Manufactured Sand – Impacts on Concrete Pavement Design Inputs, Construction, and Predicted Performance

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Iowa Better Concrete Conference
November 14, 2019
Overview

1) Background
   – Drivers of increased manufactured sand (MS) use
   – Characteristics of MS vs. natural sand (NS)
   – Advantages and disadvantages of MS
   – State specifications regarding MS

2) North/South Carolina experience with MS in paving mixtures
   – Past / future projects
   – Forecast

3) NCDOT research on MS
   – new pavement design inputs
   – predicted performance

4) Closing thoughts/questions
Drivers of increased MS use

- Growing demand for fine aggregates
- Remote location of natural sand pits
- Issues with less-desirable NS sources (silts/clay)
- Issues with permitting new sand pits
- Environmental issues with dredging
- Increased emphasis on resource recovery and sustainability
- Risk and cost
Worldwide problem

- US sand and gravel market valued at $8.3B in 2015 (USGS)
- Global demand for sand expected to increase 5.5% per year 2014-2018 (Freedonia Group)
- China 1/5 of world sand imports, used more sand in last 4 years than US has in last century (UN Trade Statistics Branch, 2016)
- Illegal quarrying, mafia activities, removal of sand from beaches

Image: Police officer guarding quarry near Bogota, Colombia (Getty Images via BBC.com)
Worldwide problem

• UAE imported $456M of sand/stone/gravel in 2014
• Desert sand is too smooth!
• Burj Khalifa, Dubai, UAE – sand imported from Australia
Characteristics of MS

- MS is produced during crushing of rock for other products
  - Byproduct of coarse aggregate production
  - Can be viewed as a waste product
- Coarse aggregate production yields 25% to 45% fines/dust \(^{(Kaya \ et \ al. \ 2009)}\)
  - Parent rock
  - Crushing equipment - jaw, impact, roll crushers
  - Crushing conditions

- MS is often more angular
  - Higher water demand
  - Often requires increase in water/admixture dosage
  - Improved bond
  - Improved aggregate interlock
<table>
<thead>
<tr>
<th><strong>Opportunities/Advantages of MS</strong></th>
<th><strong>Drawbacks/Disadvantages of MS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td></td>
</tr>
<tr>
<td>• Cost is often lower than NS</td>
<td></td>
</tr>
<tr>
<td>• Often available closer to job</td>
<td></td>
</tr>
<tr>
<td>than NS, reducing hauling</td>
<td></td>
</tr>
<tr>
<td>costs</td>
<td></td>
</tr>
<tr>
<td><strong>Sustainability</strong></td>
<td></td>
</tr>
<tr>
<td><strong>(Environment / Community Impacts)</strong></td>
<td></td>
</tr>
<tr>
<td>• Reduced land use</td>
<td>• Energy consumption</td>
</tr>
<tr>
<td>• Use of waste/byproduct</td>
<td>associated with production</td>
</tr>
<tr>
<td>• Reduced emissions from hauling</td>
<td>(?)</td>
</tr>
<tr>
<td>• Reduced traffic from hauling</td>
<td></td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>• Increased water demand:</td>
</tr>
<tr>
<td></td>
<td>- decreased workability</td>
</tr>
<tr>
<td></td>
<td>- bleedwater issues</td>
</tr>
<tr>
<td></td>
<td>- finishability challenges</td>
</tr>
<tr>
<td>• MS is manufactured product –</td>
<td>• Potentially higher cement</td>
</tr>
<tr>
<td>QC ensures consistency</td>
<td>requirement if source</td>
</tr>
<tr>
<td>• Reduced potential for impurities</td>
<td>aggregate for MS is of</td>
</tr>
<tr>
<td>• Improved bond/interlock and</td>
<td>lower quality than NS</td>
</tr>
<tr>
<td>increased particle packing</td>
<td>• Potential impact on</td>
</tr>
<tr>
<td>potential</td>
<td>equipment</td>
</tr>
<tr>
<td>• Allows MS concrete to often</td>
<td>• Can reduce skid</td>
</tr>
<tr>
<td>obtain similar or improved</td>
<td>resistance, depending on</td>
</tr>
<tr>
<td>strength properties to NS</td>
<td>source</td>
</tr>
<tr>
<td>concrete</td>
<td></td>
</tr>
<tr>
<td>• Can provide reduced permeability and improved abrasion resistance</td>
<td></td>
</tr>
</tbody>
</table>
LIMESTONE SAND IN CONCRETE MIXTURES

Introduction

The use of stone sand as a fine aggregate in concrete has been in disfavor not only in Michigan, but where this material is available. The main objections to its use are reduced workability, excessive bleeding, and a tendency to produce scaling of pavement surfaces.

