OVERALL GOAL AND OBJECTIVES

GOAL:
• Evaluation of the cost effectiveness of granular materials based on material characteristics and performance

Objectives:
1. Identify benefits associated with different types of aggregate materials based on their long-term performance
2. Investigate the economic performance of granular roads constructed with the different materials
3. Develop methodology to evaluate the cost-effectiveness of granular materials from different sources
MOTIVATION

1. More than 60% of the road network in the State of Iowa
2. Annual maintenance costs $270 million
3. Lack of high quality aggregate sources
4. Resilient and sustainable infrastructure

Same location same freeze thaw cycles
AGGREGATE SOURCES
SITE LOCATION

I-35 South
County Road J14
Test Sections

Innovative Approach to Cost Benefit Analysis of Granular Roads
TEST SECTIONS: September 2016

- LCF Class A
- 80% BFL Class A + 20% BFL Clean
- OFD Class A
- 70% BFL Class A + 30% OFD Clean
- BFL Class A - Control
- 70% BFL Class A + 30% LCF Clean
- 70% BFL Class A + 30% CRG Clean
# AGGREGATE PROPERTIES

## Particle-size analysis results (ASTM D422-03)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>BFL Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel Content (%) (&gt;4.75mm)</td>
<td>46</td>
<td>54</td>
<td>61</td>
<td>79</td>
<td>72</td>
<td>65</td>
<td>71</td>
<td>12</td>
</tr>
<tr>
<td>Sand Content (%) (4.75mm – 75μm)</td>
<td>45</td>
<td>37</td>
<td>24</td>
<td>13</td>
<td>18</td>
<td>23</td>
<td>19</td>
<td>24</td>
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<tr>
<td>Silt Content (%) (75μm – 2μm)</td>
<td>8</td>
<td>8</td>
<td>14</td>
<td>8</td>
<td>8</td>
<td>11</td>
<td>9</td>
<td>53</td>
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<tr>
<td>Clay Content (%) (&lt; 2μm)</td>
<td>1</td>
<td>1.3</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>11</td>
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<tr>
<td>Coefficient of Uniformity, C_u</td>
<td>48</td>
<td>91</td>
<td>185</td>
<td>25</td>
<td>111</td>
<td>154</td>
<td>103</td>
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<tr>
<td>Coefficient of Curvature, C_c</td>
<td>7</td>
<td>2</td>
<td>17</td>
<td>5</td>
<td>19</td>
<td>17</td>
<td>19</td>
<td>7</td>
</tr>
</tbody>
</table>

## Atterberg limits test results (ASTM D4318-10e1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>BFL Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit (%)</td>
<td>15</td>
<td>NA</td>
<td>20</td>
<td>20</td>
<td>19</td>
<td>17</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>1</td>
<td>NA</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

## AASHTO and USCS soil classification (ASTM D2487-11 & D3282-09)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>BFL Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
<th>Subgrade</th>
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</thead>
<tbody>
<tr>
<td>USCS group symbol</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>CL</td>
</tr>
<tr>
<td>USCS group name</td>
<td>Well-Graded</td>
<td>Well-Graded</td>
<td>Well-Graded</td>
<td>Well-Graded Gravel</td>
<td>Well-Graded Gravel</td>
<td>Well-Graded Gravel</td>
<td>Well-Graded Gravel</td>
<td>Sandy Lean Clay</td>
</tr>
</tbody>
</table>
CONSTRUCTION PROCEDURE

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Hauling from quarry to piles</td>
<td>Truck</td>
</tr>
<tr>
<td>Step 2</td>
<td>Scraping the existing surface</td>
<td>Motor Grader</td>
</tr>
<tr>
<td>Step 3</td>
<td>Hauling from pile to site</td>
<td>Loader and Truck</td>
</tr>
<tr>
<td>Step 4</td>
<td>Blading</td>
<td>Motor Grader</td>
</tr>
<tr>
<td>Step 5</td>
<td>Compacting</td>
<td>Drum Roller</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sections</th>
<th>Labor (hr)</th>
<th>Grader (hr)</th>
<th>Tandem Dump (hr)</th>
<th>Bottom Dump (hr)</th>
<th>Drum Roller (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCF Class A</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>OFD Class A</td>
<td>46</td>
<td>11</td>
<td>15</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>BFL Class A – Control Section</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>80% BFL Class A + 20% BFL Clean</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>70% BFL Class A + 30% OFD Clean</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>70% BFL Class A + 30% LCF Clean</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>70% BFL Class A + 30% CRG Clean</td>
<td>66</td>
<td>16</td>
<td>21</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>
CONSTRUCTION COSTS

