Batch operating limestone treatment system (BOLTS): a novel approach to treating mine drainage

Tasker, Travis; Roman, Ben; Eckenrode, James; Himes, Nicole; Warner, Henry; Neely, Buck; Denholm, Cliff; Strosnider, William; LaBar, Julie; Danehy, Tim
Typical **Auto-Flush**ing **Vertical Flow Pond** (AFVFP)

Continuous flow with periodic flush set by a timer

Flow-through

The flow out of the basin is controlled by an Agridrain box that uses stacking plates to set the depth of discharge.

Flush

At a defined time interval, the valve opens and the limestone basin rapidly flushes.
Preferential flow paths occur in heterogeneous porous media, likely attributing to a true HRT that is lower than the design HRT.

Kanavas et al. (2021) “Flow path resistance in heterogeneous porous media recast into a graph-theory problem.” *Transport in Porous Media*
Flow path also influences HRT and therefore pH → implications for metal precipitation and clogging.
A novel Batch Operating Limestone Treatment System (BOLTS) could increase efficiency of limestone (?)

Stage 1
Fill

- Float switch on (holding pond empties into limestone basin)
- Float switch off

Stage 2
Hold

- Float switch off
- Float switch on (Starts timer to hold for set HRT)

Stage 3
Flush

- Float switch off
- After HRT passes, limestone basin flushes and the cycle repeats
- Float switch off
A BOLTS was built near Puritan, PA

https://www.google.com/maps

~ 800 feet
~ 244 meters

<table>
<thead>
<tr>
<th>Monitoring Period</th>
<th>n</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Median</th>
<th>95th%tile</th>
<th>99th%tile</th>
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<tr>
<td>9/1/16 – 8/31/17</td>
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<td>261</td>
<td>137</td>
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Flow (GPM)

<table>
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<tr>
<th>Parameter</th>
<th>pH</th>
<th>Conductivity (umhos/cm)</th>
<th>Acidity (mg/l)</th>
<th>Iron (mg/l)</th>
<th>Manganese (mg/l)</th>
<th>Aluminum (mg/l)</th>
<th>Sulfate (mg/l)</th>
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<tr>
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<td>2.9</td>
<td>1242</td>
<td>77</td>
<td>3.9</td>
<td>1.1</td>
<td>7.7</td>
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<td>Maximum</td>
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<td>1526</td>
<td>150</td>
<td>9.2</td>
<td>1.6</td>
<td>14.6</td>
<td>709</td>
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<tr>
<td>Average</td>
<td>3.0</td>
<td>1358</td>
<td>114</td>
<td>6.3</td>
<td>1.4</td>
<td>12.0</td>
<td>653</td>
</tr>
<tr>
<td>Median</td>
<td>3.1</td>
<td>1328</td>
<td>110</td>
<td>6.0</td>
<td>1.4</td>
<td>12.4</td>
<td>589</td>
</tr>
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</table>
The system utilizes a holding pond, solar-powered Agri Drain Smart Drainage water level control structures, and a limestone basin to treat the MD Raw AMD Flow control (Agridrain) Limestone basin Settling pond Effluent
The system utilizes a holding pond, solar-powered Agri Drain Smart Drainage water level control structures, and a limestone basin to treat the MD.

- **Effluent**
  - SP2
  - AFVFP
    - 2,000 short tons
    - 1,530 yd$^3$ bulk volume
    - 26% porosity
    - 4.5-hr HRT at 300 gpm

- **High flow bypass**
  - BOLTS
    - 4,600 short tons
    - 3,400 yd$^3$ bulk volume
    - R-3, AASHTO#1, AASHTO#3
    - 30% porosity
    - 9-hr HRT at 376 GPM

- **Holding pond**
  - SP1
When influent flowrates are > than 282 gpm, the holding pond is full before a 12-hr batch treatment cycle is complete → flow is bypassed into an AFVFP until the batch cycle is complete.
In batch treatment mode, the BOLTS can fill and empty within 45 minutes (i.e., 0.75 hours)

0.75 hours to fill @ ? gpm
In batch treatment mode, the BOLTS can fill and empty within 45 minutes (i.e., 0.75 hours)

0.75 hours to fill @ 
(203,040 gal void volume/45 mins) = 4,512 gpm
The limestone is a mixture of R-3, AASHTO#1, and AASHTO#3 → average surface area of 556 ft²/short ton

For comparison, below are stone sizes (Cravotta et al., 2008)

- R-3
- AASHTO#1
- AASHTO#3

- 8 cm
- 0.5 cm
So. . . . what was the goal of this research?

