tarantula curve has been independently validated by contractors who have been developing optimized mixtures since the late 1990s
Questions and Discussion