Evaluation of the long-term performance of fly ash amended bioretention cells to remove phosphorous from stormwater

G. Brown, J. Vogel, D. Storm, S. Kandel, and C. Penn
Bioretention Cells (BRC)

- Stormwater runoff from urban areas transports a wide range of pollutants including P to receiving water bodies.
- BRC have been developed to treat runoff before it reaches receiving bodies.
- P removal in BRC has been reported to be highly variable, and in some cases, the cells have been an actual P source.
Grand Lake

- Grand Lake, OK, like many waters in the U.S. suffers due to phosphorus (P) over-enrichment.
- Under EPA 319 funding through the Oklahoma Conservation Commission (2005-2008), eight BRC were built in Grove, OK in the Grand Lake basin with the specific goal of reducing P inflow to the lake.
- Under EPA 319 funding through the Oklahoma Department of the Environment (2012-2015), we have gone back and sampled the cells to quantify their performance.
11 Years of Work

- Find an inexpensive filter media with high P sorption.
  - Lab screening
  - 1-D modeling
- Construct the Grove BRC
  - Standardize design and document construction
  - Quantify filter media during construction
- Perform detailed 3-D modeling of “As-Built”
- Sample filter media and water to evaluate BRC performance after running for several years.
Filter Media Section

- Batch P sorption and desorption screening for $K_d$ for several materials.
- Lab Column experiments simulated leaching within the cell and results fitted to find transport parameters.
- Long-term effluent 1-D modeled with fitted parameters.
Batch Phosphorous Adsorption

$K_d$, mL/g

<table>
<thead>
<tr>
<th>Material</th>
<th>$K_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat moss</td>
<td>-5.8</td>
</tr>
<tr>
<td>Teller loam</td>
<td>0.41</td>
</tr>
<tr>
<td>Dougherty sand</td>
<td>2.1</td>
</tr>
<tr>
<td>Expanded shale, MO</td>
<td>1.2</td>
</tr>
<tr>
<td>Limestone</td>
<td>12</td>
</tr>
<tr>
<td>Expanded shale, KS</td>
<td>280</td>
</tr>
<tr>
<td>Class C fly ash</td>
<td>2180</td>
</tr>
<tr>
<td>Sand with 5% fly ash</td>
<td>300</td>
</tr>
</tbody>
</table>
**Desorption**

- Dougherty sand desorbed average 42% of initially sorbed P, expanded shale 7%, and sand and 5% fly ash negligible amounts.
- Selected sand with fly ash as BRC filter media.
**Fly Ash**

- Class C fly ash, a byproduct of coal fueled electrical power plants, contains the metal oxides CaO, MgO, Al$_2$O$_3$ and Fe$_2$O$_4$ (23, 5, 18, and 6% respectively in our samples).
- Those oxides will react with phosphorous and heavy metals to form relatively insoluble minerals.
- The fly ash used “passed” RCRA testing.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Concentration in leachate, mg/L</th>
<th>Regulatory level, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acetic acid solution</td>
<td>De-ionized water</td>
</tr>
<tr>
<td>As</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>Cd</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Pb</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Cr</td>
<td>0.33</td>
<td>0.03</td>
</tr>
<tr>
<td>Se</td>
<td>0.28</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Column Experiments

- Column: 14.4 cm I.D., 14.3 cm long. Loading rate: 3 cm/hr.
- Influent concentration: 1 mg/L P.
1-D P Transport Modeling

- One dimensional linear equilibrium adsorption convection-dispersion transport model in CXTFIT 2.1 in the STANMOD software package developed by the U.S. Salinity Laboratory.
- Fit observed breakthrough curves by the model to estimate hydrodynamic dispersion and sorption $K_d$.
- Column $K_d$ only $\frac{1}{4}$ of batch estimate.
1-D Model Estimated Lifetime

- Filter media: sand & 5% fly ash
- Depth: 1 m
- Inflow P: 1 mg/L
- Outflow P limit: 0.037 mg/L
- Fifty years daily precipitation data were used to estimate the runoff loading.