We hypothesize that a BOLTS overcomes short circuiting and flow challenges that can occur in auto flushing vertical flow pond’s (AFVFP’s) by allowing “batches” of MD to be treated for a set HRT, producing higher acidity removal rates than a typical horizontal flow AFVFP that operates in flowthrough.
The acidity in the MD from Puritan, PA was neutralized in buckets (full of Puritan limestone) after 5-hour HRT.
A first order model was used to predict net acidity with time elapsed

\[
C_t = C_s - [(C_s - C_0) \exp(k t_d)]
\]

\[
k_{sa} = \frac{k}{(A/V)}
\]

\[
A/V = A_u \left(\frac{\rho_b}{n}\right)
\]

\[
A_u = 556 \text{ ft}^2/\text{short ton}
\]

\[
n = 0.3
\]

\[
\rho_b = 1.35 \text{ short tons/yd}^3
\]

\[
A/V = 2500 \text{ ft}^2/\text{yd}^3
\]

(Cravotta et al., 2008)
Acidity was also measured in the effluent of the limestone beds when operated in flowthrough treatment mode.

ISCO 3700 water sampler and Eureka Manta+20 water quality monitoring sonde were installed in the Agri Drain box at the outlet of the AFVFP → water samples collected during flow through and flushing.
The AFVFP had a lower acidity removal rate than the bucket tests.

![Diagram showing the comparison between the AFVFP and bucket tests.]

- **AFVFP** with a theoretical HRT of 4.5 hours and 9 hours.
- **Bucket Test** with a theoretical HRT of 4.5 hours and 9 hours.

**Simulation Results**:
- **AFVFP**:
  - $k = -0.26 \text{ hr}^{-1}$
  - $K_{sa} = -1.0 \times 10^{-4} \text{ yd}^3/\text{ft}^2\text{hr}$
- **Bucket Test**:
  - $k = -0.08 \text{ hr}^{-1}$
  - $K_{sa} = -3.1 \times 10^{-5} \text{ yd}^3/\text{ft}^2\text{hr}$

**Net Acidity (mg/L as CaCO₃)** vs. **Time (hours)** graph is shown with data points and trend lines for both methods.
Acidity was also measured in the effluent of the limestone beds when operated in Batch treatment mode.

Measured water chemistry during the 45-minute flush cycle

Treated in batch for 4.5 and 9.0 hours
The BOLTS had an acidity removal rate that was similar to the bucket tests.
The acidity removal rates were used to compare costs of treating the MD in a BOLTS or AFVFP

Mass of limestone = \[\frac{(Q \ C \ T)}{x} + \frac{(Q \ \rho_b \ t_d)}{(V_v \ x)}\] \hspace{1cm} (Hedin and Watzlaf, 1993)

- \(Q\) = flowrate
- \(\rho_b\) = bulk density of limestone
- \(t_d\) = detention time (i.e., HRT)
- \(V_v\) = bulk void volume expressed as a decimal (i.e., the porosity of the stone = \(n\))
- \(C\) = the predicted concentration of alkalinity or net acidity (i.e., \(\Delta C\))
- \(T\) = design life (i.e., \(t_L\))
- \(x\) = \(CaCO_3\) content expressed as a percentage
The acidity removal rates were used to compare costs of treating the MD in a BOLTS or AFVFP.

