Environmentally Friendly Pervious Concrete for Treating Deicer-Laden Stormwater (Phase I)

Interim Progress Report

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https://sites.google.com/site/greensmartinfrastructure

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Problem Statement

- Stormwater control is a national priority since non-point sources continue to rank as leading causes of water pollution. Deicer stormwater is a new challenge.

- Pervious concrete is considered a successful Low Impact Development (LID) technology and has been increasingly used as a stormwater BMP for parking lots, sidewalks, and other applications.

- The production of Portland cement (the most common binder in concrete) is an energy-intensive process that accounts for a significant portion of global CO₂ emissions and other greenhouse gases.
Pervious concrete pavements reduce the quantity of stormwater runoff and improve its water quality by reducing total suspended solids, total phosphorous, total nitrogen, and metals.

The utilization of nanotechnology to enable expanded use of waste and recycled materials is an unexplored area with great potential.
Project Objective

- Expand the use of industrial waste and recycled materials (such as fly ash and recycled glass) in pervious concrete (Phase I)

- Explore the potential of such “greener” pervious concrete for the treatment of deicer-laden stormwater under a variety of contaminant loading scenarios (Phase II)
Identify “Green” Constituents of Pervious Concrete

- **Locally available fly ashes**
  serve as alternative binders

- **Recycled glasses**
  serve as alternative aggregates

- **Local black liquor from pulp plants**
  serve as alternative mixing water
Identify “Green” Constituents - Fly ash

Four types of locally available fly ashes were identified as:

- **WA “C” & “F” fly ash**
  Centralia Coal Plant, Washington

- **OR “C” fly ash**
  Boardman Coal Plant, Oregon

- **MT “C” fly ash (control group)**
Identify “Green” Constituents - Recycled Glass & Black Liquor

- **Recycled glass**
  Currently working with Washington State Department of Ecology to identify reliable sources

- **Black liquors from pulp plants**
  1. Clearwater pulp plant at Lewiston, ID
  2. Michelsen pulp plant at Yakima, WA
Evaluate “Green” Constituents - Fly ash

- WA “C” & “F” ash evaluation by XRF.

<table>
<thead>
<tr>
<th>WA “C” Content</th>
<th>Percentage (wt. %)</th>
<th>WA “F” Content</th>
<th>Percentage (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>33.4%</td>
<td>SiO$_2$</td>
<td>31.4%</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>14.9%</td>
<td>Al$_2$O$_3$</td>
<td>13.3%</td>
</tr>
<tr>
<td>CaO</td>
<td>14.6%</td>
<td>CaO</td>
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</tr>
<tr>
<td>MgO</td>
<td>4.7%</td>
<td>MgO</td>
<td>3.6%</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>3.7%</td>
<td>Na$_2$O</td>
<td>4.2%</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>1.22%</td>
<td>K$_2$O</td>
<td>1.34%</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>5.4%</td>
<td>Fe$_2$O$_3$</td>
<td>7.4%</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>1.5%</td>
<td>SO$_3$</td>
<td>2.6%</td>
</tr>
</tbody>
</table>
Evaluate “Green” Constituents - Fly ash

- OR “C” & MT “C” ash evaluation by XRF.

<table>
<thead>
<tr>
<th>OR “C” Content</th>
<th>Percentage (wt. %)</th>
<th>MT “C” Content</th>
<th>Percentage (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>23.6%</td>
<td>SiO$_2$</td>
<td>20.6%</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>13.8%</td>
<td>Al$_2$O$_3$</td>
<td>14.5%</td>
</tr>
<tr>
<td>CaO</td>
<td>23.2%</td>
<td>CaO</td>
<td>30%</td>
</tr>
<tr>
<td>MgO</td>
<td>4.3%</td>
<td>MgO</td>
<td>6.2%</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>6.3%</td>
<td>Na$_2$O</td>
<td>2.5%</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.35%</td>
<td>K$_2$O</td>
<td>0.24%</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>4.8%</td>
<td>Fe$_2$O$_3$</td>
<td>4.7%</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>6.0%</td>
<td>SO$_3$</td>
<td>3.8%</td>
</tr>
</tbody>
</table>
Evaluate “Green” Constituents - Fly ash

Comparison of key contents in fly ash
Evaluate “Green” Constituents - Fly ash

- Evaluate the identified fly ashes as cementitious binder

- OR “C” & WA “F” fly ash
- Montmorillite nanoclay
- Water reducing admixture
- Sodium Borate
- Styrene-butadiene rubber (SBR) latex
- Air entraining admixture
Evaluate “Green” Constituents - Fly ash

