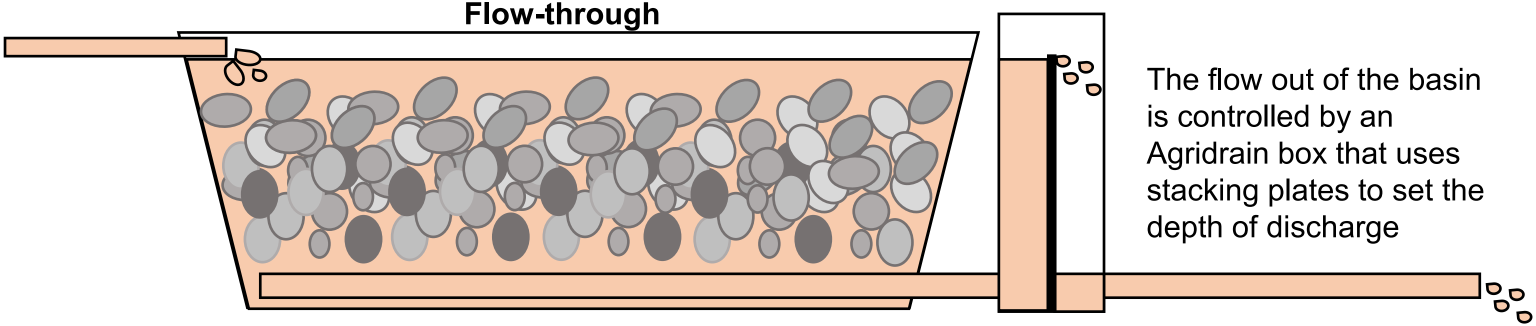
Batch operating limestone treatment system (BOLTS): a novel approach to treating mine drainage

Tasker, Travis; Roman, Ben; Eckenrode, James; Himes, Nicole; Warner, Henry; Neely, Buck; Denholm, Cliff; Strosnider, William; LaBar, Julie; Danehy, Tim

Typical Auto-Flushing Vertical Flow Pond (**AFVFP**)

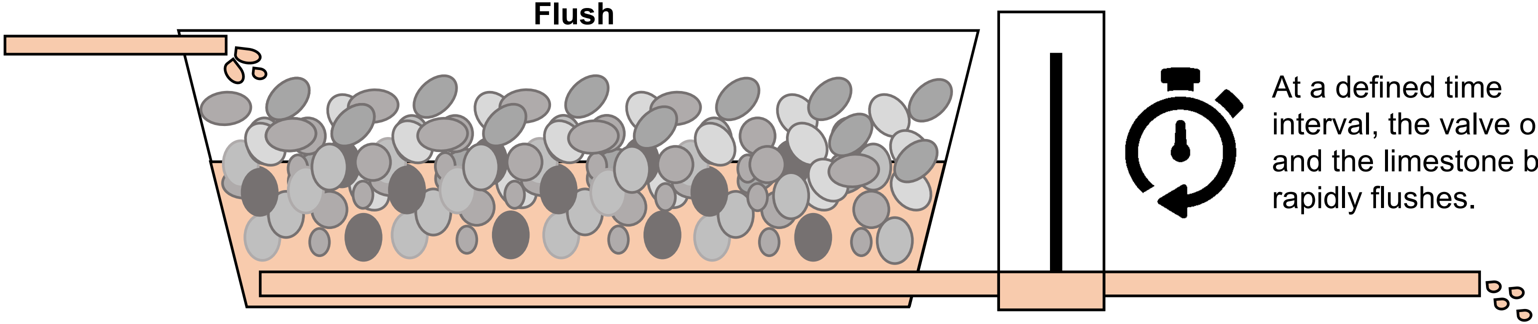
Continuous flow with periodic flush set by a timer

Flow-through



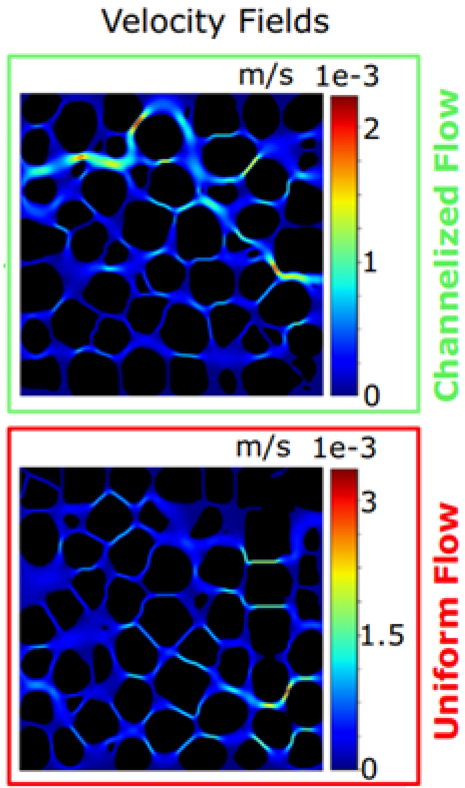
The flow out of the basin is controlled by an Agridrain box that uses stacking plates to set the depth of discharge

Flush

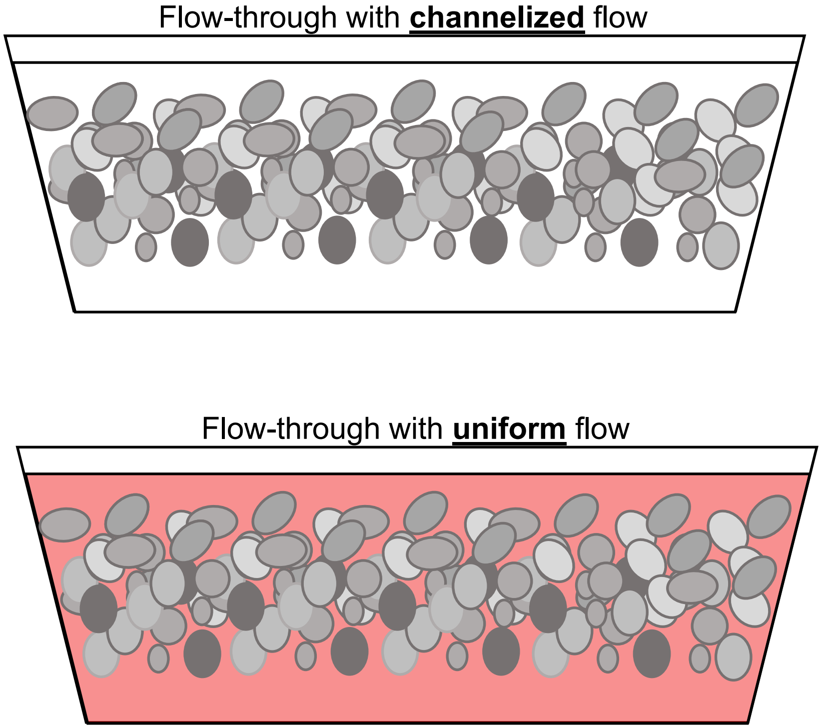


At a defined time interval, the valve opens and the limestone basin rapidly flushes.

Preferential flow paths occur in heterogenous porous media, likely attributing to a true HRT that is lower than the design HRT.

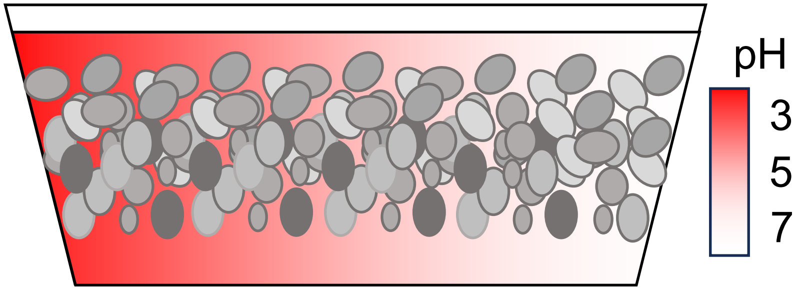


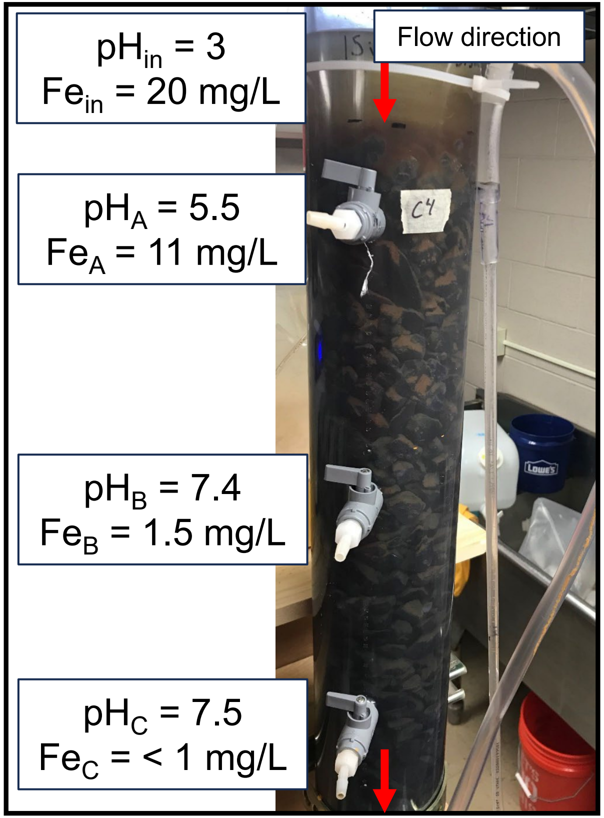
Kanavas et al. (2021) “Flow path resistance in heterogenous porous media recast into a graph-theory problem.” *Transport in Porous Media*

