Drainability of Base Aggregate and Sand
Project TPF 5(341)

Final Project Presentation

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Statement of Problem

• Lack of proper pore water drainage is one of the main causes of geosystem failure (e.g., roadway base course, retaining wall backfills).

• Proper drainage required to minimize elevated pore pressure, minimize freeze-thaw damage.

• Simple and reliable tools capable of estimating drainability parameters for common aggregate types will aid in material selection and design.

  • Saturated hydraulic conductivity, $K_{\text{sat}}$
  • SWCC parameters, $n$ & $\alpha$
  • Drainable porosity ($n_d$), field capacity ($\theta_f$), minimum saturation ($S_{\text{min}}$)
Project Objectives

• Conduct laboratory permeability and water retention tests on materials used in or considered for use in pavement base systems.

• Evaluate general and specific empirical correlations for estimating drainability properties ($K_{sat}$ and SWCC).

• Develop simple predictive tools that may be used to assess drainability from other properties (e.g., gradation, fines content, etc.)
Drainability: An Unsaturated Soils Problem

1) Material Properties (Permeability, Water Retention Characteristics)

2) Pavement System Design (Layering, Slope, Drainage Boundaries)

3) Environmental Conditions (Precipitation, Temperature)
## Samples Obtained

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3149 Super Sand (MnDOT)</td>
</tr>
<tr>
<td>2</td>
<td>MN Class 5 (MnDOT)</td>
</tr>
<tr>
<td>3</td>
<td>1007 Type 5 DGB (MoDOT)</td>
</tr>
<tr>
<td>4</td>
<td>1007 Type 7 DGB (MoDOT)</td>
</tr>
<tr>
<td>5</td>
<td>1010 Man. Sand (MoDOT)</td>
</tr>
<tr>
<td>6</td>
<td>MCC Freeborn West Quarry Crushed Stone (WisDOT)</td>
</tr>
<tr>
<td>7</td>
<td>Lannon Lisbon Pit (North Ave.) Structural Backfill (WisDOT)</td>
</tr>
<tr>
<td>8</td>
<td>Lannon Lisbon Pit (Mukwonago) Structural Backfill (WisDOT)</td>
</tr>
<tr>
<td>9</td>
<td>Lannon Stone Product Chips (WisDOT)</td>
</tr>
<tr>
<td>10</td>
<td>Super Aggregate Pit Granular Backfill (WisDOT)</td>
</tr>
<tr>
<td>15</td>
<td>Bryan Redrock Class 5, MnDOT Pit 70006</td>
</tr>
<tr>
<td>16</td>
<td>Bryan Redrock Ball Diamond material, MnDOT Pit 70006</td>
</tr>
<tr>
<td>A1</td>
<td>1¾” Base (WisDOT)</td>
</tr>
<tr>
<td>A2</td>
<td>¾” Washed (WisDOT)</td>
</tr>
<tr>
<td>A3</td>
<td>Manufactured Sand (WisDOT)</td>
</tr>
<tr>
<td>A4</td>
<td>¾” Base Cs. (WisDOT)</td>
</tr>
<tr>
<td>A5</td>
<td>Breaker Run (limestone/dolomite) (WisDOT)</td>
</tr>
</tbody>
</table>
(1) 3149 Super Sand