- Experiment by using uniform design scheme

- Nanoclay to Class “C” fly ash ratio ($X_1$)
  - 0%
  - 0.6%
  - 1.2%

- SBR to Class “C” fly ash ratio ($X_2$)
  - 0%
  - 6%
  - 12%

- Class “F” to Class “C” fly ash ratio ($X_3$)
  - 0%
  - 10%
  - 20%

- Water to Binder Ratio ($X_4$)
  - 20%
  - 22%
  - 24%

- Air-entraining agent dosage ($X_5$)
  - 0ml/kg
  - 25ml/kg
  - 50ml/kg

5 Factors at 3 Levels
Evaluate “Green” Constituents
- Fly ash

- Sample (2”x4” cylinders) fabrication & testing
## Evaluate “Green” Constituents - Fly ash

### Experiment results (total 27 groups; 324 samples)

Table 2 28-day Compressive Strength of Mortars with Different Factor Levels

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Factor 1 ($X_1$)</th>
<th>Factor 2 ($X_2$)</th>
<th>Factor 3 ($X_3$)</th>
<th>Factor 4 ($X_4$)</th>
<th>Factor 5 ($X_5$)</th>
<th>$f_c$(psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lev. 2</td>
<td>Lev. 2</td>
<td>Lev. 3</td>
<td>Lev. 2</td>
<td>Lev. 1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Lev. 2</td>
<td>Lev. 2</td>
<td>Lev. 2</td>
<td>Lev. 2</td>
<td>Lev. 2</td>
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<td>……</td>
<td>……</td>
<td>……</td>
</tr>
<tr>
<td>26</td>
<td>Lev. 3</td>
<td>Lev. 1</td>
<td>Lev. 3</td>
<td>Lev. 2</td>
<td>Lev. 3</td>
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<tr>
<td>27</td>
<td>Lev. 3</td>
<td>Lev. 1</td>
<td>Lev. 2</td>
<td>Lev. 3</td>
<td>Lev. 2</td>
<td></td>
</tr>
</tbody>
</table>
Evaluate “Green” Constituents - Fly ash

- Experiment results (total 27 groups; 324 samples)

Figure 1: Compressive Strength of Mortars with Different Factor Levels
Evaluate “Green” Constituents
- Fly ash

- Experiment results analysis by ANOVA and regression techniques

3-day $f_c$ (psi) = $925.8 - 316 \times X_2 - 77.9 \times X_4 - 134.5314 \times X_1^2 - 102.6 \times X_3X_5$

7-day $f_c$ (psi) = $1129.8 - 366.3 \times X_2 - 83.3 \times X_4 - 83.4 \times X_1^2 + 95 \times X_3^2 - 93 \times X_2X_4$

14-day $f_c$ (psi) = $1738.1 - 422.8 \times X_2 - 97 \times X_4 - 116.9 \times X_1^2 + 101.3 \times X_3^2 - 101 \times X_2X_4$

28-day $f_c$ (psi) = $1839.3 - 450.8 \times X_2 - 114 \times X_4 - 158 \times X_1^2 + 118.3 \times X_3^2 - 103.8 \times X_2X_4$

compressive strength models
Evaluate “Green” Constituents - Fly ash

- Model Visualization & Verification (1)

3D contour diagram of 3-day compressive strength model and model prediction vs. actual data

\[ y = 1.0384x + 444.62 \]
\[ R^2 = 0.82092 \]
Evaluate “Green” Constituents
- Fly ash

Model Visualization & Verification (2)

3D contour diagram of 28-day compressive strength model and model prediction vs. actual data
Evaluate “Green” Constituents - Fly ash

- Model Errors

Normal probability plot for 3-day $f'_c$ model

Normal probability plot for 28-day $f'_c$ model
Evaluate “Green” Constituents - Fly ash

- Effects of each mixture component on compressive strength

Trace plot for 3-day $f'_c$ model

Trace plot for 28-day $f'_c$ model
Evaluate “Green” Constituents - Fly ash

- Elastic Modulus of Mortars

<table>
<thead>
<tr>
<th>Elastic Modulus E (ksi)</th>
<th>Control</th>
<th>0% SBR</th>
<th>6% SBR</th>
<th>12% SBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
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<tr>
<td>2000</td>
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<td></td>
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</tbody>
</table>

Effect of SBR on elastic modulus at 28-Day. Control: MT C ash.

<table>
<thead>
<tr>
<th>Elastic Modulus E (ksi)</th>
<th>3-Day</th>
<th>7-Day</th>
<th>14-Day</th>
<th>28-Day</th>
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<tr>
<td>4500</td>
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<td>5500</td>
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</tbody>
</table>

Elastic modulus over time with 0% SBR
Evaluate “Green” Constituents - Fly ash

- SEM/WDS Analysis (1)

SEM micrograph of mortar surface cured for 7 days.