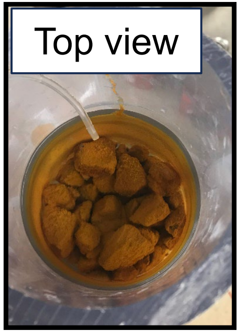


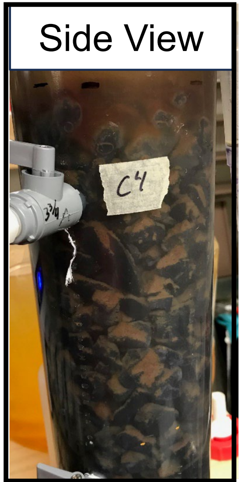
Flow path also influences HRT and therefore pH → implications for metal precipitation and clogging

Hypothetical pH gradient across horizontal flow direction

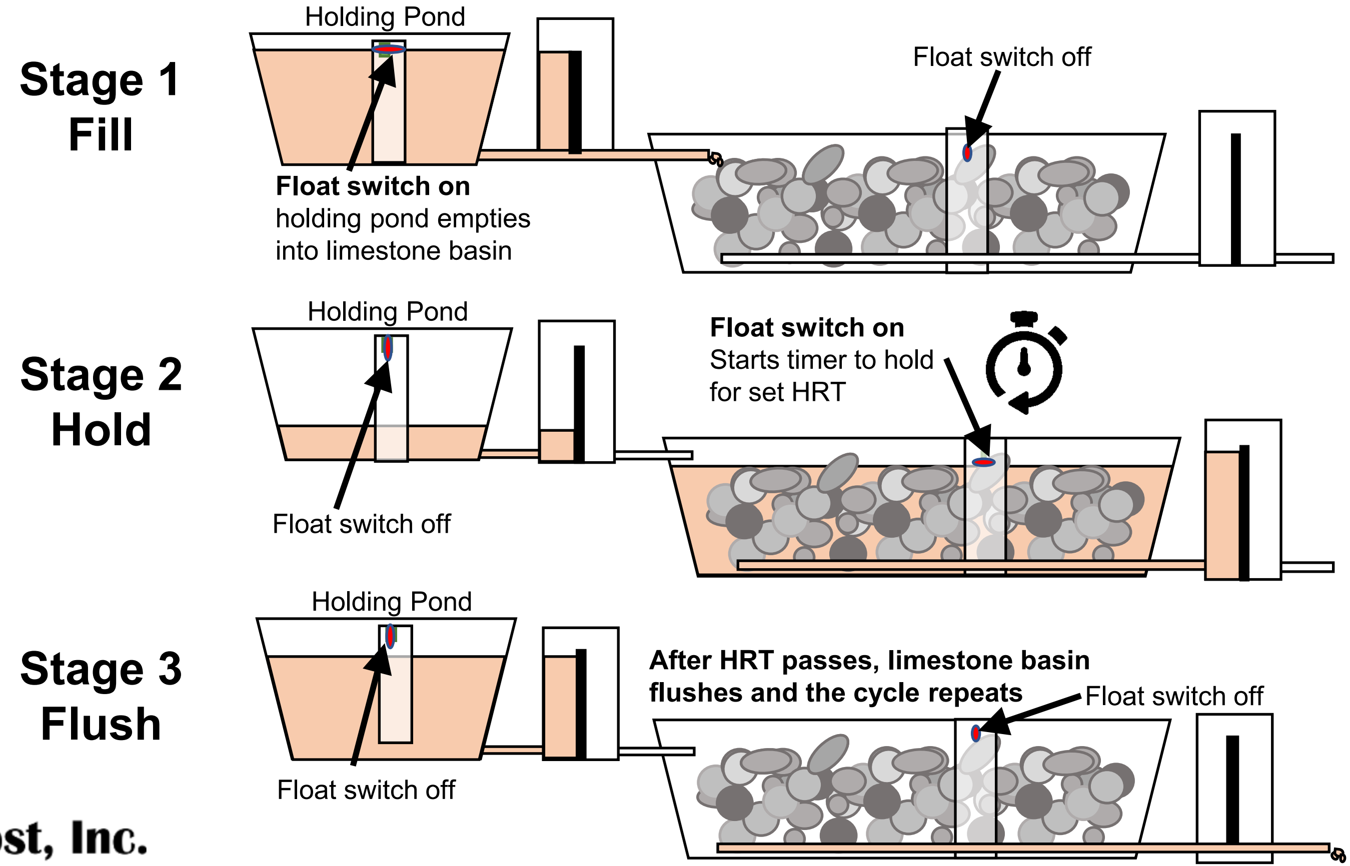








A novel Batch Operating Limestone Treatment System (BOLTS) could increase efficiency of limestone (?)



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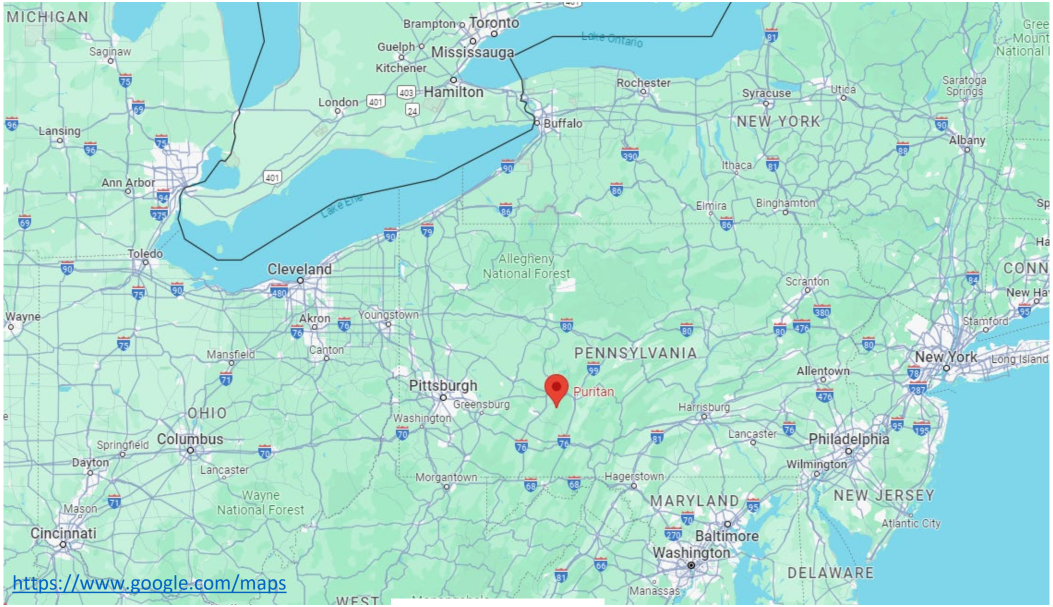
A BOLTS was built near Puritan, PA



https://www.google.com/maps

Monitoring Period	n	Minimum	Maximum	Average	Median	95th%tile	99th%tile
		Flow (GPM)					
9/1/16 – 8/31/17	30,618	110	1599	261	137	558	664
9/1/17 – 8/31/18	28,886	110	1374	242	209	599	724

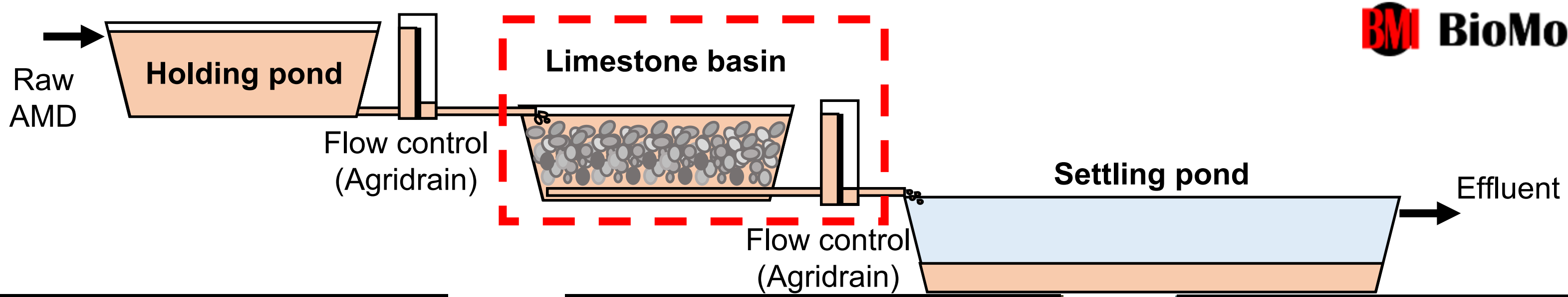
Parameter	pH s.u.	Conductivity umhos/cm	Acidity mg/L	Iron mg/L	Manganese mg/L	Aluminum mg/L	Sulfate mg/L
Minimum	2.9	1242	77	3.9	1.1	7.7	584
Maximum	3.1	1526	150	9.2	1.6	14.6	709
Average	3.0	1358	114	6.3	1.4	12.0	653
Median	3.1	1328	110	6.0	1.4	12.4	589

~ 800 feet
~ 244 meters

BioMost, Inc.

The system utilizes a holding pond, solar-powered Agri Drain Smart Drainage water level control structures, and a limestone basin to treat the MD

BioMost, Inc.