Mass of limestone = \[\frac{(Q\ C\ T)}{x}\] + \[\frac{(Q\ \rho_b\ t_d)}{(V_v\ x)}\] \hspace{1cm} (Hedin and Watzlaf, 1993)

Substitute:

\[C_t = C_s - \left(\frac{(C_s - C_0)}{\exp(k\ t_d)}\right)\] \hspace{1cm} \rightarrow \hspace{1cm} t_d = \frac{\ln(C_t - C_s)/(C_0 - C_s)}{k}

\[k = k_{sa}(A/V)\]

\[A/V = A_u\frac{\rho_b}{n}\]

\[V_v = n\]

\[C = \Delta C\]

\[T = t_L\]

Mass of limestone = \[M_s = \frac{(Q/x)[(t_L\ \Delta C)]}{(Q/x)[\ln([C_t - C_s]/(C_0 - C_s))/(k_{sa} A_u)]}\]
An AFVFP would require ~2x more limestone than a BOLTS to treat the Puritan MD to -20 mg/L net acidity

Assumptions:
- \( Q = 300 \text{ gpm} \)
- \( C_0 = 250 \text{ mg/L net acidity} \)
- \( C_t = -20 \text{ mg/L net acidity} \)
- \( C_s = -113 \text{ mg/L net acidity} \)
- \( t_L = 20 \text{ years} \)
- \( x = 0.9 \) (limestone purity)
- \( A_u = 556 \text{ ft}^2/\text{short ton} \) (AASHTO#1 to AASHTO#3)
- \( n = 0.3 \)
- \( \rho_b = 1.35 \text{ short tons/yd}^3 \)
- \( k_{sa} = -1.2 \times 10^{-4} \text{ yd}^3/\text{ft}^2\text{hr} \) for BOLTS
- \( k_{sa} = -3.1 \times 10^{-5} \text{ yd}^3/\text{ft}^2\text{hr} \) for AFVFP

BOLTS:
\[
M_s = \frac{Q}{x} [t_L \Delta C] + \frac{Q}{x} \left[ \ln \left( \frac{C_t - C_s}{C_o - C_s} \right) \right] \left( k_{sa} A_u \right)
\]

\[
M_s = 3952 + 2020 = 5,972 \text{ short tons for BOLTS}
\]

AFVFP:
\[
M_s = 3952 + 7822 \text{ short tons}
\]

\[
= 11,774 \text{ short tons for AFVFP}
\]
The BOLTS is cheaper than an AFVFP for treating the Puritan MD

Assumptions:

- $\rho_b = 1.35$ short tons/yd$^3$
- Agri Drain Smart Drain® in BOLTS = $17,960$ per structure
- Agri Drain Smart Drain® in AFVFP = $15,230$ per structure
- $17.35$/short ton of limestone
- $6.50$/yd$^3$ of excavation w/ clay liner
- $13$/ft of 12-inch perforated DR-26 HDPE pipe
- $7.5$/ft of 6-inch perforated D pipe
- $1$/yd$^2$ of geotextile
- Depth of basins = 8 feet
- Side slopes = 2:1
- Length to width ratio = 5:1
In summary, the BOLTS produced higher acidity removal rates than the AFVFP → new ideas for treating MD?

Questions?

Dr. Travis Tasker
Associate Professor
Saint Francis University
ttasker@francis.edu

An experiment was performed to see how long it took the BOLTS to fill at continuous influent flow of ~376 gpm.
The BOLTS has a bulk volume of 3,400 yd³, void volume of 203,040 gallons (i.e., 1005 yd³), and porosity of 30%.

540 minutes x 376 gal/min = 203,040 gallon void volume (i.e., 1005 yd³)

1005 yd³ void volume / 3,400 yd³ bulk volume = 30% porosity

 Bulk density = 4,600 short tons / 3,400 yd³ bulk volume = 1.35 short tons / yd³
An experiment was performed to see how long it took the AFVFP to fill at continuous influent flow of ~295 gpm.
The AFVFP has a bulk volume of 1,530 yd\(^3\), void volume of 79,650 gallons (i.e., 394 yd\(^3\)), and porosity of 26%.
Average net acidity in the effluent during flowthrough treatment mode (9-hour theoretical HRT) was 71 mg/L
BOLTS with 9 hour hold time → the average net acidity during the flush was -26 mg/L
AFVFP would be cheaper than the BOLTS if sized with same $k_{sa}$ as BOLTS

Assumptions:

- $\rho_b = 1.35$ short tons/yd$^3$
- Agri Drain Smart Drain® in BOLTS = $17,960$ per structure
- Agri Drain Smart Drain® in AFVFP = $15,230$ per structure
- $17.35$/short ton of limestone
- $6.50$/yd$^3$ of excavation w/ clay liner
- $13$/ft of 12-inch perforated DR-26 HDPE pipe
- $7.5$/ft of 6-inch perforated D pipe
- $1$/yd$^2$ of geotextile
- Depth of basins = 8 feet
- Side slopes = 2:1
- Length to width ratio = 5:1
Could the MD be treated faster with smaller stone size?

