Sustainable phosphorus removal with BOF steel slag and apatite: mechanisms and challenges

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Senior Research Engineer
Background

- Current P consents driven by Urban Wastewater Treatment Directive

<table>
<thead>
<tr>
<th>STW size (p.e.)</th>
<th>Total Phosphorus consent (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10,000</td>
<td>none</td>
</tr>
<tr>
<td>10,000 – 100,000</td>
<td>2</td>
</tr>
<tr>
<td>&gt; 100,000</td>
<td>1</td>
</tr>
</tbody>
</table>

- Water Framework Directive: good status for all waters by a set deadline

For Thames Water 48 STWs with new consents in AMP6, as low as 0.3 mg TP/L regardless of STW size.
Background

- Fertilizer production based on phosphate rock.
- Fertilizer demand not going to stop!
- Phosphate rock production meant to reach a peak.
- Shift towards technologies that promote reusing and recycling phosphorus as a fertilizer.
Conventional solution for small STWs: chemical dosing + tertiary filtration
Background

Conventional solution for small STWs: chemical dosing + tertiary filtration
Sustainable solution: Constructed wetlands with reactive media
Background

Sustainable solution: Constructed wetlands with reactive media
# P-reactive materials

<table>
<thead>
<tr>
<th></th>
<th>Basic Oxygen Furnace Steel Slag</th>
<th>Apatite 1</th>
<th>Apatite 2</th>
<th>Apatite 3</th>
<th>Apatite 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supplier</strong></td>
<td>Tarmac</td>
<td>TIMAB (Roullier Group)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Origin</strong></td>
<td>Wales</td>
<td>France</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Waste</td>
<td>Manufactured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>£</td>
<td>£££</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Density (g/mL)</strong></td>
<td>1.76</td>
<td>1.37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td>0.482</td>
<td>0.413</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: Images of materials not included in the text.*
## Column experiments with synthetic wastewater

### Methodology

<table>
<thead>
<tr>
<th>Column</th>
<th>Material, size</th>
<th>HRT (h)</th>
<th>Flow type</th>
<th>Water type</th>
<th>Time in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SS, 10mm</td>
<td>6</td>
<td></td>
<td></td>
<td>3 years</td>
</tr>
<tr>
<td>2</td>
<td>SS 7mm</td>
<td></td>
<td></td>
<td></td>
<td>3 years</td>
</tr>
<tr>
<td>3</td>
<td>SS 5mm</td>
<td></td>
<td></td>
<td></td>
<td>3 years</td>
</tr>
<tr>
<td>4</td>
<td>APA1 5mm</td>
<td>6</td>
<td>Downward, submerged</td>
<td>Synthetic (NH$_4$H$_2$PO$_4$ + tap water)</td>
<td>2.7 years</td>
</tr>
<tr>
<td>5</td>
<td>APA2 5mm</td>
<td></td>
<td></td>
<td></td>
<td>8.5 months</td>
</tr>
<tr>
<td>6</td>
<td>APA3 5mm</td>
<td></td>
<td></td>
<td></td>
<td>2.5 months</td>
</tr>
</tbody>
</table>
Column experiments with synthetic wastewater

Results – Effect of Steel Slag particle size on P removal

![Graph showing effect of Steel Slag particle size on P removal](chart.png)
Column experiments with synthetic wastewater

Results – Media conditioning

$\text{Ca}^{2+} + 2\text{OH}^- \rightleftharpoons \text{H}_2\text{O}$

CaCO$_3$ deposition limits CaO dissolution

Effluent P increases

Embedded CaPO$_4$ promotes a seed reaction

P removal is increased
Column experiments with synthetic wastewater

Results – Effect of Steel Slag particle size on effluent pH
Column experiments with synthetic wastewater

Results – Metal leaching from Steel Slag

Reed beds effluent: $V=730 \ \mu g/L$
EA limit: $V=60 \ \mu g/L$
Dilution ensures $V<60 \ \mu g/L$ in Final Effluent
Column experiments with synthetic wastewater

Results – Apatite performance

![Graph showing effluent pH against cumulative TP load/kg media (mg TP/kg media)]
Column experiments with synthetic wastewater

Results – Apatite performance
Column experiments with synthetic wastewater

Results – Apatite performance

Extrapolated to 24h HRT at full-scale:
Apatite reed bed lifetime estimated to be 12 years
Full-scale reed beds

Configuration – Site with 7,500 p.e.