(2) Mn Class 5

(3) 1007 Type 5 DGB

(4) 1007 Type 7 DGB
Particle Size Distributions

Fines (hydrometer)
## Indices and Classification

9 sands & 7 gravels; fines from ~0% to ~23%

<table>
<thead>
<tr>
<th>Sample</th>
<th>D$_{10}$ (mm)</th>
<th>D$_{30}$ (mm)</th>
<th>D$_{50}$ (mm)</th>
<th>D$_{60}$ (mm)</th>
<th>C$_{u}$</th>
<th>% Fines</th>
<th>% Gravels</th>
<th>$\gamma_d$ (kN/m$^3$)</th>
<th>USCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.09</td>
<td>0.30</td>
<td>0.46</td>
<td>0.55</td>
<td>5.91</td>
<td>8.82</td>
<td>100.00</td>
<td>18.57</td>
<td>SP-SM</td>
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<tr>
<td>#2</td>
<td>0.10</td>
<td>0.36</td>
<td>0.72</td>
<td>1.38</td>
<td>13.53</td>
<td>8.18</td>
<td>75.73</td>
<td>19.63</td>
<td>SW-SM</td>
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<tr>
<td>#3</td>
<td>0.03</td>
<td>0.36</td>
<td>2.28</td>
<td>3.65</td>
<td>114.78</td>
<td>20.8</td>
<td>67.18</td>
<td>17.76</td>
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<td>#4</td>
<td>0.05</td>
<td>2.50</td>
<td>4.90</td>
<td>7.09</td>
<td>154.13</td>
<td>12.5</td>
<td>49.24</td>
<td>17.80</td>
<td>GM</td>
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<tr>
<td>#5</td>
<td>0.27</td>
<td>0.52</td>
<td>0.90</td>
<td>1.26</td>
<td>4.75</td>
<td>1.89</td>
<td>99.75</td>
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<td>SP</td>
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<tr>
<td>#6</td>
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<td>10.9</td>
<td>14.0</td>
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<td>0.19</td>
<td>0.59</td>
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<td>#7</td>
<td>0.22</td>
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<td>1.70</td>
<td>2.20</td>
<td>10.09</td>
<td>2.03</td>
<td>95.17</td>
<td>18.65</td>
<td>SW</td>
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<tr>
<td>#8</td>
<td>0.18</td>
<td>0.45</td>
<td>1.30</td>
<td>1.82</td>
<td>10.11</td>
<td>2.39</td>
<td>96.40</td>
<td>20.10</td>
<td>SP</td>
</tr>
<tr>
<td>#9</td>
<td>5.00</td>
<td>6.60</td>
<td>8.05</td>
<td>8.95</td>
<td>1.79</td>
<td>2.17</td>
<td>7.37</td>
<td>16.57</td>
<td>GP</td>
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<tr>
<td>#10</td>
<td>0.20</td>
<td>0.33</td>
<td>0.53</td>
<td>0.72</td>
<td>3.60</td>
<td>3.24</td>
<td>97.72</td>
<td>18.26</td>
<td>SP</td>
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<td>0.04</td>
<td>1.58</td>
<td>6.35</td>
<td>9.50</td>
<td>256.76</td>
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<td>44.37</td>
<td>18.66</td>
<td>GM</td>
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<tr>
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<td>0.02</td>
<td>0.13</td>
<td>0.44</td>
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<td>99.88</td>
<td>17.69</td>
<td>SM</td>
</tr>
<tr>
<td>A1</td>
<td>0.13</td>
<td>1.82</td>
<td>7.00</td>
<td>9.92</td>
<td>76.31</td>
<td>7.05</td>
<td>41.03</td>
<td>18.63</td>
<td>GW-GM</td>
</tr>
<tr>
<td>A2</td>
<td>7.19</td>
<td>11.2</td>
<td>12.8</td>
<td>14.4</td>
<td>2.00</td>
<td>0.84</td>
<td>1.39</td>
<td>15.94</td>
<td>GP</td>
</tr>
<tr>
<td>A3</td>
<td>0.19</td>
<td>0.40</td>
<td>0.80</td>
<td>1.10</td>
<td>5.73</td>
<td>2.27</td>
<td>99.33</td>
<td>17.27</td>
<td>SP</td>
</tr>
<tr>
<td>A4</td>
<td>0.08</td>
<td>0.93</td>
<td>5.20</td>
<td>7.99</td>
<td>102.44</td>
<td>9.89</td>
<td>48.06</td>
<td>19.18</td>
<td>GW-GM</td>
</tr>
</tbody>
</table>

Note: D$_{10}$, D$_{30}$, D$_{50}$, D$_{60}$ = particle sizes corresponding to 10%, 30%, 50%, 60% finer, respectively, in particle-size distribution curve; C$_{u}$ = coefficient of uniformity; C$_{c}$ = coefficient of curvature; USCS = unified soil classification system
$K_{\text{sat}}$ and SWCC Testing

Constant Head Apparatus
($K_{\text{sat}}$)

Hanging Column Apparatus
(SWCC)
$K_{sat}$: Effect of Hydraulic Gradient

- Potential fines migration
- Turbulent flow regime (gravels?)