Holding pond

Limestone basin

Settling pond

The system utilizes a holding pond, solar-powered Agri Drain Smart Drainage water level control structures, and a limestone basin to treat the MD

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

SP1

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

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

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

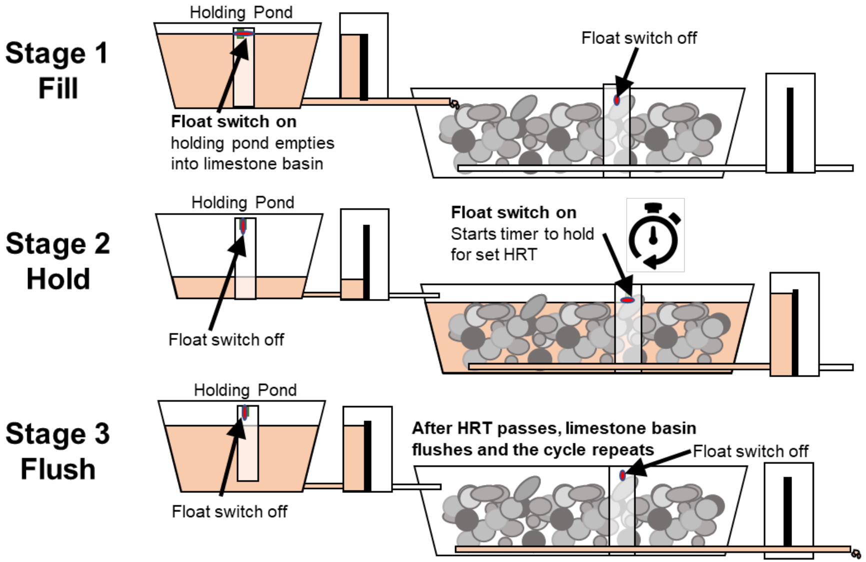
SP1

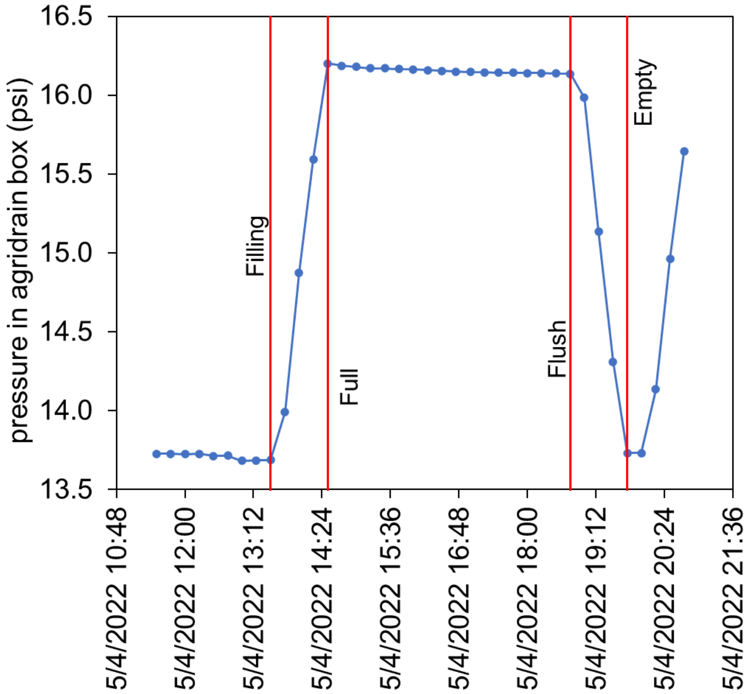
BOLTS
4,600 short tons
3,400 yd^3 bulk volume
R-3, AASHTO#1, AASHTO#3
30% porosity
9-hr HRT at 376 GPM

Holding pond

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

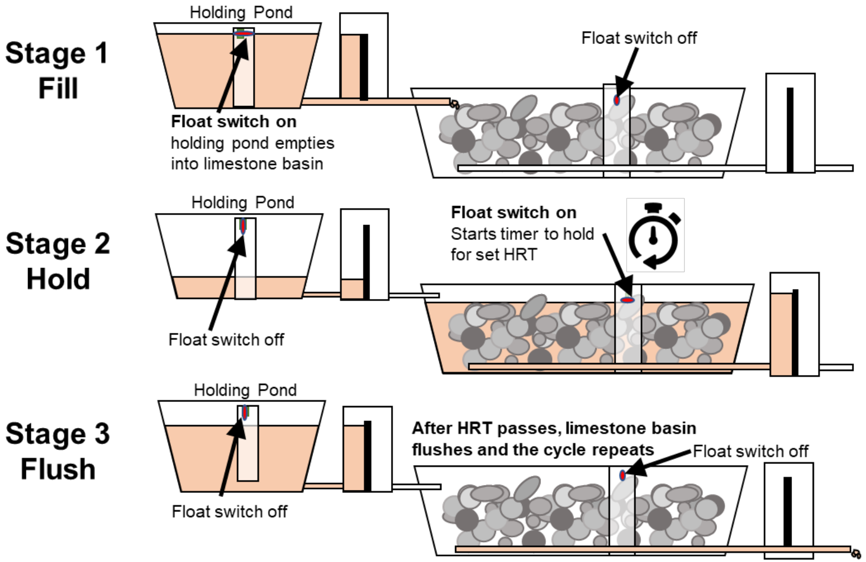
0.75 hours to fill @ ? gpm

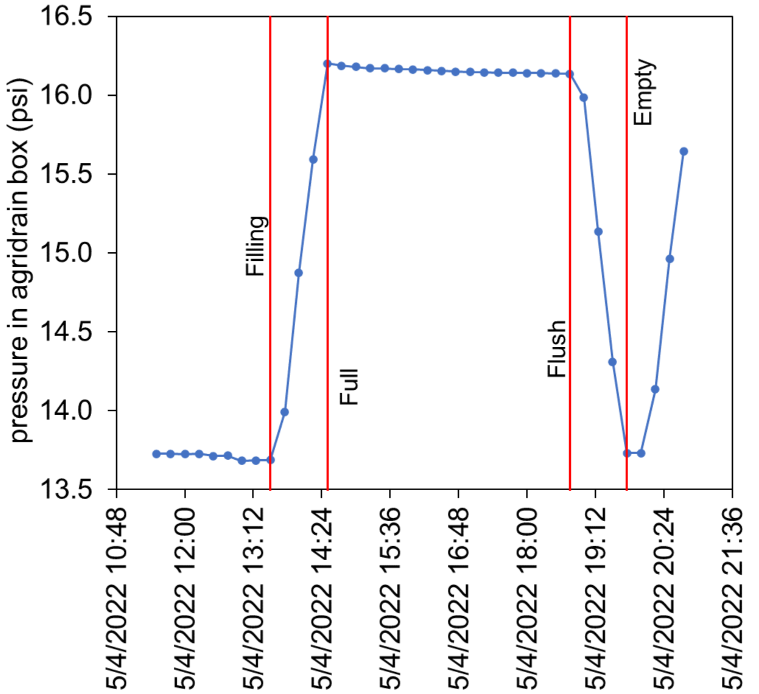




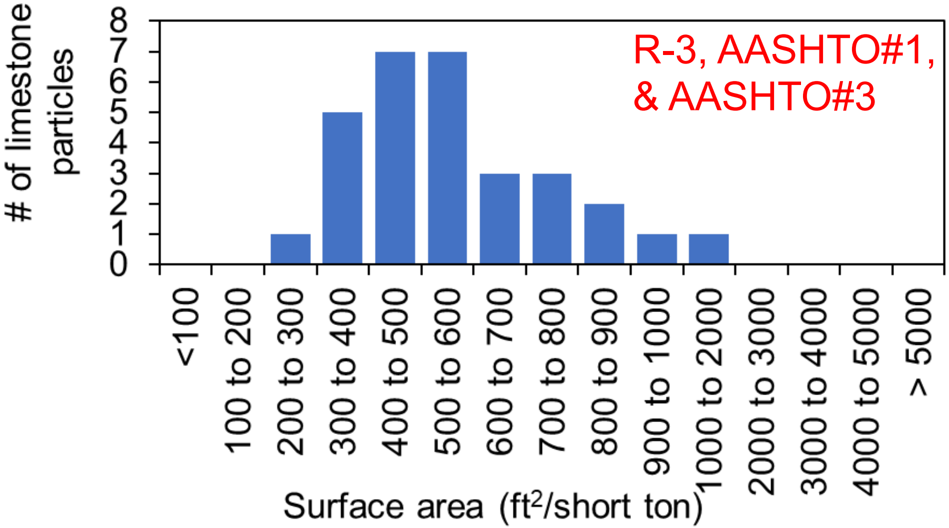
In batch treatment mode, the BOLTS can fill and empty within 45 minutes (i.e., 0.75 hours)

0.75 hours to fill @ (203,040 gal void volume/45 mins) = 4,512 gpm





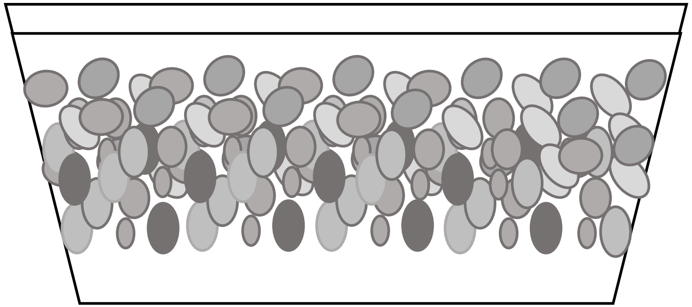
The limestone is a mixture of R-3, AASHTO#1, and AASHTO#3 → average surface area of 556 ft^2/short ton



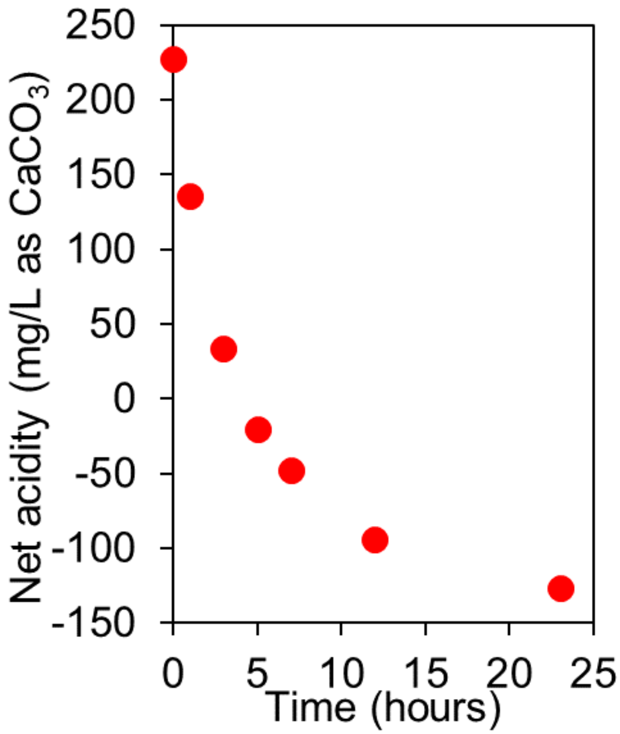
For comparison, below are stone sizes (Cravotta et al., 2008)

So. . . . what was the goal of this research?

