Development and Implementation of Aggregate Grading for Pavements

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Acknowledgements

- Oklahoma Department of Transportation (ODOT)
- Oklahoma Transportation Center
- CP Tech Center
- FHWA Highways for Life
Reoccurring Aggregate Questions:

• How do you proportion aggregate?
• Are packing models useful?
• Is one better than another?
• Do they provide practical answers?
“The role of the cement paste is to fill the voids between aggregates, to give a certain workability (like the grease in a ball bearing) and to bind the aggregate together when the past hardens.”

-Golterman, Johansen, Palbol 1997
Theory of Packing

• By reducing the voids between aggregates then we reduce the paste we need.
• While it is a good idea to reduce voids in a mixture, *we still need to have a mixture that is workable*. 
Packing Models

• Modified Toufar Method (2004)
  – Theoretical method that assumes spherical and monosized particles

• De Larrard (CPM) (1999)
  – Theoretical method that takes into account the actual packing, maximum packing density, and the wall effect of the container

• Specific Surface Area

• Combined dry-rodded unit weight
Graphical Methods

- Coarseness Factor
- Power 45
- Percent Retained
What part of a paver is the most critical for concrete consolidation?
• We want 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 a sharp edge (cohesiveness)
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>Description</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>
Edge Slumping

Bottom Edge Slumping

Top Edge Slumping
No Edge Slump  Edge Slump
Evaluating Mixtures with the Box Test

1. Mix Concrete
2. Conduct: Slump and Box Test
3. Did it Pass the Box Test?
   - Yes: Testing Complete
   - No: Put Material Tested Back into Mixer.
     - Add WR and Remix
     - Conduct: Slump and Box Test
Summary of the Box Test

• The box test evaluates the response of a concrete mixture to vibration and the ability to hold an edge.
• We did this because no other test exists that can tell us this information.
• Low amounts of water reducer is good
• High amounts are bad
Validation

- Single operator +/- 1.5 oz./cwt
- Multiple operators +/- 3.2 oz./cwt
- Same box test performance was found if the WR was added up front or if added in small dosages
- If the sample did not pass the box test within one hour it was discarded
- The box test has compared well with field paving mixes
Mixtures

- .45 w/cm
- 5 Sacks total cementitious (470 lbs)
- A single sand source
- 3 coarse and intermediate aggregates:
  - Limestone A
  - Limestone B
  - Crushed River Gravel
60/40 blend by volume

+ Minimum voids from Modified Toufar
+ Tight fit on Power 45
Coarseness Chart

- 3/4" Crushed Limestone A
- 3/4" Crushed Limestone B
- 3/4" River Rock
- 1.5" Crushed Limestone A
- 1.5" River Rock

Legend:
- ▲: 3/4" Crushed Limestone A
- ▼: 3/4" Crushed Limestone B
- □: 3/4" River Rock
- ×: 1.5" Crushed Limestone A
- ●: 1.5" River Rock

Boundary

Workability Factor (%) vs. Coarseness Factor (%) Chart

<table>
<thead>
<tr>
<th>Workability Factor (%)</th>
<th>Coarseness Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>37</td>
<td>41</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

Legend:

- I: 3/4" Crushed Limestone A
- II: 3/4" River Rock
- III: 1.5" Crushed Limestone A
- IV: 1.5" River Rock
- V: Boundary
Dry Rodded Unit Weight of Coarse and Fine

<table>
<thead>
<tr>
<th>WR (oz/100 cwt)</th>
<th>Void Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES!</td>
<td></td>
</tr>
<tr>
<td>NO WAY!</td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>YES!</td>
<td></td>
</tr>
</tbody>
</table>
Modified Toufar

WR (oz/100 cwt) vs Void Content (%)

- YES!
- NO!
- NO WAY!
Summary

• None of the following show good correlation to the box test results:
  – Voids content in the two packing models
  – Specific surface area
  – Voids content in the combined dry rodded unit weight
  – Location in the Coarseness Factor Chart
NO WAY!
NO!
The percent retained chart did a good job of indicating which gradation would have a good performance in the box test!