$$Q = kA$$
Soil-Water Characteristic Curves

(Gravels)  

\[ \theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (\alpha \psi)^n} \right]^{1 - 1/n} \]

(Sands)  

Van Genuchten (1980) Model
# K\text{sat} and SWCCs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hydraulic Conductivity Testing</th>
<th>Soil-Water Characteristic Curve Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \gamma_d ) (kN/m(^3))</td>
<td>Min. ( K_{\text{sat}} ) (cm/s)</td>
</tr>
<tr>
<td>#1 (SP-SM)</td>
<td>18.6</td>
<td>0.002</td>
</tr>
<tr>
<td>#2 (SW-SM)</td>
<td>19.6</td>
<td>0.003</td>
</tr>
<tr>
<td>#3 (SM)</td>
<td>17.8</td>
<td>0.007</td>
</tr>
<tr>
<td>#4 (GM)</td>
<td>17.8</td>
<td>0.150</td>
</tr>
<tr>
<td>#5 (SP)</td>
<td>15.9</td>
<td>0.048</td>
</tr>
<tr>
<td>#6 (GP)</td>
<td>16.2</td>
<td>0.387</td>
</tr>
<tr>
<td>#7 (SW)</td>
<td>18.7</td>
<td>0.021</td>
</tr>
<tr>
<td>#8 (SP)</td>
<td>20.1</td>
<td>0.005</td>
</tr>
<tr>
<td>#9 (GP)</td>
<td>16.6</td>
<td>0.389</td>
</tr>
<tr>
<td>#10 (SP)</td>
<td>18.3</td>
<td>0.015</td>
</tr>
<tr>
<td>#11 (GW-GM)</td>
<td>18.6</td>
<td>0.025</td>
</tr>
<tr>
<td>#12 (GP)</td>
<td>15.9</td>
<td>0.396</td>
</tr>
<tr>
<td>#13 (SP)</td>
<td>17.3</td>
<td>0.019</td>
</tr>
<tr>
<td>#14 (GW-GM)</td>
<td>19.2</td>
<td>0.072</td>
</tr>
<tr>
<td>#15 (GM)</td>
<td>18.7</td>
<td>0.015</td>
</tr>
<tr>
<td>#16 (SM)</td>
<td>17.7</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Gravel average \( K_{\text{sat}} = 0.324 \text{ cm/s} \)
Sand average \( K_{\text{sat}} = 0.014 \text{ cm/s} \)
Empirical Equations for $K_{sat}$

Literature search was conducted to summarize equations for predicting saturated hydraulic conductivity from grain size, compaction indices, and fluid properties (e.g., d10, porosity, viscosity)

The equations used in this study were as follows:
- Alyamani and Sen (Equation C.21)
- Beyer (Equation C.12)
- Harleman et al. (Equation C.11)
- Original Hazen (Equation C.1a)
- Modified Hazen (Equation C.1b)
- Kozeny (Equation C.9)
- Kozeny-Carman (Equation C.10)
- Sauerbrei (Equation C.19)
- Slichter (Equation C.3)
- Terzaghi (Equation C.5)
- U.S. Bureau of Reclamation (Equation C.20)
- Salarashayeri and Siosemarde (Equation C.25)
- Chapuis (Equation C.28)

$$K[\text{m/s}] = \beta \frac{g}{\nu} \log \frac{500}{c_u} d_{10}^2$$

(Beyer, 1964)
Empirical Equation Performance
(Gravels excluded)
Dataset Specific Correlations

(Example using D₃₀)

\[ K_{sat} = 0.0684 \times D_{30} - 0.004 \quad (R^2 = 0.85) \]
Field Capacity, Drainable Porosity, & Minimum Saturation

\[ n_d = n - \theta_f \]

\[ S_{\text{min}} = 1 - \frac{n_d}{n} = \frac{\theta_f}{n} \]