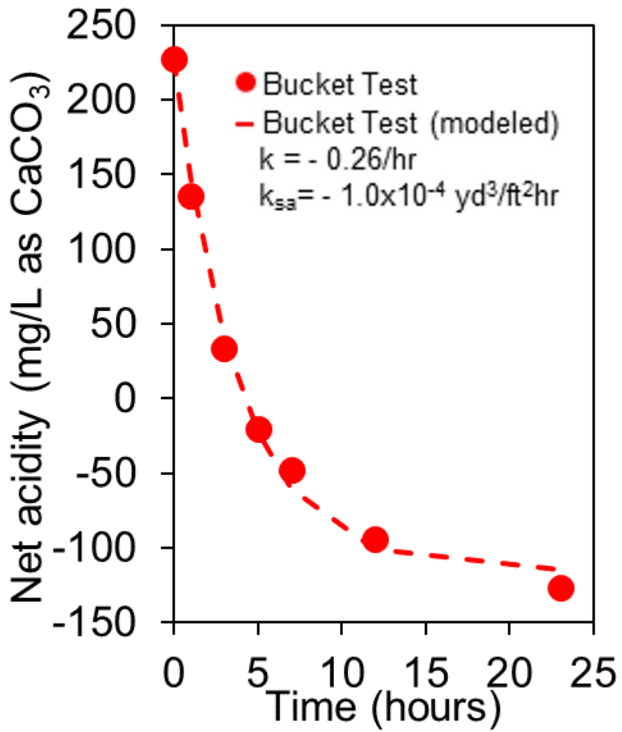
We hypothesize that a BOLTS overcomes short circuiting and flow challenges that can occur in auto flushing vertical flow pond's (AFVFP's) by allowing "batches" of MD to be treated for a set HRT, producing higher acidity removal rates than a typical horizontal flow AFVFP that operates in flowthrough.



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



$C_t = C_s - [(C_s - C_0)\exp(k\,t_d)]$ (Cravotta et al., 2008)

$k_{sa} = k/(A/V)$

$A/V = A_u\,(\rho_b/n)$

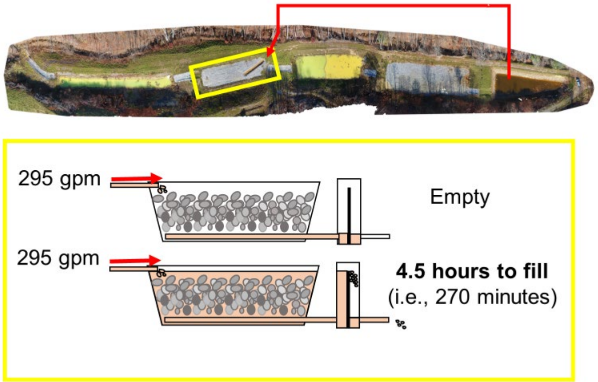
$A_u = 556\ ft^2/\text{short ton}$

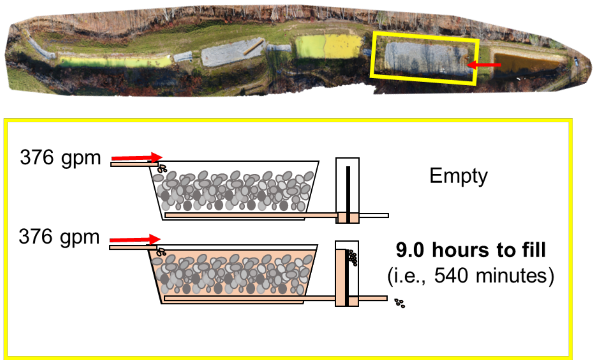
$n = 0.3$

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

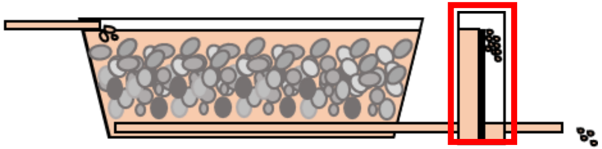
$A/V = 2500\ ft^2/yd^3$

Acidity was also measured in the effluent of the limestone beds when operated in flowthrough treatment mode

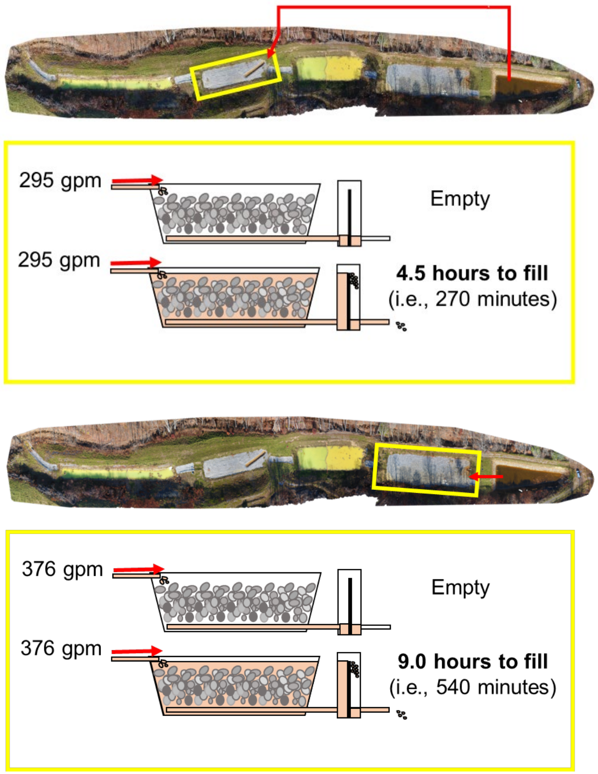


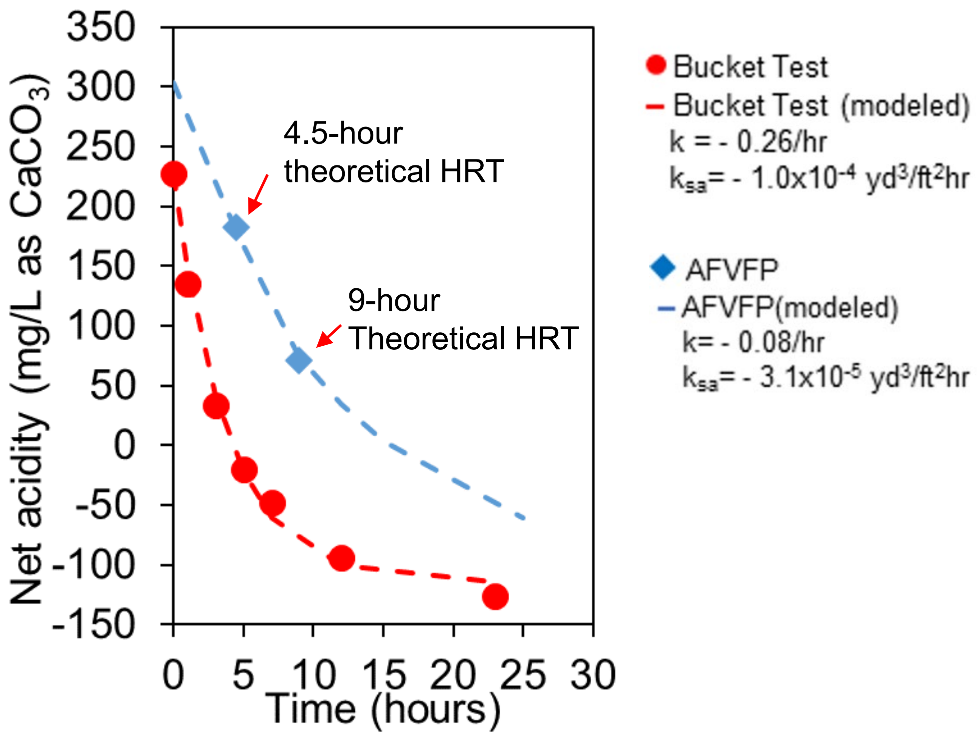


ISCO 3700 water sampler and Eureka Manta+20 water quality monitoring sonde were installed in the Agri Drain box at the outlet of the AFVFP → water samples collected during flow through and flushing



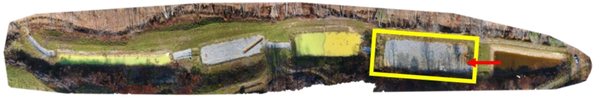
The AFVFP had a lower acidity removal rate than the bucket tests