<table>
<thead>
<tr>
<th></th>
<th>Pavements</th>
<th>Lawns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport $K_d$</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Batch $K_d$</td>
<td>12</td>
<td>34</td>
</tr>
</tbody>
</table>
Construction: Design

- 3% to 5% of area.
- Sized for runoff:
  - ½” in pool
  - ½” in filter
- 1’ topsoil.
- Filter media a blend of sand and 5% fly ash.
- Bottom drain to atmosphere.
- Sand plugs on 25% of surface for infiltration.
Construction
As Built: Fly ash distribution
As Built Hydraulics

30% reduction in peak flow
3-D Model

- BRC modeled in COMSOL Multiphysics, Earth Science Module, with saturated conditions.
- Finite element model, 7.5 x 7.5 x 1.5 m, with 75,088 elements.
- 9 configurations representing different constructions designs and construction quality examined.
3-D Modeling of flow and transport

- Filter conductivity and P sorption varied for each 1 liter volume using fly ash distribution measured during construction.
- 20 random realizations for each configuration
- 180 simulations in total.

6 plug model $K$ distribution
3-D Model Concentration Results

- 17 nominal years of complete treatment
- More than 144 years of some P removal
3-D Model Effluent Concentration

[Graph showing effluent concentration over time, with a steady increase and a dashed line indicating a standard of 0.035 mg/L.]

Effluent

0.035 mg/L Standard
2014 Sampling: Filter Media

- Six core samples from BRC at four sites.

Analysis

- Total acid digestion (EPA 3050) for total elemental P.
- WSP extraction (1:10 soil:solution) for soluble P.
- Mehlich-P (weak acid) extraction for plant available P.
2014 Sampling: Filter Media P

<table>
<thead>
<tr>
<th>Site</th>
<th>0-15</th>
<th>15-30</th>
<th>30-45</th>
<th>45-60</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GHS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spicer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Total Phosphorus (TP) mg/kg**
- **Water Soluble (P) mg/kg**
- **Mehlich 3 (P) mg/kg**
2014 Sampling: Filter Mineralogy

- Mineralogy of the adsorbed P determined with Brookhaven National Synchrotron Light Source II by X-ray absorption near edge structure analysis (XANES).
- Most P was held as calcium phosphates: brushite, monetite, hydroxyapatite, tricalcium P, and octacalcium P.
2014 Sampling: Water

- Automated Samplers installed on inflow, drain and overflow.
- Volume weighted composite samples analyzed for each storm event.
2014 Sampling: Water Total P Reduction

- P concentration: 24 to 90% reduction
- Total mass: 77 to 97% reduction
Model with PhROG: Using filter and water sampling results

**Input**
- Site hydrology
  1. Peak flow rate
  2. Annual flow volume
  3. Dissolved P level
  4. Max footprint
- P removal & lifetime
  1. Target P removal (%)
- PSM characterization
  1. P sorption
  2. Safety
  3. Physical properties

**Output**
- Design parameters
  1. Area
  2. Mass of PSM
  3. Depth of PSM
  4. Pipe reqmt

Recently developed by Dr. Chad Penn, Plant & Soil Science (OSU)
Long term P removal

Long Term Performance of Fly ash Filter media

For influent P of 1 mg/L

Site: - GEC

Cumulative Dissolved P (lbs)
Other work on these cells includes:

- Heavy metal adsorption
- Bacteria
- Construction costs
- Maintenance issues
- Planting
- Plant survival
- Initial water quality
- Hydraulics
- Construction standards

If someone wanted to work with these cells, call us.
Conclusions

- Fly ash amended filter media is effectively removing P from stormwater in the Grove BRC.
- The BRC are expected to continue to remove P for ~20 to 100+ years.
- All lab, modeling and field results justify expanded use of fly ash in stormwater systems where P is a concern.