How about the Power 45?
Between 10 & 20 oz./cwt of WR
No!

Percent Passing (%) vs. Sieve Number (mm)

- Maximum Passing Boundary
- Maximum Density Line
- Minimum Passing Boundary
Lower than 10 oz./cwt of WR
Yes!
How can you tell the difference?
This helps a lot!
To better compare the performance we sieved the aggregates to have the exact same gradation.
Why is the WR dosage different?

Crushed Limestone A
Flat Shaped
Medium Angular
Medium Texture

Crushed Limestone B
Cubic Shaped
Medium Angular
Low Texture

Crushed Gravel
Slightly Flat Shaped
Low Angular
Low Texture

Crushed Limestone A
Flat Shaped
Medium Angular
Medium Texture

0.0 oz/cwt

3.0 oz/cwt

6.9 oz/cwt
While the individual percent retained chart did the best job of the techniques investigated, the aggregate flatness and texture plays a role in performance.
Use of the Box Test to Evaluate Gradations

- .45 w/cm
- 20% fly ash
- Three sand sources
- Used 5 coarse aggregates
  - Three limestones
  - Two river gravels
- All mixtures are 4.5 sack (423 lbs/cy)
Proportioning of Coarse to Intermediate

Stopped at 43
13.3
12.7
6.0
4.3
6.3
3.9
2.9
11.9

% Retained

Sieve No.

#200 #100 #50 #30 #16 #8 #4 3/8" 1/2" 3/4" 1" 1.5"
Proportioning Fine Aggregate

% Retained

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

Proportioning:

- 9.9
- 11.6
- 19.1
- 40.4
The **TARANTULA** curve!!!!

- Excessive amount creates workability issues.
- Creates surface finishability problems normally associated with manufactured sands.
- 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.

#30-#200 from 24 to 34%.
ASTM 4791

• Measures flatness, elongation, and overall shape of a particle.
• This is based off ratios such as 1:1, 1:3, or 1:5.
• A common limit is less than 15% on the 1:5 for flat, elongated, or flat & elongated.
ASTM D 4791 for Flatness of 1:2
Application

- Five different concrete producers have tried this system and all have seen improvements in their concrete.
- 10 miles of CRCP for the FHWA hfl project have been placed with this system in Texas.
- The contractors saw a 10% cost savings with a 25% reduction in the carbon footprint!
Minnesota Field Mixtures

- We tracked optimized graded concrete pavement mixtures from 1996 to 2010 in Minnesota
Minnesota 1996-1998

Percent Retained (%) vs. Sieve Number

Data from Maria Masten
Minnesota 2009
87% of mixtures met the sand criteria

Data from Maria Masten
Minnesota
2010
98% of mixtures met the sand criteria

Data from Maria Masten
Field Concrete

• Over time the contractors have iterated on their concrete pavement mixtures to improve them.
• They are doing this with trial and error and no knowledge of the Tarantula Curve
• The large majority of their mixtures are fitting within the Tarantula Curve.
Conclusions

• A single location or region on the Coarseness Factor chart, minimum voids content, or specific surface area does not predict the workability of a mixture with the box test and with these materials.

• The voids content and specific surface area may still be important. More research needs to be done.
Conclusions

• The individual percent retained chart was a useful tool to evaluate mixtures.
• The shape and texture of aggregates does have an impact on the workability.
• The Tarantula Curve seems to be a useful technique to determine an aggregate gradation
• The recommendations from the Tarantula Curve seem to match field performance of Minnesota pavement mixtures
Questions?

www.optimizedgraded.com

www.tylerley.com

May the Force be with you!!!!
What about Strength?

<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>

All mixtures had 4.5 sacks of total cementitious with 20% fly ash
More than 20 oz./cwt of WR
Reference