<table>
<thead>
<tr>
<th>Bed</th>
<th>Material</th>
<th>Flow type</th>
<th>HRT (h)</th>
<th>Operational time (years)</th>
<th>Population treated (p.e.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SS 10-20mm</td>
<td>Horizontal sub-surface flow</td>
<td>24</td>
<td>1.8</td>
<td>~200</td>
</tr>
<tr>
<td>2</td>
<td>SS 4-10mm</td>
<td></td>
<td>24</td>
<td>1.8</td>
<td>~200</td>
</tr>
<tr>
<td>3</td>
<td>SS 2-6mm</td>
<td></td>
<td>24</td>
<td>1.6</td>
<td>~200</td>
</tr>
<tr>
<td>4</td>
<td>Apatite 2-8mm</td>
<td></td>
<td>12</td>
<td>2</td>
<td>~300</td>
</tr>
</tbody>
</table>
Full-scale reed beds

Results – Effluent P

- Large Steel slag
- Medium Steel slag
- Small Steel slag
- Apatite
- Limit of detection

Graph showing TP effluent (mg TP/L) against Cumulative P load per kg of media (mg TP/kg media).
Full-scale reed beds

Results – Effluent pH
### Full-scale reed beds

#### Results – P removal

<table>
<thead>
<tr>
<th>Material</th>
<th>P removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large SS</td>
<td>90.1</td>
</tr>
<tr>
<td>Medium SS</td>
<td>94.7</td>
</tr>
<tr>
<td>Small SS</td>
<td>95.2</td>
</tr>
<tr>
<td>Apatite</td>
<td>95.6</td>
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![Graph showing P removal across different materials](graph.png)
### Column experiments with real wastewater

#### Configuration – Easthampstead Park STW

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</tr>
<tr>
<td>3</td>
<td>SS 5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>APA1 5mm</td>
<td>6</td>
<td>Downward, submerged</td>
<td>Tertiary effluent</td>
<td>11 months</td>
</tr>
<tr>
<td>5</td>
<td>APA2 5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>APA4 5mm</td>
<td></td>
<td></td>
<td></td>
<td>1 month</td>
</tr>
</tbody>
</table>
Column experiments with real wastewater

Results – P removal

[Diagram showing TP removal over cumulative P load/kg media for different media sizes and inlets.]
Column experiments with real wastewater

Results – Effluent pH

![Graph showing effluent pH over cumulative P load/kg media (mg TP/kg media)]
### Full-scale implementation

<table>
<thead>
<tr>
<th>Phosphorus removal</th>
<th>Suitable for new P consents of 0.5 mg/L and above (apatite) and 1 mg/L and above (slag).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>Low tech, low energy, sustainable solution.</td>
</tr>
<tr>
<td>Media lifetime</td>
<td>No breakthrough achieved yet. No issue for latest apatite formulation.</td>
</tr>
<tr>
<td></td>
<td>At least 12 years for apatite. Challenge with slag, linked to removal mechanism.</td>
</tr>
<tr>
<td>Effluent pH</td>
<td>No issue for latest apatite formulation.</td>
</tr>
<tr>
<td></td>
<td>Challenge with slag, linked to removal mechanism.</td>
</tr>
<tr>
<td>Footprint</td>
<td>Vertical system – smaller footprint (1.5 m in depth as apposed to 0.6m in horizontal systems)</td>
</tr>
<tr>
<td>Proven technology</td>
<td>~ 20 installations on continent (Apatite1).</td>
</tr>
<tr>
<td></td>
<td>Apatite4 tested in columns: same performance and no pH increase.</td>
</tr>
</tbody>
</table>
Thank you