There has been a feeling on the part of certain sections of the available local sources of desirable natural stone sand to become depleted and because of the fact that there is a need for certain areas of Michigan, the Research Laboratory of the Michigan State Highway Department has been requested to study the advisability of using stone sand in concrete construction.

The purpose of the study is to establish future policies in regard to the use of stone sand as a fine aggregate in concrete construction.
State Specifications Regarding MS

• Many agencies do not allow MS in concrete
• Many agencies do allow MS in concrete

• Acceptance requirements for MS:
  – Some agencies allow MS if it meets requirements for NS
  – Often conformance to AASHTO M 6 is required
  – Some agencies require MS to come from an approved source
  – Some agencies provide enhanced testing for deleterious substances

• Use restrictions for MS
  – Some agencies do not allow MS on a frictional surface
  – Some agencies restrict certain types of MS to avoid polishing issues
Proposed (adopted today?)
Iowa DOT Specifications

Section 4110. Fine Aggregate for Portland Cement Concrete

4110.01 DESCRIPTION.
Natural sands resulting from disintegration of rock through erosional processes unless specified otherwise on the source approval. Acquire mineral aggregate from an approved source as described in Materials I.M. 409.

4110.02 GRADATION.
Meet the requirements for Gradation No. 1 of the Aggregate Gradation Table, Article 4109.02.

4110.03 QUALITY.
Meet the requirements of Table 4110.03-1:
A. The DME may approve a gravel source to allow up to 20 percent crushed particles in the fine aggregate with the concurrence of the Chief Iowa DOT Geologist. This allowance would require a new source approval with a revised target fineness modules.

Meet the following requirements:

- The proportioning must be through a controlled and measured process.

- The crushed material must be from an approved Class 3 or 3i source with not less than 70 percent igneous and metamorphic particles and meeting the requirements of Article 4115 of the Standard Specifications.

- The fine aggregate angularity as determined using AASHTO T 304 (modified) may not exceed 42%.

- The crushed fine aggregate must meet Gradation 1 and the fineness modules restrictions listed in this section.

- The crushed material must be compared to the uncrushed and tested using ASTM C 1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method) and shall not exceed the uncrushed results by 0.10% which is the Precision and Bias of the Test Method.
North/South Carolina Experience with MS in Paving Mixtures

Most NS pits
North Carolina DOT specifications

SECTION 1014
AGGREGATE FOR PORTLAND CEMENT CONCRETE

1014-1  FINE AGGREGATE

(A) General

Use fine aggregate from sources participating in the Department’s Aggregate QC/QA Program as described in Section 1006. A list of sources participating in the Department’s QC/QA Program in North Carolina and adjoining states is available from the Materials and Tests Unit.

Use fine aggregate consisting of natural sand or manufactured sand having clean, durable, hard, uncoated particles, or other inert materials having similar characteristics. Produce manufactured sand from fractured stone material. Use fine aggregate free from dirt, wood, paper, burlap and all other foreign material.

MS must meet same requirements as NS for:
- Soundness (AASHTO T 104, sodium sulfate, ≤ 15% loss)
- Clay content (sand equivalent, AASHTO T 176, min % specified in table)
- Deleterious materials (AASHTO T 112, ≤ 3%)
- Fine aggregate angularity (AASHTO T 304)
North Carolina DOT specifications

When natural sand is blended with natural sand, the blend shall meet the gradation for No. 2S fine aggregate. When manufactured sand is blended with natural sand or with manufactured sand, the blend shall meet the gradation for No. 2MS fine aggregate and neither component shall exceed the gradation limits on the No. 200 sieve shown in Table 1005-2.

<table>
<thead>
<tr>
<th>Std. Size #</th>
<th>3/8&quot;</th>
<th>#4</th>
<th>#8</th>
<th>#16</th>
<th>#30</th>
<th>#50</th>
<th>#100</th>
<th>#200</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>100</td>
<td>90-100</td>
<td>80-100</td>
<td>40-85</td>
<td>0-20</td>
<td>0-3</td>
<td></td>
<td>Blotting Sand, Asphalt Retreatment</td>
<td></td>
</tr>
<tr>
<td>2S</td>
<td>100</td>
<td>95-100</td>
<td>80-100</td>
<td>45-95</td>
<td>25-75</td>
<td>5-30</td>
<td>0-10</td>
<td>0-3</td>
<td></td>
</tr>
<tr>
<td>2MS</td>
<td>95-100</td>
<td>80-100</td>
<td>45-95</td>
<td>25-75</td>
<td>5-35</td>
<td>0-20</td>
<td>0-8A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4S</td>
<td>100</td>
<td>95-100</td>
<td></td>
<td>15-45</td>
<td>0-10</td>
<td>0-5</td>
<td></td>
<td>Mortar</td>
<td></td>
</tr>
</tbody>
</table>
North/South Carolina Experience with MS in Paving Mixtures