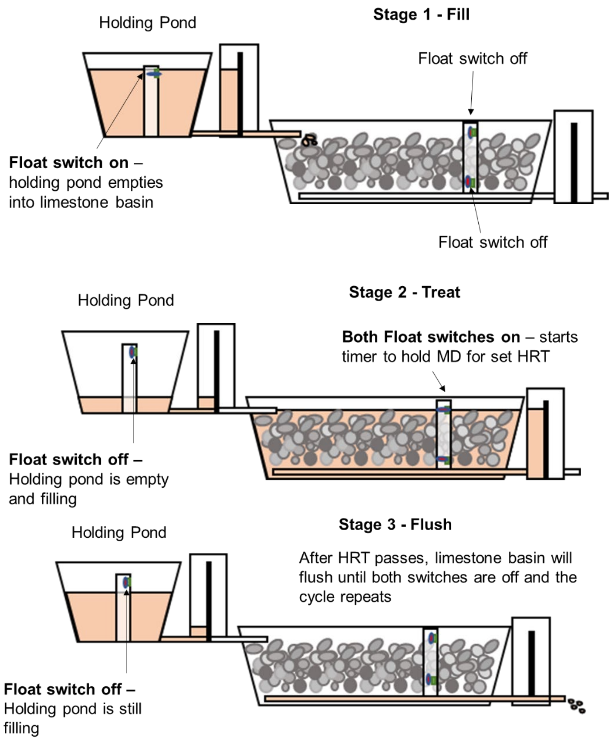




Acidity was also measured in the effluent of the limestone beds when operated in Batch treatment mode

Treated in batch for 4.5 and 9.0 hours

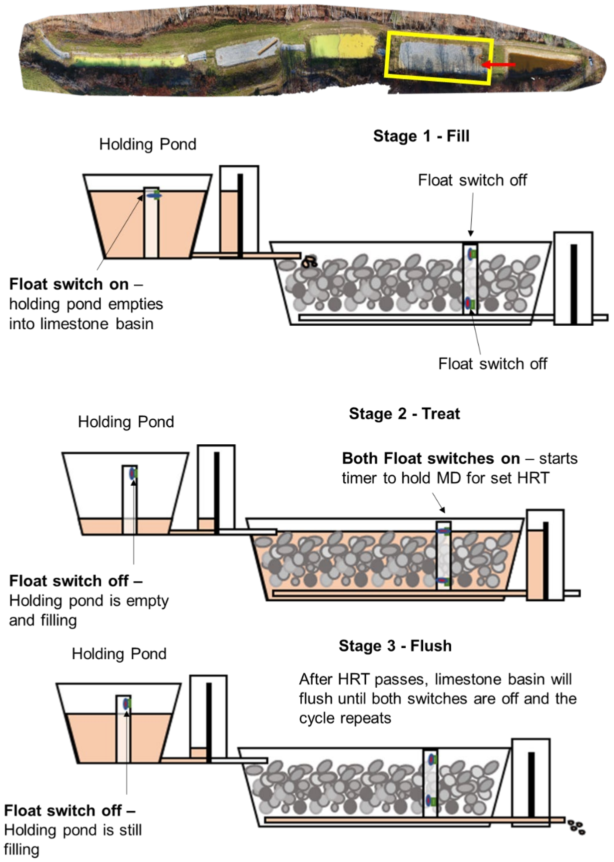


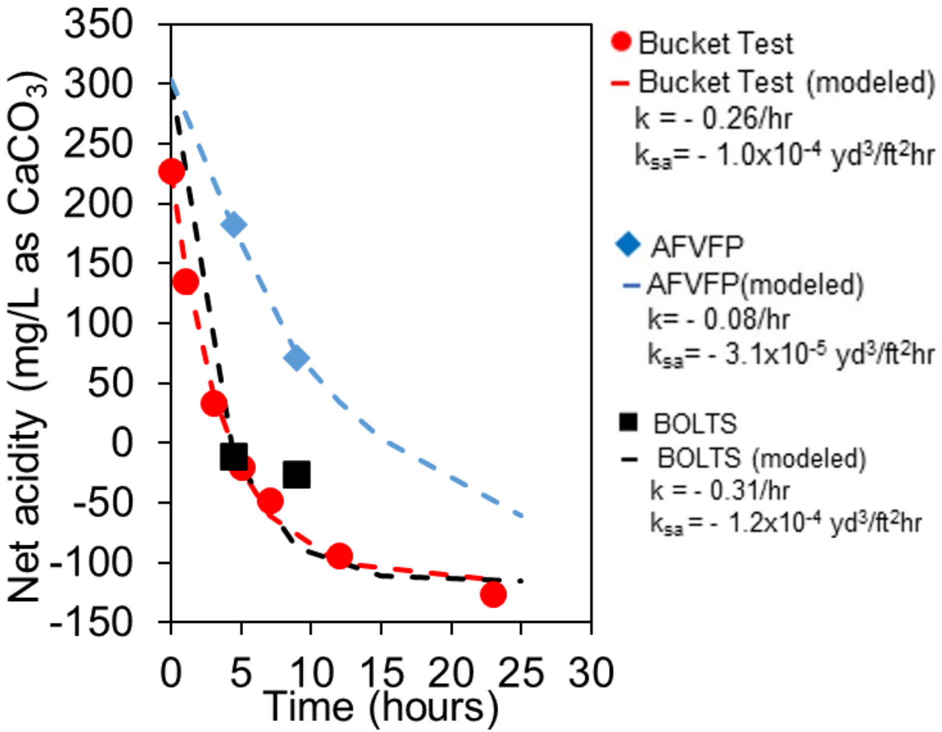


Measured water chemistry during the 45-minute flush cycle

The BOLTS had an acidity removal rate that was similar to the bucket tests

Treated in batch for 4.5 and 9.0 hours





The acidity removal rates were used to compare costs of treating the MD in a BOLTS or AFVFP

Mass of limestone = $[(Q\ C\ T)/x] + [(Q\ \rho_b\ t_d)/(V_v\ x)]$ (Hedin and Watzlaf, 1993)

Q = flowrate

ρ_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., ΔC)

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 = $[(Q\ C\ T)/x] + [(Q\ \rho_b\ t_d)/\ (V_v\ x)]$ (Hedin and Watzlaf, 1993)

Substitute:

$C_t = C_s - [(C_s - C_0)\ \exp(k\ t_d)]$ → $t_d = [\ln(C_t\text{-}C_s)/C_0\text{-}C_s)]/k$

$k = k_{sa}(A/V)$

$A/V = A_u\ (\rho_b/n)$

$V_v = n$

$C = \Delta C$

$T = t_L$

Mass of limestone = $M_s = (Q/x)[(t_L\ \Delta C)] + (Q/x)[\ln[(C_t - C_s)/(C_o - C_s)]/(k_{sa}\ A_u)]$

An AFVFP would require ~2x more limestone than a BOLTS to treat the Puritan MD to -20 mg/L net acidity