33 kPa
<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Porosity (n = θₚ)</th>
<th>Field Capacity (θᵋ)</th>
<th>Effective Porosity (nₑ)</th>
<th>Minimum Saturation (Sₘᵋᵣ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (SP-SM)</td>
<td>0.29</td>
<td>0.09</td>
<td>0.2</td>
<td>0.32</td>
</tr>
<tr>
<td>#2 (SW-SM)</td>
<td>0.24</td>
<td>0.08</td>
<td>0.17</td>
<td>0.31</td>
</tr>
<tr>
<td>#3 (SM)</td>
<td>0.32</td>
<td>0.15</td>
<td>0.16</td>
<td>0.48</td>
</tr>
<tr>
<td>#4 (GM)</td>
<td>0.32</td>
<td>0.11</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>#5 (SP)</td>
<td>0.38</td>
<td>0.03</td>
<td>0.36</td>
<td>0.08</td>
</tr>
<tr>
<td>#6 (GP)</td>
<td>0.37</td>
<td>0.03</td>
<td>0.35</td>
<td>0.07</td>
</tr>
<tr>
<td>#7 (SW)</td>
<td>0.28</td>
<td>0.03</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>#8 (SP)</td>
<td>0.23</td>
<td>0.002</td>
<td>0.22</td>
<td>0.01</td>
</tr>
<tr>
<td>#9 (GP)</td>
<td>0.36</td>
<td>0.02</td>
<td>0.34</td>
<td>0.06</td>
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<tr>
<td>#10 (SP)</td>
<td>0.3</td>
<td>0.04</td>
<td>0.26</td>
<td>0.14</td>
</tr>
<tr>
<td>#15 (GM)</td>
<td>0.28</td>
<td>0.19</td>
<td>0.09</td>
<td>0.69</td>
</tr>
<tr>
<td>#16 (SM)</td>
<td>0.32</td>
<td>0.17</td>
<td>0.15</td>
<td>0.53</td>
</tr>
<tr>
<td>A1 (GW-GM)</td>
<td>0.28</td>
<td>0.12</td>
<td>0.16</td>
<td>0.41</td>
</tr>
<tr>
<td>A2 (GP)</td>
<td>0.39</td>
<td>0.04</td>
<td>0.35</td>
<td>0.09</td>
</tr>
<tr>
<td>A3 (SP)</td>
<td>0.34</td>
<td>0.005</td>
<td>0.33</td>
<td>0.01</td>
</tr>
<tr>
<td>A4 (GW-GM)</td>
<td>0.26</td>
<td>0.10</td>
<td>0.17</td>
<td>0.36</td>
</tr>
</tbody>
</table>

\[
S_{\text{min}} = 0.025(\%F) + 0.062 \quad (R^2 = 0.75)
\]
Estimating van Genuchten SWCC parameters (Benson et al., 2014)

\[ \alpha = \alpha_1 N_\alpha \]
\[ n = n_1 N_n \]

\[ \alpha_1 = 0.0008 \times D_{30}^2 + 0.1843 \times D_{30} + 0.3567 \quad (R^2 = 0.85) \]

\[ N_\alpha = -0.12 \ln(C_u) + 0.7155 \]

\[ n_1 = 0.0419 \times D_{30}^2 + 0.0073 \times D_{30} + 2.4052 \quad (R^2 = 0.65) \]

\[ N_n = 1.5107 \times C_u^{-0.3187} \]
### Proposed Drainability Rating System

<table>
<thead>
<tr>
<th>Qualitative Drainability</th>
<th>$K_{sat}$ (cm/s)</th>
<th>Minimum Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>$K_{sat} \geq 0.35$</td>
<td>$S_{min} \leq 0.10$</td>
</tr>
<tr>
<td>Marginal</td>
<td>$0.02 \leq K_{sat} &lt; 0.35$</td>
<td>$0.10 &lt; S_{min} \leq 0.30$</td>
</tr>
<tr>
<td>Poor</td>
<td>$K_{sat} &lt; 0.02$</td>
<td>$S_{min} &gt; 0.30$</td>
</tr>
</tbody>
</table>