Greg Dean, Carolinas Concrete Paving Association

MS not preferred by contractors at this time however,
Contractors aware MS use is likely to be increasingly necessary

- Sometimes MS mixtures trial batched for comparison, not used
- MS mixtures used as 100% replacement in a few projects
- In one notable project MS mixture was initially used, contractor needed to switch to NS mixture due to workability/strength issues
- Combination of MS/NS mixtures used on a few Carolinas paving projects
  - Improves mixture economics and workability
Interview with QC Manager

- Contractor’s batch plant was basically on quarry site
- “MS was stupid cheap. There was no way we were NOT going to use it.”

- 100% MS mixture used
  - Higher water demand
  - More bleedwater
  - More difficult to finish
  - Strengths slightly lower than NS mixtures
  - “We made it work.”
I-85 Widening – Concord, NC

- 80 lane miles successfully completed
- Finishability may affect initial IRI
  - paving rate may have also played a role

- Adjacent I-485/85 interchange project
  - 100% NS
  - IRI 30-40 in/mile after first diamond grind

- I-85 Concord, NC widening project
  - 100% MS
  - IRI approx. 70 in/mile after first grind, needed some localized additional grinding
I-85 Widening – Concord, NC

Interview with Paving Superintendent

• Confirmed higher initial IRI from initial profilograph readings
• Finishers disliked MS mixture
• Tougher on equipment
  – Use Dowel Bar Inserter technology
  – Harsher MS mixture resulted in additional wear to nose pieces, overbuild devices on oscillating correcting beam
  – Similar sized projects
    • 100% NS mixture – required 1 replacement set of nose pieces, 1 set of overbuild devices
    • 100% MS mixture – required 5 sets of each

Company Execs:
“More of it is coming (MS), so you better get used to it.”
I-85 Reconstruction and Widening – Gaffney, SC

- 21 miles, 6 lanes = 126 lane miles
- Contractor concerned about consistent availability of NS
- Also concerned about availability of trucks to haul NS
  - Potential impacts to schedule

Using 50/50 MS/NS blend

- Capitalize on some cost savings
- Mitigate mixture impacts of MS
- Mixture is “a little bit stickier and a little bit tougher to work with” but do-able
- Higher strengths on the back end from MS mixture

http://www.85widening.com
I-85/I-385 Gateway – Greenville, SC

Interview with Project Manager

- 260,000 SY of pavement, with 10-15% shoulders
- 100% MS mixture utilized
- Water demand was considered, mitigated

- Paving in mid-day, summertime no issues with bleedwater
- Paving at night when temperature cooler – more bleeding
- Somewhat lower strength than NS mixtures, depending on source

http://www.85385gateway.com
Other Considerations

From **Project Manager**

- Consider available plant equipment/operations
  - Use of blends of MS/NS helps improve mixture workability, but requires an extra bin
  - If adding intermediate aggregate to optimize mixture gradation, would require ANOTHER bin

- If plant can support blends, can optimize MS
  - 70/30 blends have been used in other Southeastern US projects
  - Balance between economy and workability/other impacts
Impact of Local M-EPDG Calibration Using Sustainable Materials

Tara Cavalline, PhD, PE
Brett Tempest, PhD, PE
Edward Blanchard
Clay Medlin
Rohit Chimmula
Mechanistic-Empirical Pavement Design (M-EPDG)

- NCDOT has used Pavement ME Design software program for design of pavements (based on M-EPDG)
- Best results are obtained using locally calibrated input values
- Local inputs for concrete pavements needed
- Thermal inputs are of particular interest