Stone sizes (Cravotta et al., 2008)

<table>
<thead>
<tr>
<th>Stone Size</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>8 cm</td>
<td>#2</td>
</tr>
<tr>
<td>0.5 cm</td>
<td>#5</td>
</tr>
<tr>
<td>#1</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td></td>
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<td>#5</td>
<td></td>
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<td>#7</td>
<td></td>
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<tr>
<td>#8</td>
<td></td>
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<td>#10</td>
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\[
C_t = C_s - [(C_s - C_0) \exp(k \cdot t_d)]
\]

\[
k_{sa} = k/(A/V)
\]

\[
A/V = A_u (\rho_b/n)
\]

\[
k = k_{sa}[A_u (\rho_b/n)]
\]

\[
A_u = 556 \text{ ft}^2/\text{short ton}
\]

for AASHTO#1 / AASHTO#3

\[
A_u = 2,800 \text{ ft}^2/\text{short ton}
\]

for AASHTO#7
If stone size was reduced, the MD could be treated faster.
If stone size was reduced, would require 27% less limestone to treat the MD

Assumptions:

- \( Q = 300 \text{ gpm} \)
- \( C_o = 250 \text{ mg/L net acidity} \)
- \( C_t = -20 \text{ mg/L net acidity} \)
- \( C_s = -113 \text{ mg/L net acidity} \)
- \( t_L = 20 \text{ years} \)
- \( x = 0.9 \) (limestone purity)
- \( A_u = 556 \text{ ft}^2/\text{short ton} \) (AASHTO#1 to #3)
- \( A_u = 2,800 \text{ ft}^2/\text{short ton} \) (AASHTO#7)
- \( n = 0.3 \)
- \( \rho_b = 1.35 \text{ short tons/yd}^3 \)
- \( k_{sa} = -1.2 \times 10^{-4} \text{ yd}^3/\text{ft}^2\text{hr} \) for BOLTS
- \( k_{sa} = -3.1 \times 10^{-5} \text{ yd}^3/\text{ft}^2\text{hr} \) for AFVFP

\[
M_s = \frac{(Q/x)[t_L \Delta C]}{[\ln((C_t - C_s)/(C_o - C_s))/(k_{sa} A_u)]}
\]

\( k_{sa} = -1.2 \times 10^{-4} \text{ yd}^3/\text{ft}^2\text{hr} \) for BOLTS

\( A_u = 556 \text{ ft}^2/\text{short ton} \) for AASHTO#1 to #3

\( M_s = 5,972 \text{ short tons} \) for AASHTO#1 / AASHTO#3

\( A_u = 2,800 \text{ ft}^2/\text{short ton} \) for AASHTO#7

\( M_s = 4,340 \text{ short tons} \) for AASHTO#7
Cost of BOLTS would decrease from $200,000 to $150,000 if used smaller stone size

Assumptions:

- $\rho_b = 1.35 \text{ short tons/yd}^3$
- Agri Drain Smart Drain® in BOLTS = $17,960$ per structure
- Agri Drain Smart Drain® in AFVFP = $15,230$ per structure
- $17.35$ per short ton of limestone
- $6.50$/yd$^3$ of excavation w/ clay liner
- $13$/ft of 12-inch perforated DR-26 HDPE pipe
- $7.5$/ft of 6-inch perforated D pipe
- $1$/yd$^2$ of geotextile
- Depth of basins = 8 feet
- Side slopes = 2:1
- Length to width ratio = 5:1

![Graph showing flowrate vs. cost with two lines, one labeled BOLTS $K_{sa}(this\ study) = AASHTO\#1\ to\ #3$ and the other labeled BOLTS $K_{sa}(this\ study) = AASHTO\#7$.]