**Approach 1:** Direct measurement of $K_{sat}$ and $S_{min}$

**Approach 2:** Estimation of $K_{sat}$ and $S_{min}$ from grain size ($D_{30}$, $C_u$)

**Approach 3:** Estimation of $K_{sat}$ and $S_{min}$ from % fines
Based on Direct Measurements

<table>
<thead>
<tr>
<th>Sample</th>
<th>$K_{\text{sat}}$ (cm/s)</th>
<th>Minimum Saturation</th>
<th>$K_{\text{sat}}$ Criterion</th>
<th>$S_{\text{min}}$ Criterion</th>
<th>Overall Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (SP-SM)</td>
<td>0.0021</td>
<td>0.32</td>
<td>Poor</td>
<td>Marginal</td>
<td>Poor-Marginal</td>
</tr>
<tr>
<td>#2 (SW-SM)</td>
<td>0.0027</td>
<td>0.31</td>
<td>Poor</td>
<td>Marginal</td>
<td>Poor-Marginal</td>
</tr>
<tr>
<td>#3 (SM)</td>
<td>0.0073</td>
<td>0.48</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>#4 (GM)</td>
<td>0.1693</td>
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<td>Marginal</td>
<td>Poor</td>
<td>Marginal</td>
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<tr>
<td>#5 (SP)</td>
<td>0.0489</td>
<td>0.08</td>
<td>Marginal</td>
<td>Excellent</td>
<td>Marg - Excellent</td>
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<tr>
<td>#6 (GP)</td>
<td>0.6957</td>
<td>0.07</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
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<td>0.10</td>
<td>Marginal</td>
<td>Excellent</td>
<td>Marginal</td>
</tr>
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<td>#8 (SP)</td>
<td>0.0050</td>
<td>0.01</td>
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<td>Excellent</td>
<td>Marginal</td>
</tr>
<tr>
<td>#9 (GP)</td>
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<td>Excellent</td>
<td>Excellent</td>
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<td>#10 (SP)</td>
<td>0.0104</td>
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<td>Marginal</td>
<td>Poor-Marginal</td>
</tr>
<tr>
<td>#15 (GM)</td>
<td>0.0159</td>
<td>0.69</td>
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<td>Poor</td>
<td>Poor</td>
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<td>#16 (SM)</td>
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<td>Poor</td>
<td>Poor</td>
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<td>A1 (GW-GM)</td>
<td>0.0298</td>
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<td>Marginal</td>
<td>Poor</td>
<td>Poor-Marginal</td>
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<tr>
<td>A2 (GP)</td>
<td>0.5618</td>
<td>0.09</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
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<td>A3 (SP)</td>
<td>0.0224</td>
<td>0.01</td>
<td>Marginal</td>
<td>Excellent</td>
<td>Marg - Excellent</td>
</tr>
<tr>
<td>A4 (GW-GM)</td>
<td>0.1759</td>
<td>0.36</td>
<td>Poor</td>
<td>Marginal</td>
<td>Poor-Marginal</td>
</tr>
</tbody>
</table>
Based on Grain Size

\[ K_{\text{sat}} = 0.0684 \times D_{30} - 0.004 \ (R^2 = 0.85) \]

\[ \alpha_1 = 0.0008 \times D_{30}^2 + 0.1843 \times D_{30} + 0.3567 \ (R^2 = 0.85) \]

\[ N_{\alpha} = -0.12 \ln(C_u) + 0.7155 \]

\[ n_1 = 0.0419 \times D_{30}^2 + 0.0073 \times D_{30} + 2.4052 \ (R^2 = 0.65) \]

\[ N_n = 1.5107 \times C_u^{-0.3187} \]

\[ \alpha = \alpha_1 N_{\alpha} \]

\[ n = n_1 N_n \]

\[ S_{\text{min}} = \left[ \frac{1}{1 + (\alpha 33)^n} \right]^{1 - \frac{1}{n}} \leq 1.0 \]

<table>
<thead>
<tr>
<th>Sample</th>
<th>( K_{\text{sat}} ) (cm/s)</th>
<th>Minimum Saturation</th>
<th>( K_{\text{sat}} ) Criterion</th>
<th>( S_{\text{min}} ) Criterion</th>
<th>Overall Rating</th>
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<td>Excellent</td>
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Based on % Fines

\[ K_{sat} = 0.0684 \times D_{30} - 0.004 \quad (R^2 = 0.85) \]

\[ S_{min} = 0.025(\% F) + 0.062 \quad (R^2 = 0.75) \]
## Comparison of 3 Approaches

<table>
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<tr>
<th>Sample</th>
<th>Direct Measurement</th>
<th>Estimation from Grain Size</th>
<th>Estimation from Percent Fines</th>
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Project Reports and Papers