Durable/Sustainable Materials

- Portland Limestone Cements (PLC) have been shown to reduce the carbon footprint of concrete
- MS increasingly utilized
- Increased use of fly ash
<table>
<thead>
<tr>
<th>Mixture ID*</th>
<th>Cement</th>
<th>Fly Ash</th>
<th>Coarse Aggregate</th>
<th>Fine Aggregate</th>
<th>Selected Proportions, pcy</th>
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<tbody>
<tr>
<td>C.A.N.M</td>
<td>None</td>
<td>Coastal</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
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<tr>
<td>M.A.N.M</td>
<td>None</td>
<td>Mountain</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
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<tr>
<td>P.A.N.N</td>
<td>None</td>
<td>Piedmont</td>
<td>Natural Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>P.A.A.M</td>
<td>Source A</td>
<td></td>
<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
<tr>
<td>P.A.B.M</td>
<td>Source B</td>
<td></td>
<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
<tr>
<td>C.B.N.M</td>
<td>None</td>
<td>Coastal</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>M.B.N.M</td>
<td>None</td>
<td>Mountain</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>P.B.N.N</td>
<td>None</td>
<td>Piedmont</td>
<td>Natural Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>P.B.A.M</td>
<td>Source A</td>
<td></td>
<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
<tr>
<td>P.B.B.M</td>
<td>Source B</td>
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<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
<tr>
<td>C.BL.N.M</td>
<td>None</td>
<td>Coastal</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
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<tr>
<td>M.BL.N.M</td>
<td>None</td>
<td>Mountain</td>
<td>Manuf. Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>P.BL.N.N</td>
<td>None</td>
<td>Piedmont</td>
<td>Natural Sand</td>
<td></td>
<td>573 0</td>
</tr>
<tr>
<td>P.BL.A.M</td>
<td>Source A</td>
<td></td>
<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
<tr>
<td>P.BL.B.M</td>
<td>Source B</td>
<td></td>
<td>Manuf. Sand</td>
<td></td>
<td>460 137</td>
</tr>
</tbody>
</table>

*Note: Explanation of Mixture ID coding: First letter, coarse aggregate type (C = Coastal, P = Piedmont, M = Mountain), Second letter, cement type (A = OPC source A, B = OPC source B, BL = PLC), Third letter, fly ash type (N = None, A = fly ash source A, B = fly ash source B), Fourth letter, fine aggregate type: M = manufactured sand, N = natural sand.
<table>
<thead>
<tr>
<th>Test</th>
<th>Protocol</th>
<th>Age(s) in days</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fresh</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air content</td>
<td>ASTM C231 and Super air meter</td>
<td>Fresh</td>
<td>1 each type of test, each batch</td>
</tr>
<tr>
<td>Slump</td>
<td>ASTM C143</td>
<td>Fresh</td>
<td>1</td>
</tr>
<tr>
<td>Fresh density (unit weight)</td>
<td>ASTM C138</td>
<td>Fresh</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>AASHTO T309</td>
<td>Fresh</td>
<td>1</td>
</tr>
<tr>
<td><strong>Hardened</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>ASTM C39</td>
<td>3, 7, 28, 90</td>
<td>3 each age</td>
</tr>
<tr>
<td>Resistivity</td>
<td>AASHTO TP95-11</td>
<td>3, 7, 28, 90</td>
<td>3 each age</td>
</tr>
<tr>
<td>Modulus of rupture</td>
<td>ASTM C78</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>Modulus of elasticity and Poisson’s ratio</td>
<td>ASTM C469</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td><strong>Coefficient of thermal expansion</strong></td>
<td>AASHTO T336</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>ASTM C2766</td>
<td>56</td>
<td>3</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>ASTM E1952</td>
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<td>3</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>ASTM C157</td>
<td>per standard</td>
<td>3</td>
</tr>
<tr>
<td>Cracking potential</td>
<td>ASTM C1581</td>
<td>per standard</td>
<td>3</td>
</tr>
<tr>
<td>Rapid chloride permeability</td>
<td>ASTM C1202</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>Freezing and thawing resistance</td>
<td>ASTM C666, procedure A</td>
<td>per standard</td>
<td>3</td>
</tr>
<tr>
<td>Thaumasite attack**</td>
<td>CSA A3004-C8</td>
<td>per standard</td>
<td>6</td>
</tr>
</tbody>
</table>
Thermal Property Test Equipment
Summary of Findings - Thermal Properties

**Coefficient of Thermal Expansion**

- Measured CTE values are **consistently lower** than the CTE values currently used by NCDOT and **significantly lower** than the recommended values suggested in the MEPDG literature for granitic gneiss and limestone.

- Mixtures containing NS had a notably **higher** coefficient of thermal expansion than those containing the MS.

  - Movement towards use of MS associated with lower CTE and potentially improved thermal performance
  - Implications on CTE for concrete mixtures that are blends of manufactured and natural sand?

GOOD NEWS! :)}
Summary of Findings - Thermal Properties

**Thermal Conductivity**

- **MS mixtures** – suggested input 0.80 to 0.90 BTU/(ft·hr·°F)
  - Significantly lower than the default input value is 1.25 BTU/(ft·hr·°F).