<u>Assumptions:</u>

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

<u>BOLTS:</u>

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

M_s = 3952 + 2020
= 5,972 short tons for BOLTS

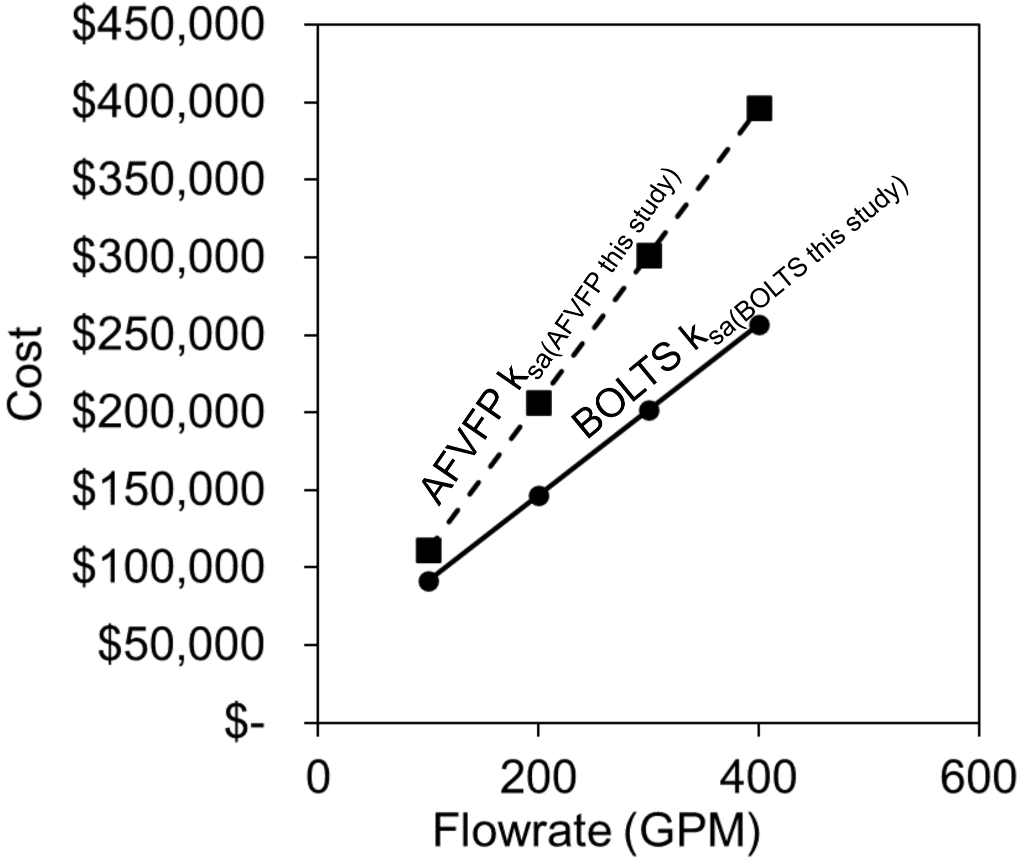
<u>AFVFP:</u>

M_s = 3952 + 7822 short tons
= 11,774 short tons for AFVFP

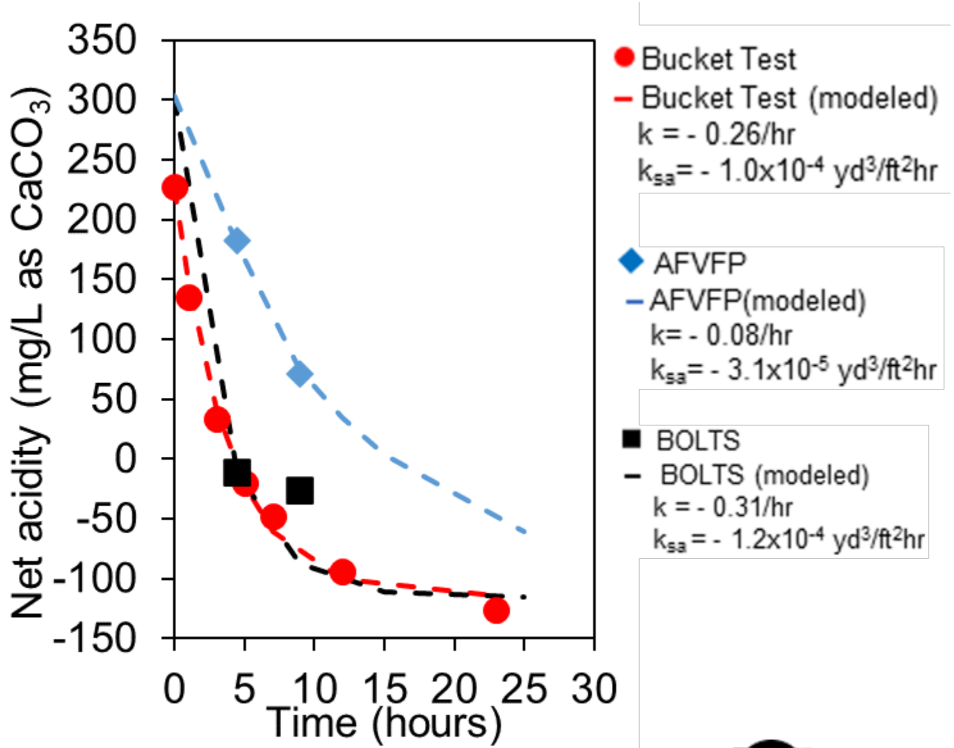
The BOLTS is cheaper than an AFVFP for treating the Puritan MD

<u>Assumptions:</u>

- ρ_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?

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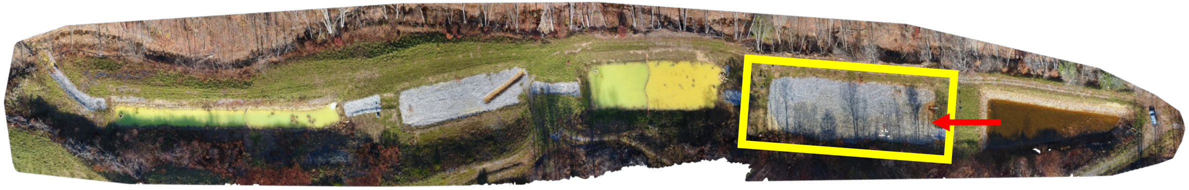
References

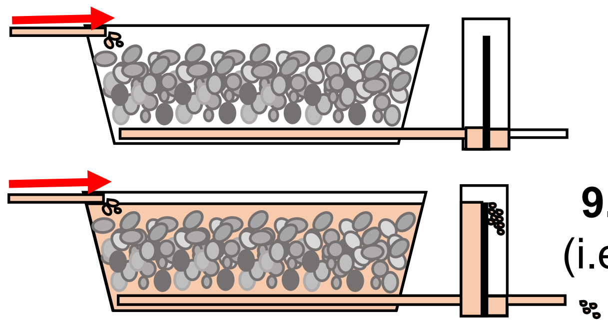
Cravotta III, C. A. (2008). Laboratory and field evaluation of a flushable oxic limestone drain for treatment of net-acidic drainage from a flooded anthracite mine, Pennsylvania, USA. *Applied Geochemistry*, 23(12), 3404-3422.

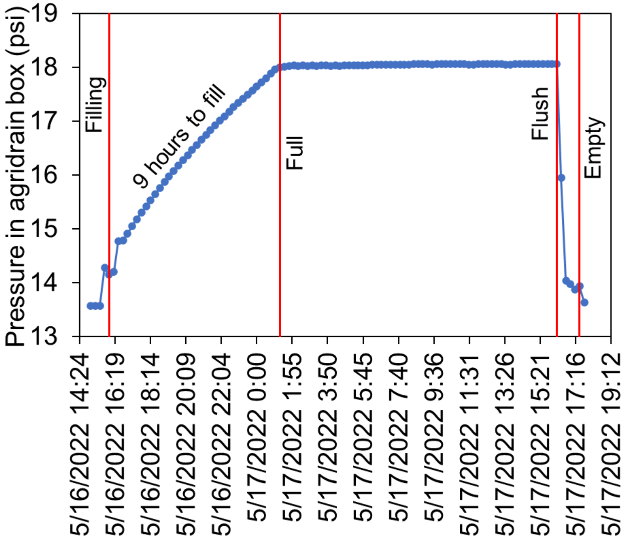
Hedin, R. S., & Watzlaf, G. R. (1993). The effects of anoxic limestone drains on mine water chemistry. Proceedings American Society of Mining and Reclamation. *Proceedings America Society of Mining and Reclamation*, 185 – 194.

An experiment was performed to see how long it took the BOLTS to fill at continuous influent flow of ~376 gpm

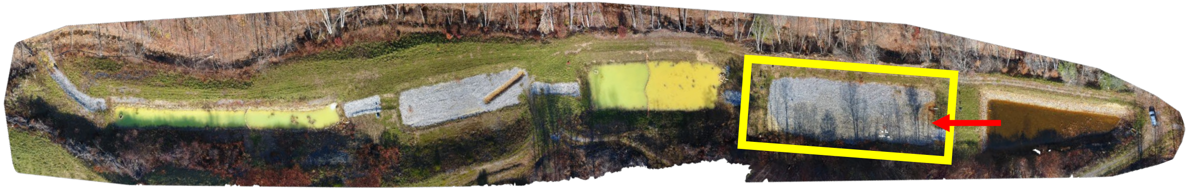


9 hours to fill @ 376 gpm

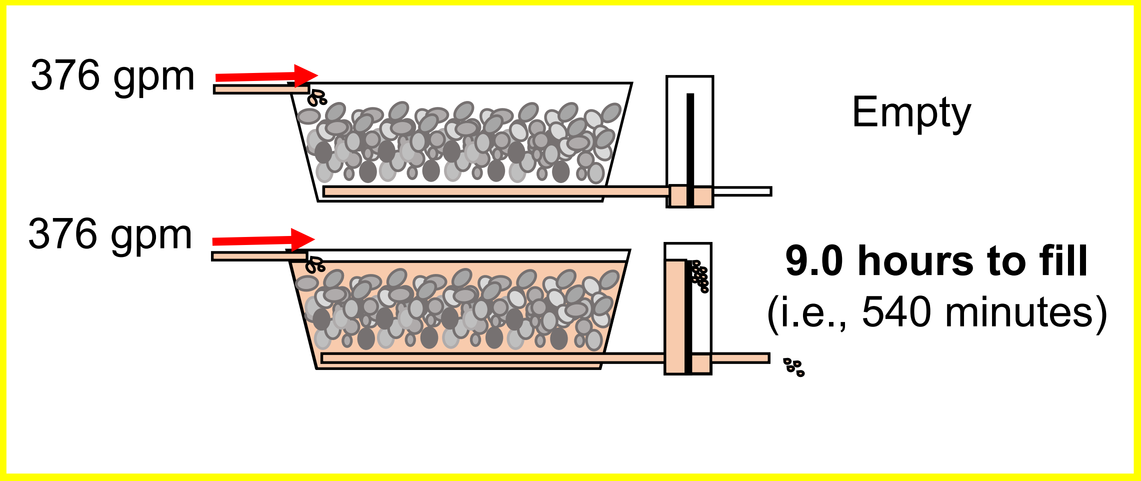




The BOLTS has a bulk volume of 3,400 yd^3, void volume of 203,040 gallons (i.e., 1005 yd^3), and porosity of 30%



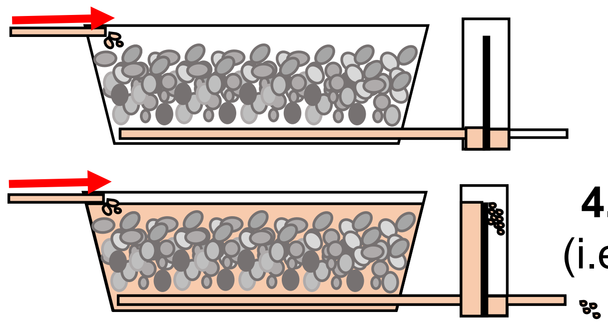
540 minutes x 376 gal/min
= **203,040 gallon void volume (i.e., 1005 yd^3)**