- Section 7 - 70% BFL Class A + 30% CRG Clean
- Section 6 - 70% BFL Class A + 30% LCF Clean
- Section 5 - 70% BFL Class A + 30% OFD Clean
- Section 4 - 80% BFL Class A + 20% BFL Clean
- Section 3 - BFL Class A
- Section 2 - OFD Class A
- Section 1 - LCF Class A

Cost (Thousand-US$)

- Base Case: 40,665
- Hauling Costs: 53,249
- Material Costs: 34,697
- Hauling Costs: 32,328
- Hauling Costs: 32,279
- Hauling Costs: 33,920

(a)
# MAINTENANCE PROCEDURE

<table>
<thead>
<tr>
<th>Maintenance Procedure</th>
<th>Labor (hr)</th>
<th>Grader (hr)</th>
<th>Tandem Dump (hr)</th>
<th>Loader (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCF Class A</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>OFD Class A</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>BFL Class A – (Control Section)</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>80% BFL Class A + 20% BFL Clean</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>70% BFL Class A + 30% OFD Clean</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>70% BFL Class A + 30% LCF Clean</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>70% BFL Class A + 30% CRG Clean</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>
MAINTENANCE COSTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
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<tbody>
<tr>
<td>7</td>
<td>70% BFL Class A + 30% CRG Clean</td>
</tr>
<tr>
<td>6</td>
<td>70% BFL Class A + 30% LCF Clean</td>
</tr>
<tr>
<td>5</td>
<td>70% BFL Class A + 30% OFD Clean</td>
</tr>
<tr>
<td>4</td>
<td>80% BFL Class A + 20% BFL Clean</td>
</tr>
<tr>
<td>3</td>
<td>BFL Class A</td>
</tr>
<tr>
<td>2</td>
<td>OFD Class A</td>
</tr>
<tr>
<td>1</td>
<td>LCF Class A</td>
</tr>
</tbody>
</table>

Base Case

Material Costs

Hauling Costs

Cost (Thousand-US$)
PERFORMANCE MEASURES

First Group
1. Breakage
2. Fines Content
3. Gravel/Sand Ratio

Second Group
1. FWD
2. DCP

Third Group
1. Dustometer
2. IRI
PERFORMANCE MEASURES: *First Group*

Material Loss

Fines Content

Gravel/Sand Ratio

Total Breakage

Hardin B., “Crushing of Soil Particles” - 1985
PERFORMANCE MEASURES: Second Group

Shear Strength (CBR) → DCP

Surface Elastic Modulus → FWD
PERFORMANCE MEASURES: Third Group

Dust Production → Dustometer

Surface Roughness → Roadroid
**SCENARIO DEVELOPMENT: Maintenance Intervals**

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Best Case</th>
<th>Most Likely Case</th>
<th>Worst Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Performance</td>
<td>3 Years</td>
<td>2 Years</td>
<td>1 Year</td>
</tr>
<tr>
<td>Medium Performance</td>
<td>4 Years</td>
<td>3 Years</td>
<td>2 Years</td>
</tr>
<tr>
<td>High Performance</td>
<td>5 Years</td>
<td>4 Years</td>
<td>3 Years</td>
</tr>
</tbody>
</table>
ECONOMIC ANALYSIS ELEMENTS

Performance-Based Cost Analysis

Benefits
- User cost saving
- Maintenance cost saving

Costs
- Construction costs
- Maintenance costs

Factors
- Service life
- Discount rate
- Maintenance interval
COST ANALYSIS: Summary

Defining Benefits:

- **User Cost Saving**
  
  Travel delay cost = \[(1 - T_t) \times P \times V_p + T_t \times V_t\]

- **Maintenance Cost Saving**

  Cost savings = New frequency \times New cost \(- Conventional frequency \times Conventional cost\)

NPV = Construction Costs

\[
+ \sum_{k=1}^{n} \text{Maintenance Cost}_k \left[ \frac{1}{(1 + i)^{n_k}} \right] - \text{Salvage Value} \left[ \frac{1}{(1 + i)^{n_k}} \right]
\]