A) 1000X magnification.
B) 10000X magnification
SEM/WDS Analysis (2)

SEM micrograph of cenosphere with clustered small spheres inside.
Evaluate “Green” Constituents - Fly ash

- SEM/WDS Analysis (3)

Elemental mapping of mortar surface at 7 days. 1) Al. 2) Ca.
Evaluate “Green” Constituents - Fly ash

- SEM/WDS Analysis (4)

Elemental mapping of mortar surface at 7 days. 1) Si. 2) S.
Evaluate “Green” Constituents
- Fly ash

SEM/WDS Analysis Conclusion– Preliminary DOE

- Since Si & Al dissolution rates from fly ash spheres are at the same level (Brouwers 2002), the lack of Si indicates that Al is mainly from C₃A or Kleinite in fly ash and the dissolution of glassy structure of fly ash is slow.

- The element maps show that hydration products are rich in Al, Ca and S, which indicates that hydration products are mainly ettringite and monosulfate. (consistent with observation from Wang, 2004)

- Only very small amount of Si is detected, which indicates the hydration of fly ash sphere is at very low level and C-S-H gel (key hydration product from cement) is not the main hydration product.
A group of pure fly ash mortars show the highest compressive strength of 3000 psi at 28 days. ASTM C270 requires a minimum compressive strength of 1800 psi for Type S mortar at 28 days.

The close correlation between the experimental values and predicted values confirms the fitness of the compressive strength models.

Predictive equations (Models) could help optimize compression strength of the “green” mortars subject to other constraints (e.g., cost).

SEM/WDS tools can shed light on the hydration mechanism of fly ashes.
Evaluate “Green” Constituents - Fly ash

To further improve the fly ash mortar strength: 2nd DOE

- **Additives to improve ions transport behavior**
  1. A (max. 4% improvement)
  2. B (max. 5% improvement)
  3. C (max. 2% improvement)
  4. D (max. 8% improvement)

- **Chemical activators to improve fly ash reactivity**
  1. E (max. 15% improvement)
  2. F (max. 5% improvement)
  3. G (max. 32% improvement)
  4. H (max. 34% improvement)
  5. I (max. 21% improvement)
  6. J (max. 13% improvement)
Evaluate “Green” Constituents
- Fly ash

Improve the fly ash mortar strength - cont’d

- Mechanical activation to improve ash reactivity
  1. Grind fly ash (max. 19% improvement)

- New sequence of fabrication
Evaluate “Green” Constituents - Fly ash

2nd DOE: Synergy effects of activators

5 Factors at 3 Levels

- A to “C” fly ash ratio ($X_1$)
  - 1%
  - 3%
  - 7%

- B to “C” fly ash ratio ($X_2$)
  - 2%
  - 5%
  - 10%

- C to “C” fly ash ratio ($X_3$)
  - 0.5%
  - 1%
  - 2%

- Water to Binder Ratio ($X_4$)
  - 20%
  - 22%
  - 24%

- D to “C” fly ash ratio ($X_5$)
  - 1%
  - 2%
  - 3%
Evaluate “Green” Constituents - Fly ash

Preliminary Conclusion – 2nd DOE

- A group of pure fly ash mortars show the highest compressive strength of 3200 psi at 7 days, which shows about 75% improvement from 1st DOE (1800 psi at 7 days).

- The identified chemical activators are very effective to improve the reactivity of OR “C” fly ash.

- There are certainly synergistic effects of different activators, compared with the strength improvement from each individual chemical activator.
Future Research Focuses – 2nd DOE

- Develop compressive strength models to describe the synergistic effects of different chemical activators.

- SEM/WDS analysis of hydration products with chemical activators.

- Categorize class “C” fly ashes into non-reactive, low-reactivity and high-reactivity fly ashes based on the understanding of hydration mechanisms learned from this project.

- Utilize the improved fly ash pastes with recycled glass, black liquor, and nano-materials to develop pervious concretes.
Additional Testing of “Green” Pervious Concretes

- Compressive strength, elastic modulus, splitting tensile strength
- Abrasion resistance
- Salt scaling resistance (to be conducted by WTI)
- Total porosity
- Potential for treating deicer-laden stormwater
Products and Timeline

- One poster presented at Academic Showcase, WSU, March 27, 2015: “Environmentally Friendly Mortars with Coal Fly Ashes as Cementitious Binder”.

- One poster to present at the 6th Advances in Cement-Based Materials, July 20-22, 2015, Manhattan, KS.

- Two papers in preparation for the TRB 2016 Annual Meeting, Washington, D.C. and also for peer-reviewed journals.

- One patent application to be prepared by Dec. 2015.

- Project end date: extend from Sept. 30 to Dec. 30, 2015.
Acknowledgements

- Thanks for funding from CESTiCC
- Thanks to BASF, Boral and Lafarge for donated materials
- Thanks to Composite Materials and Engineering Center (CMEC) at WSU for providing test equipment.

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