- **NS mixtures** - had a higher thermal conductivity, closer to the default value of 1.25 BTU/(ft·hr·°F).

**Heat Capacity**

- All measured values for heat capacity (typically around 0.20 BTU/lb·ft) were notably lower than the default values suggested in the MEPDG literature (0.28 BTU/lb·ft)

- The effect of sand type on heat capacity is not readily evident.
Influence of Specimen Moisture Condition on Thermal Conductivity

Thermal Conductivity (BTU/(ft.hr.°F))

- Natural sand: MEPDG Default input = 1.25
- Manufactured sand

Specimen Moisture Condition:
- C.A.N.M
- M.A.N.M
- P.A.N.M
- P.A.N.N
- P.A.A.M
- P.A.B.M
- C.B.N.M
- M.B.N.M
- P.B.N.M
- P.B.N.N
- P.B.A.M
- P.B.B.M
- C.BL.N.M
- M.BL.N.M
- P.BL.N.M
- P.BL.N.N
- P.BL.A.M
- P.BL.B.M

Oven Dried, 50% Relative Humidity, SSD

UNC CHARLOTTE
## Proposed Catalog of Inputs

<table>
<thead>
<tr>
<th>Materials</th>
<th>M-EPDG Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggr.</td>
<td>Fine Aggr.</td>
</tr>
<tr>
<td>Piedmont Man. Sand</td>
<td>No</td>
</tr>
<tr>
<td>Piedmont Man. Sand</td>
<td>Yes</td>
</tr>
<tr>
<td>Piedmont Natural Sand</td>
<td>No</td>
</tr>
<tr>
<td>Mountain Man. Sand</td>
<td>No</td>
</tr>
<tr>
<td>Coastal Man. Sand</td>
<td>No</td>
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<tr>
<td>NCDOT often utilized</td>
<td>150</td>
</tr>
<tr>
<td>MEPDG suggested</td>
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</tbody>
</table>
Implications of New Inputs on Concrete Pavement Design

NCDOT Selected Projects of Interest

- Project: R-2536 – Asheboro Bypass, Randolph Co.
- Project: U-2519 – Fayetteville Outer Loop, Cumberland Co.
### Sensitivity Analysis Results
Effect of Increase of Each Input on Predicted Distress

<table>
<thead>
<tr>
<th>Input</th>
<th>Terminal IRI (in/mile)</th>
<th>Mean Joint Faulting (in)</th>
<th>Transverse Cracking (% slabs cracked)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight ↑</td>
<td>Decrease (VS)</td>
<td>Decrease (S)</td>
<td>Decrease (N)</td>
</tr>
<tr>
<td>Modulus of rupture ↑</td>
<td>Decrease (VS)</td>
<td>Neutral (N)</td>
<td>Decrease (VS)</td>
</tr>
<tr>
<td>Modulus of elasticity ↑</td>
<td>Increase (S)</td>
<td>Increase (S)</td>
<td>Increase (S)</td>
</tr>
<tr>
<td>Poisson's ratio ↑</td>
<td>Increase (S)</td>
<td>Increase (S)</td>
<td>Increase (S)</td>
</tr>
<tr>
<td>CTE ↑</td>
<td>Increase (VS)</td>
<td>Increase (VS)</td>
<td>Increase (S)</td>
</tr>
<tr>
<td>Thermal conductivity ↑</td>
<td>Increase, then decrease (N)</td>
<td>Increase (S)</td>
<td>Decrease (VS)</td>
</tr>
<tr>
<td>Heat Capacity ↑</td>
<td>Decrease (N)</td>
<td>Neutral (N)</td>
<td>Decrease (S)</td>
</tr>
</tbody>
</table>

VS = Very Sensitive, S = Sensitive, N = Neutral
Implications on Concrete Pavement Design

• Recommended catalog of PCC inputs for M-EPDG was presented for use in local calibration efforts.

• Some recommended inputs differ significantly from MEPDG default/recommended values

• Coarse aggregate type not highly influential in MEPDG inputs

Shift in use from NS to MS may have performance implications on North Carolina PCC pavements

Predicted to be mostly favorable if workability challenges are not an issue
Thank you!

- Greg Dean – Carolinas Concrete Paving Association
- Fred White, Chris Ange, Willie Barnett – Lane Construction
- John Romaine, Adam Bruner – Zachry Construction
- Clark Morrison, Brian Hunter, Sam Fredrick, Chris Peoples, Nilesh Surti - NCDOT
- Brett Tempest – UNC Charlotte
- Edward Blanchard, Clayton Medlin, Rohit Chimmula – formerly UNC Charlotte
Resources