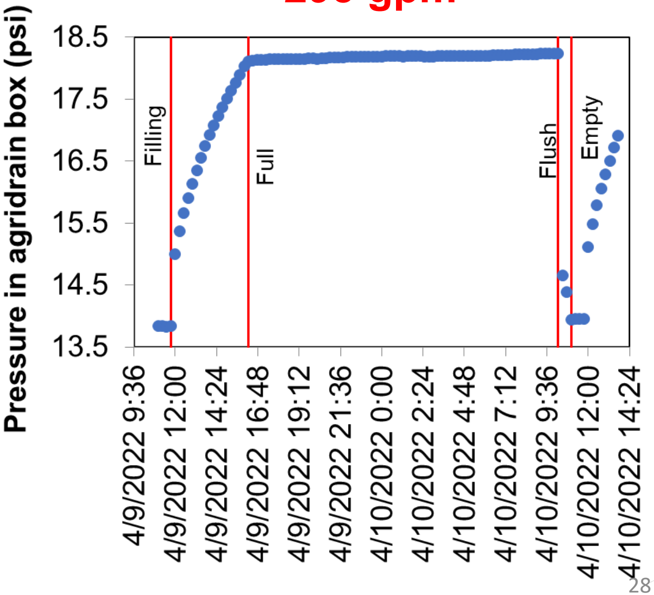
1005 yd^3 void volume /
3,400 yd^3 bulk volume
= **30% porosity**

Bulk density = 4,600 short tons /
3,400 yd^3 bulk volume
= **1.35 short tons / yd^3**

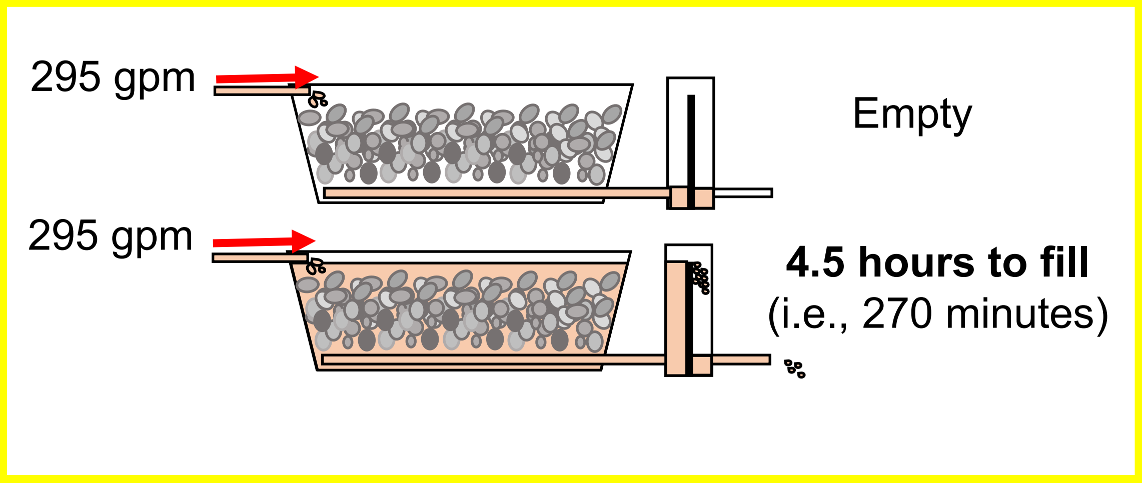
An experiment was performed to see how long it took the AFVFP to fill at continuous influent flow of ~295 gpm



4.5 hours to fill @ 295 gpm



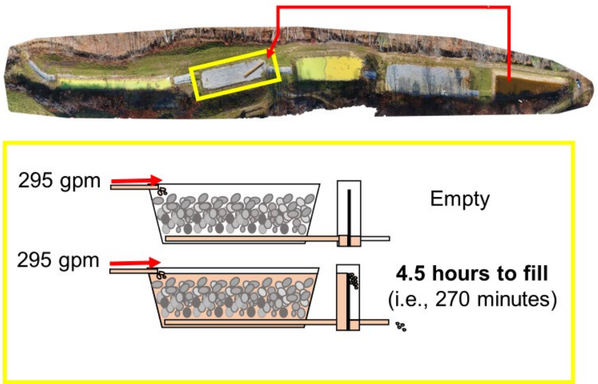
The AFVFP has a bulk volume of 1,530 yd^3, void volume of 79,650 gallons (i.e., 394 yd^3), and porosity of 26%

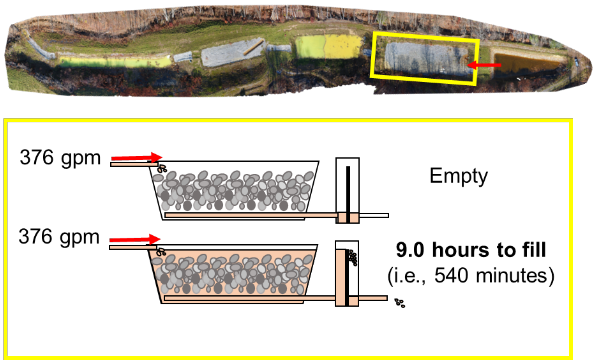


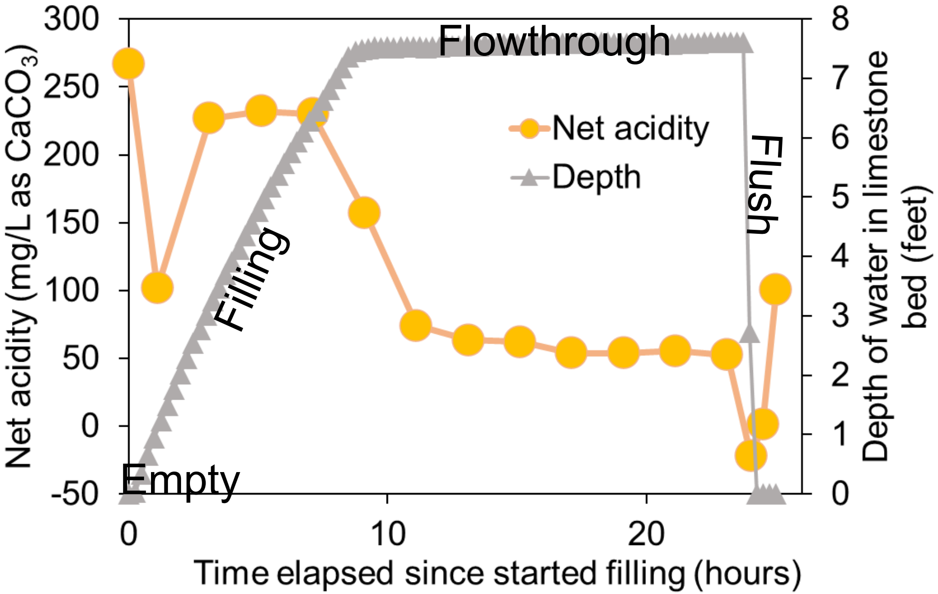
270 minutes x 295 gal/min
= 79,650 gallon void volume (i.e., 394 yd^3)

394 yd^3 void volume /
1,530 yd^3 bulk volume =
26% porosity

Average net acidity in the effluent during flowthrough treatment mode (9-hour theoretical HRT) was 71 mg/L

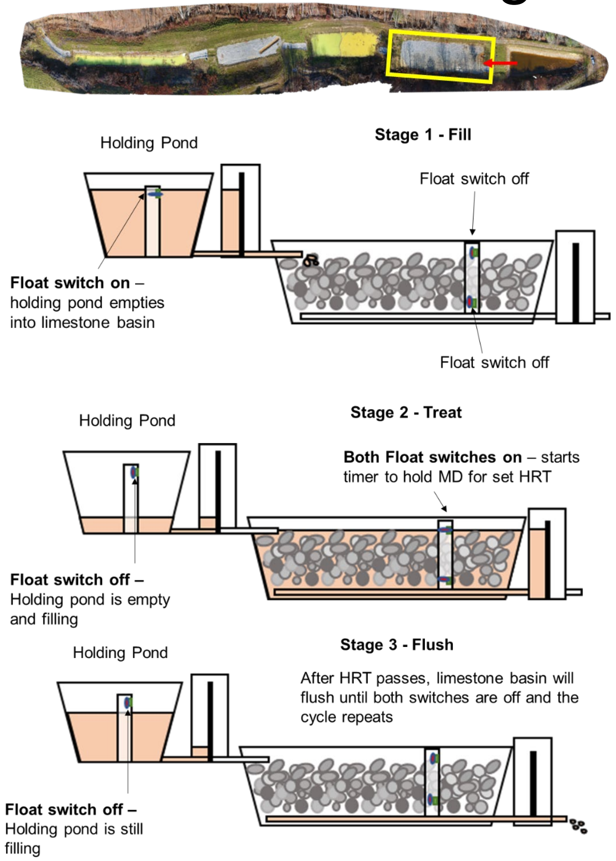


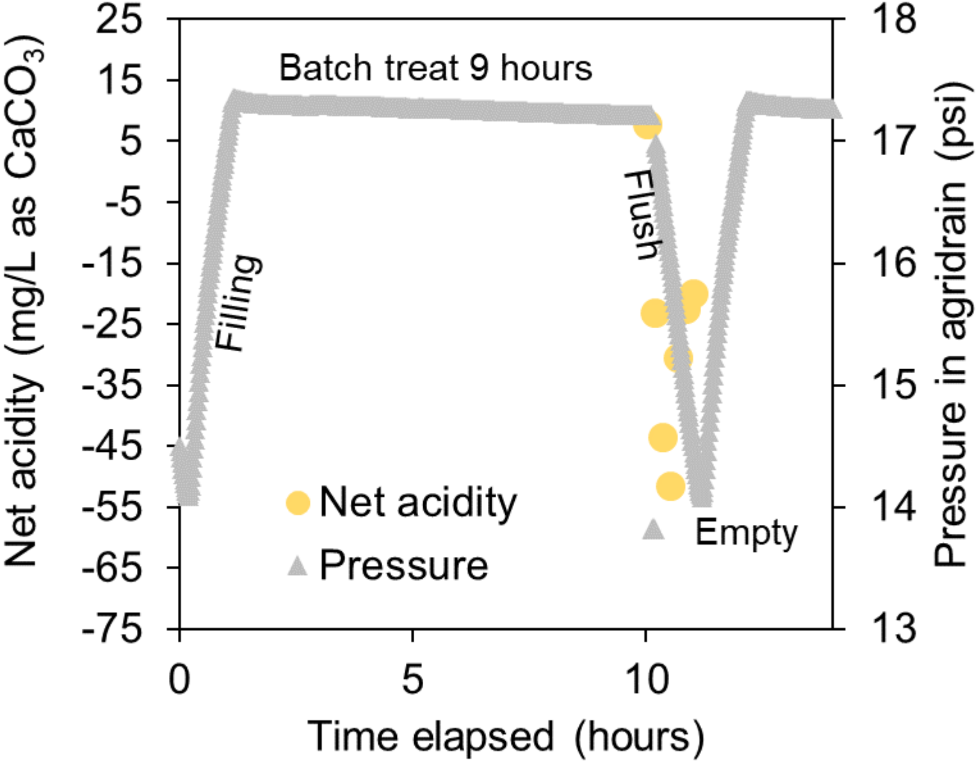




BOLTS with 9 hour hold time → the average net acidity during the flush was -26 mg/L