Benefit Cost Ratio = \[
\frac{\text{NPV (Benefits)}}{\text{NPV (Costs)}}
\]
BCA: Material Loss

![Material Loss Bar Graph]

- **Material Loss/Length of the Section (ton/ft)**
- **High**
  - >0.15
- **Medium**
  - 0.1 - 0.15
- **Low**
  - <0.1

- LCF Class A
- OFD Class A
- BFL Class A
- 80% BFL Class A + 20% BFL Clean
- 70% BFL Class A + 30% OFD Clean
- 70% BFL Class A + 30% LCF Clean
- 70% BFL Class A + 30% CRG Clean
BCA: Material Loss

Material & Thickness Loss BCR

- LCF Class A
- OFD Class A
- 80% BFL Class A + 20% BFL Clean
- 70% BFL Class A + 30% OFD Clean
- 70% BFL Class A + 30% LCF Clean
- 70% BFL Class A + 30% CRG Clean
BCA (First Group): Total Breakage

- LCF Class A
- OFD Class A
- BFL Class A
- 80% BFL Class A + 20% BFL Clean
- 70% BFL Class A + 30% OFD Clean
- 70% BFL Class A + 30% LCF Clean
- 70% BFL Class A + 30% CRG Clean

Breakage Categories:
- High (>0.3)
- Medium (0.15 - 0.3)
- Low (<0.15)
BCA (First Group): Total Breakage

Breakage BCR

<table>
<thead>
<tr>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.26</td>
<td>2.04</td>
<td>1.54</td>
<td>0.92</td>
<td>2.47</td>
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</tbody>
</table>
BCA (First Group): *Fines Content*

![Bar chart showing fines content for different classes and blends.](chart-image-url)
BCA (First Group): Fines Content

Fines Content BCR

<table>
<thead>
<tr>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
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</thead>
<tbody>
<tr>
<td>Service Life (Years)</td>
<td>BCR</td>
<td>Service Life (Years)</td>
<td>BCR</td>
<td>Service Life (Years)</td>
<td>BCR</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Worst Case</td>
<td>2.26</td>
<td></td>
<td>2.04</td>
<td></td>
<td>2.15</td>
</tr>
<tr>
<td>Most Likely Case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best Case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
BCA (First Group): *Gravel/Sand Ratio*
BCA (First Group): *Gravel/Sand Ratio*

**Gravel/Sand BCR**

- **LCF Class A**
- **OFD Class A**
- **80% BFL Class A + 20% BFL Clean**
- **70% BFL Class A + 30% OFD Clean**
- **70% BFL Class A + 30% LCF Clean**
- **70% BFL Class A + 30% CRG Clean**
BCA (Second Group): *FWD*
BCA (Second Group): *FWD*

![BCA Graph](image)

**FWD BCR**

- LCF Class A
- OFD Class A
- 80% BFL Class A + 20% BFL Clean
- 70% BFL Class A + 30% OFD Clean
- 70% BFL Class A + 30% LCF Clean
- 70% BFL Class A + 30% CRG Clean

<table>
<thead>
<tr>
<th>Service Life (Years)</th>
<th>BCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.44</td>
</tr>
<tr>
<td>30</td>
<td>1.44</td>
</tr>
<tr>
<td>40</td>
<td>1.44</td>
</tr>
<tr>
<td>50</td>
<td>1.44</td>
</tr>
</tbody>
</table>

*Iowa State University*
BCA (Second Group): \textit{DCP}

![Bar Chart](Image)

- LCF Class A
- OFD Class A
- BFL Class A
- BFL Class A + 20% BFL Clean
- BFL Class A + 30% OFD Clean
- BFL Class A + 30% LCF Clean
- 80% BFL Class A + 30% CRG Clean

<table>
<thead>
<tr>
<th>CBR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
</tr>
<tr>
<td>120</td>
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<tr>
<td>100</td>
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<tr>
<td>80</td>
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<tr>
<td>60</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- High: >120%
- Medium: 100% - 120%
- Low: <100%
BCA (Second Group): $DCP$

