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

• Portland Cement Concrete
  ➢ A hard strong building material made by mixing a cementing material (as portland cement) and a mineral aggregate (as sand and gravel) with sufficient water to cause the cement to set and bind the entire mass (Merriam-Webster.com).
Concrete 101

• Materials used in portland cement concrete (PCC)
  ➢ Hydraulic cement – reacts with water
Concrete 101

• Materials used in portland cement concrete (PCC)
  ➢ Supplementary cementitious materials
    ➢ Fly ash
      – Class C
      – Class F
    ➢ Slag cement
    ➢ Natural pozzolan
Concrete 101

- Materials used in portland cement concrete (PCC)
  - Admixtures
    - Air entrainers
    - Water reducers
    - Retarders
    - Accelerators

![Concrete Diagram](image)
Concrete 101

• Materials used in portland cement concrete (PCC)
  ➢ Water
Concrete 101

• Materials used in portland cement concrete (PCC)
  ➢ Aggregates – coarse and fine
  ➢ Can influence the following concrete properties:
    ➢ Durability
    ➢ Workability
    ➢ Dimensional changes
    ➢ Strength
Typical concrete proportions (non-optimized)
- 6.5 sacks of cementitious materials (611 lb/yd$^3$)
- 6% air
- 0.45 water:cementitious materials ratio (275 lb/yd$^3$)(33 gal)
- 60% coarse aggregate (1,800 lb/yd$^3$)
- 40% fine aggregate (1,200 lb/yd$^3$)
Concrete 101

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

Diagram:
- Paste (35%)
  - Portland Cement (10%)
  - Fly Ash (3%)
  - Air (6%)
  - Water (16%)
- Mortar (61%)
  - Fine Aggregate (26%)
  - Coarse Aggregate (40%)
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
• 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?

• Paste quality
  ➢ Low permeability
    ➢ W/CM less than or equal to 0.42
    ➢ Use of SCMs
  ➢ Air entrained – Minimum of 5% behind the paver
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
Optimized Gradation – Historical Perspective

• 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 = \( \frac{% \text{Retained Above 3/8" Sieve}}{% \text{Retained Above #8 Sieve}} \times 100 \)

Workability Factor = % Passing #8 (+2.5% for every 94 lb/yd\(^3\) over 564 lb/yd\(^3\))
Optimized Gradation – Historical Perspective

• Percent retained on individual sieves

![Theoretical "Haystack" Particle Distribution Graph]

- Combined Percent Retained
- Sieve Size:
  - 2½"
  - 2"
  - 1½"
  - 1"
  - ¾"
  - ½"
  - ¼"
  - #4
  - #8
  - #16
  - #30
  - #50
  - #100
  - #200

- Percent Retained:
  - 0%
  - 5%
  - 10%
  - 15%
  - 20%
  - 25%
  - 30%
Optimized Gradation – Historical Perspective

- 0.45 power chart
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
Optimized Gradation – Best Practices

• A 1” diameter stinger vibrator is inserted into the center of the box over a three count and then removed over a three count
Optimized Gradation – Best Practices

• The sides of the box are then removed and inspected for honey combing 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

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<tbody>
<tr>
<td>Rating</td>
<td></td>
<td></td>
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<tr>
<td>Voids</td>
<td>Over 50% overall surface voids.</td>
<td>30-50% overall surface voids.</td>
<td>10-30% overall surface voids.</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

[Diagram]

1. Mix Concrete
   - Conduct: Slump and Box Test
   - Did it Pass the Box Test?
     - No
       - Put Material Tested Back into Mixer.
       - Add WR and Remix
       - Conduct: Slump and Box Test
     - Yes
       - Testing Complete
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 sieve analysis with % Retained on the y-axis and Sieve No. on the x-axis. Key points highlighted: 17.1%, 12.7%, 16.1%, and 8.3 oz/cwt. WR dosage to pass the box test.]
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.
Optimized Gradation – Best Practices

- What about the Haystack?
- Box test results are no better than for a typical mixture
• 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?
• 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
Optimized Gradation – Best Practices

• 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
Optimized Gradation – Best Practices

• 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

- Determine how fine aggregate gradation impacts the box test:
  - Vary the fine sand (#30 to #200) while holding the #16 through 1” constant
• 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

- 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

• 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 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)

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

Not in Scope of work

Greater than 15% on the sum of #8, #16, and #30
24-34% of fine sand (#30-200)
• Tarantula Curve validation
  ➢ MNDOT implements a combined gradation specification in the late 1990s (incentive for Zone II) (data from Maria Masten)

1996-1998
• 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)
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)

### Non-optimized mixture
- **Portland Cement**: 10%
- **Fly Ash**: 3%
- **Air**: 6%
- **Water**: 16%
- **Fine Aggregate**: 26%
- **Coarse Aggregate**: 40%

### Optimized mixture
- **Portland Cement**: 7%
- **Fly Ash**: 2%
- **Air**: 6%
- **Water**: 11%
- **Combined Aggregate**: 74%
**Aggregate System**

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

Put it all together

<table>
<thead>
<tr>
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<th>Tarantula</th>
<th>50/50</th>
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<tbody>
<tr>
<td>Void ratio</td>
<td>125</td>
<td>150</td>
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<tr>
<td>Cementitious</td>
<td>427</td>
<td>505</td>
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<tr>
<td></td>
<td>125</td>
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[Graph showing V Kelly against Vp/Vv, with two lines representing different mixture proportions: G1.0 50 and G1.0 Tarantula.]
Optimized Gradation – Best Practices

• Strength will not be adversely affected
  ➢ 338 lb/yd$^3$ of portland cement
  ➢ 85 lb/yd$^3$ 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>
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<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>
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</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 mixture's 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