Treated in batch for 4.5 and 9.0 hours





AFVFP would be cheaper than the BOLTS if sized with same k_{sa} as BOLTS

Assumptions:

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- Agri Drain Smart Drain® in AFVFP = $15,230 per structure
- $17.35/short ton of limestone
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- $1/yd^2 of geotextile
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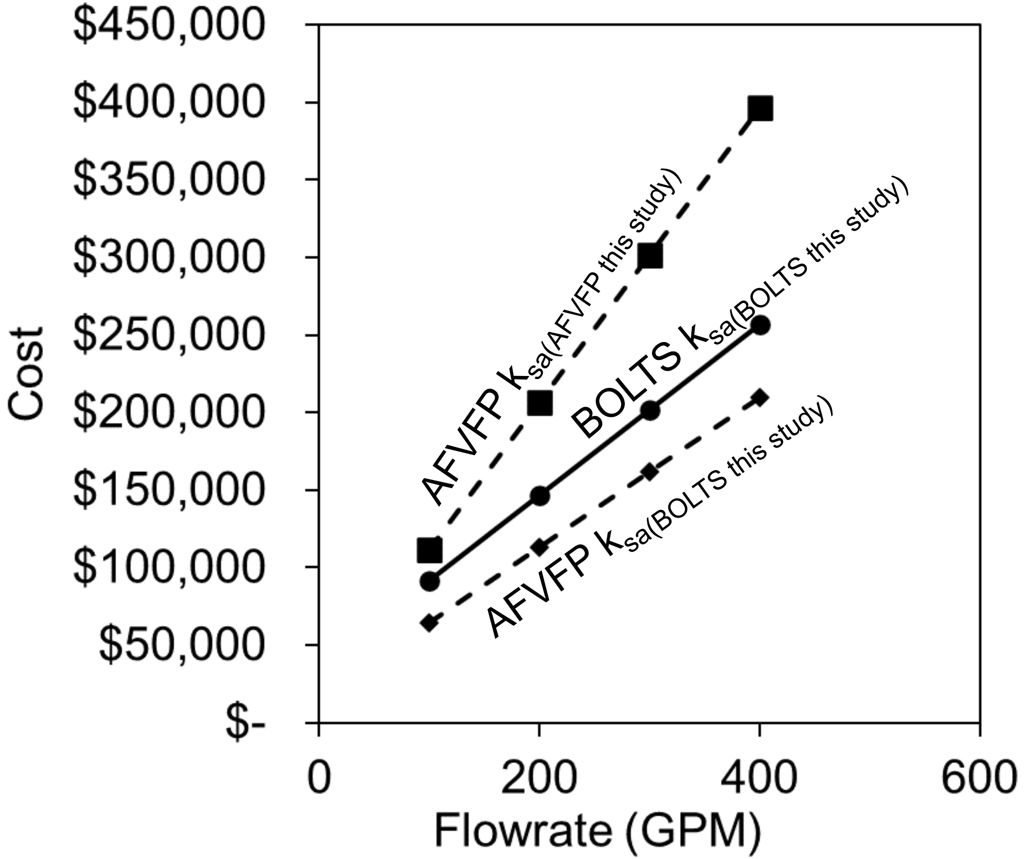
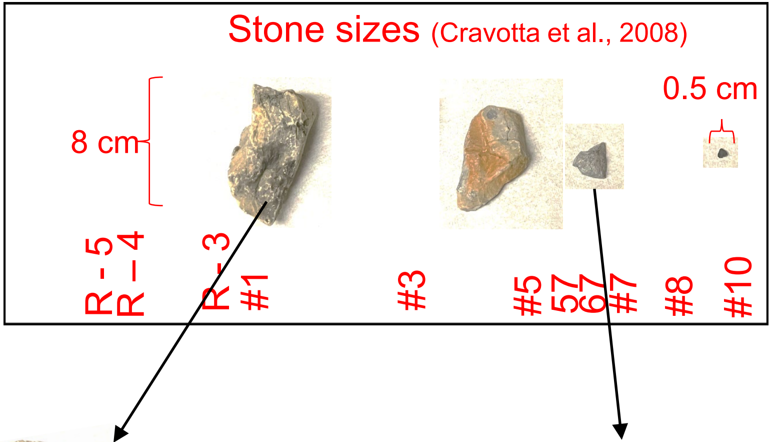


Could the MD be treated faster with smaller stone size?



A_u = 556 ft^2/short ton for AASHTO#1 / AASHTO#3

A_u = 2,800 ft^2/short ton for AASHTO#7

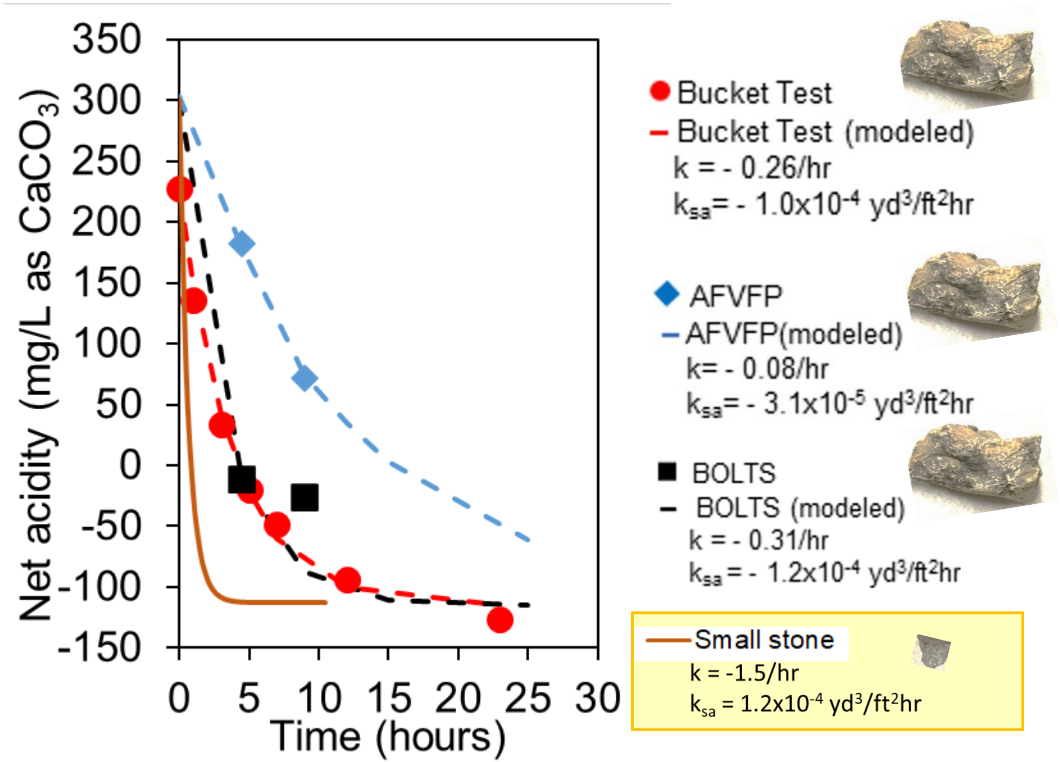
$$C_t = C_s - [(C_s - C_0)\exp(k\,t_d)]$$

$$k_{sa} = k/(A/V)$$

$$A/V = A_u\,(\rho_b/n)$$

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

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 gpm
C_o = 250 mg/L net acidity
C_t = -20 mg/L net acidity
C_s = -113 mg/L net acidity
t_L = 20 years
x = 0.9 (limestone purity)
A_u = 556 ft^2/short ton (AASHTO#1 to AASHTO#3)
Au = 2,800 ft^2/short ton (AASHTO#7)
n = 0.3
ρ_b =1.35 short tons/yd^3
k_{sa} = -1.2x10^{-4} yd^3/ft^2hr for BOLTS
k_{sa} = -3.1x10^{-5} yd^3/ft^2hr for AFVFP

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

k_{sa} = -1.2x10^{-4} yd^3/ft^2hr for BOLTS

A_u = 556 ft^2/short ton for AASHTO#1 to #3

M_s = 5,972 short tons for AASHTO#1 / AASHTO#3

A_u = 2,800 ft^2/short ton for AASHTO#7

M_s = 4,340 short tons for AASHTO#7

Cost of BOLTS would decrease from $200,000 to $150,000 if used smaller stone size

<u>Assumptions:</u>

- ρ_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