**BCP BCR**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>BCR</th>
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<tbody>
<tr>
<td>LIF Class A</td>
<td>1.91</td>
</tr>
<tr>
<td>OFD Class A</td>
<td>1.48</td>
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<tr>
<td>80% BFL Class A + 20% BFL Clean</td>
<td>2.62</td>
</tr>
<tr>
<td>70% BFL Class A + 30% OFD Clean</td>
<td>1.44</td>
</tr>
<tr>
<td>70% BFL Class A + 30% LCF Clean</td>
<td>1.82</td>
</tr>
<tr>
<td>70% BFL Class A + 30% CRG Clean</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Service Life (Years)
BCA (Third Group): *Dust Production*

![Graph showing dust production levels for different road classes and materials.](image)
BCA (Second Group): *Dust Production*

<table>
<thead>
<tr>
<th>LCF Class A</th>
<th>OFD Class A</th>
<th>80% BFL Class A + 20% BFL Clean</th>
<th>70% BFL Class A + 30% OFD Clean</th>
<th>70% BFL Class A + 30% LCF Clean</th>
<th>70% BFL Class A + 30% CRG Clean</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCR</td>
<td>BCR</td>
<td>BCR</td>
<td>BCR</td>
<td>BCR</td>
<td>BCR</td>
</tr>
<tr>
<td>Worst Case</td>
<td>Most Likely Case</td>
<td>Best Case</td>
<td>Worst Case</td>
<td>Most Likely Case</td>
<td>Best Case</td>
</tr>
</tbody>
</table>

Dust Production BCR

Service Life (Years)
BCA (Third Group): *Surface Roughness*
BCA (Second Group): *Surface Roughness*

**Ride Quality BCR**

- **LCF Class A**
  - Worst Case: 0.91
  - Most Likely Case: 1.91
  - Best Case: 1.91

- **OFD Class A**
  - Worst Case: 1.81
  - Most Likely Case: 1.81
  - Best Case: 1.81

- **80% BFL Class A + 20% BFL Clean**
  - Worst Case: 2.15
  - Most Likely Case: 2.15
  - Best Case: 2.15

- **70% BFL Class A + 30% OFD Clean**
  - Worst Case: 0.92
  - Most Likely Case: 0.92
  - Best Case: 0.92

- **70% BFL Class A + 30% LCF Clean**
  - Worst Case: 1.82
  - Most Likely Case: 1.82
  - Best Case: 1.82

- **70% BFL Class A + 30% CRG Clean**
  - Worst Case: 2.33
  - Most Likely Case: 2.33
  - Best Case: 2.33

**Service Life (Years)**: 20, 30, 40, 50
Performance – Based Economic Analysis

Overall: Weighted average of mechanistic results & Material/Thickness Loss

Material Loss
\[ \times 1 \]

First Group
\[ \times 0.75 \]

Second Group
\[ \times 0.5 \]

Third Group
\[ \times 0.25 \]
Performance – Based Economic Analysis

Overall Mechanistic Performance & Material Loss BCR

- **BCR**
- **Service Life (Years)**
- **LCF Class A**
- **OBD Class A**
- **80% BFL Class A + 20% BFL Clean**
- **70% BFL Class A + 30% OFD Clean**
- **70% BFL Class A + 30% LCF Clean**
- **70% BFL Class A + 30% CRG Clean**

- **Worst Case**
- **Most Likely Case**
- **Best Case**
CONCLUSIONS

- **OFD Class A**
  - Highest Construction Costs
  - Highest Maintenance Costs

- **80% BFL Class A + 20% BFL Clean**
  - Lowest Construction Costs

- **70% BFL Class A + 30% OFD Clean**
  - Lowest Maintenance Costs
CONCLUSIONS

70% BFL Class A + 30% LCF Clean
- Fines Content
- Total Breakage
- Overall
- Dust Production
- FWD
- Material Loss

70% BFL Class A + 30% CRG Clean
- Gravel/Sand Ratio
- Ride Quality
Thank You!

QUESTIONS??
Appendix
FALLING WEIGHT DEFLECTOMETER

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of receivers</td>
<td>9</td>
</tr>
<tr>
<td>Receiver spacing (m)</td>
<td>0.15 to 0.31</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>1.38</td>
</tr>
<tr>
<td>Distance from the source to the first receiver (m)</td>
<td>0</td>
</tr>
</tbody>
</table>
FALLING WEIGHT DEFLECTOMETER

Backcalculation Methods

• Boussinesq
• BAKFAA
• Modulus 7

Layer Numbers in Calculation

• Two Layers
• Three Layers