Using Blast Furnace Slag to Remove Ortho Phosphorus From Stormwater

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Todd B. Weik, PLA, CPESC
toddweik@cbceng.com
262-219-2938

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Phosphorus is a Real Problem

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Tools to Reduce Phosphorus

- P Absorption Materials – Meta Materia, Bold-Gold, ACBS
- Watershed Adaptive Management Plans
- Wet Ponds and Wetlands
- Lear Litter Pick-Up Programs
- Wastewater Treatment Upgrades
- Education

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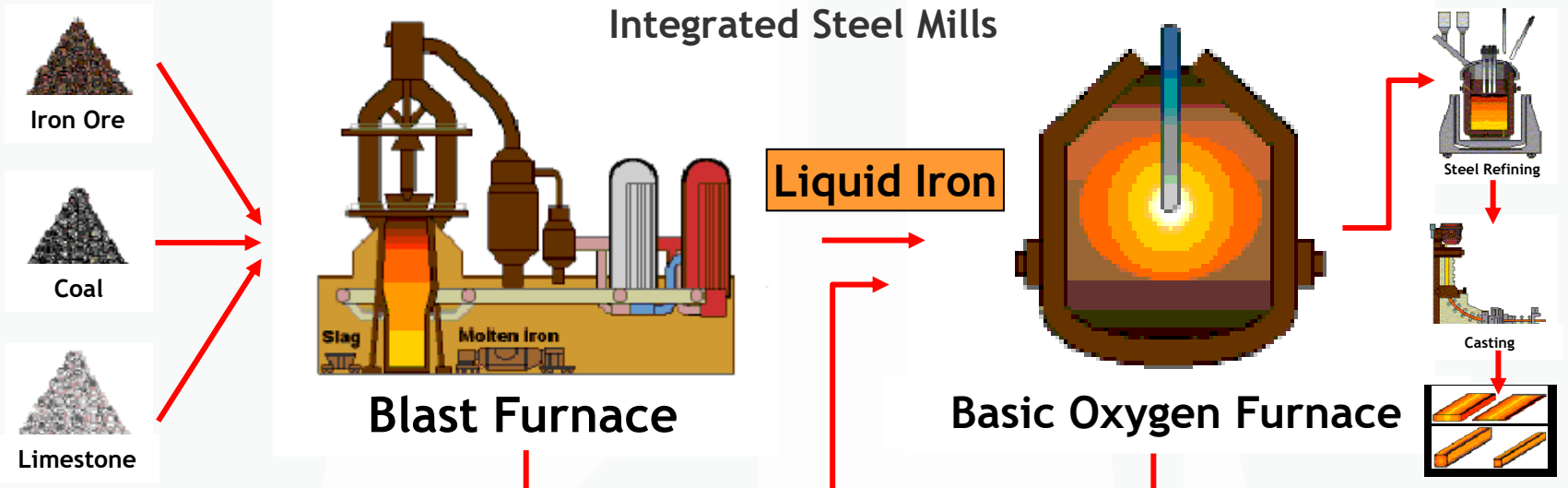
What kinds of slag exist in US?

- **All slags generated from high temperature (metals processing) industries**
- **Iron- and Steel-Making Slags (BF, BOF, EAF, Ladle, Stainless)**
  - Highly controlled material by virtue of steel making process.
  - High environmental quality. Granular, but reactive
  - After iron recovery, BF/BOF/EAF slags is crushed and screened to make aggregates.
- **Copper & Lead Smelting Slags**
  - Typically associated with Superfund & RCRA sites (Raritan Bay, NJ, others)
- **Chromium Slags (aka: Chromite Ore Processing Residue; COPR)**
  - Typically associated with Superfund & RCRA sites (New Jersey, Baltimore)
- **Foundry Slags**
- **Power Generation Slags**
  - Incinerator and Bottom Ashes & Slags
- **Scoria & Volcanic Materials**
  - Found in cool places (Hawaii) and great wine destinations (Italy, Greece, Napa)

How are iron-and steel-making slags produced?



Blast Furnace Slag

Recycled Steel

Steel Furnace Slag

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Unprocessed slag

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Regulatory Oversight

- May 8, 2017 – Conditional grant of exemption from licensing for use of BFS as granular fill in pavement subgrade and stormwater control systems (NR528)
- April 17, 2018 – Act 285: Iron and steel process slag is exempted from the definition of “solid waste.”

BF Slag Geochemistry by XRF & QXRD

XRF Chemical Analysis	
Element	Wt%
Ca	26.42
Si	17.68
Mg	6.36
Al	4.64
S	1.32
K	0.51
Fe	0.44
C	0.32
Ti	0.29
Mn	0.27
Na	0.22
Cr	0.02
P	0.01
Total	58.50

Normalized Elemental Composition					
	Total Sample	Amorphous Fraction		Crystalline Fraction	
Element	Wt%	Wt%	Distribution	Wt%	Distribution
Ca	45.2%	33.6%	17.5%	48.7%	82.5%
Si	30.2%	24.0%	18.6%	32.1%	81.4%
Mg	10.9%	5.5%	12.0%	12.5%	88.0%
Al	7.9%	16.0%	47.2%	5.5%	52.8%
S	2.3%	6.9%	72.0%	0.8%	28.0%
K	0.9%	3.7%	100.0%	0.0%	0.0%
Fe	0.8%	2.0%	60.7%	0.4%	39.3%
C	0.5%	2.3%	100.0%	0.0%	0.0%
Ti	0.5%	2.1%	100.0%	0.0%	0.0%
Mn	0.5%	1.9%	100.0%	0.0%	0.0%
Na	0.4%	1.6%	100.0%	0.0%	0.0%
Cr	0.0%	0.2%	100.0%	0.0%	0.0%
P	0.0%	0.1%	100.0%	0.0%	0.0%
Total	100.0%	100.0%		100.0%	

Quantitative X-Ray Diffraction Analysis		
Compounds		
Mineral Name	Formula	Wt%
Amorphous Material		24.4
Akermanite	Ca2MgSi2O7	57.3
Gehlenite	Ca2Al2SiO7	11.6
Diopside	CaMgSi2O6	4.2
Epidote	Ca2FeAl2Si3O12(OH)	1.5
Oldhamite	CaS	0.8
Merwinite	Ca3Mg(SiO4)2	0.2
Total		100.0

Major Oxides	
Oxide	Wt.%
CaO	37.0
SiO2	37.8
Al2O3	8.8
Fe2O3	0.6
MgO	10.5
LOI	0.0
Sum	94.7

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WDNR Testing Suite - DIW Leach

	NR 538, WI Admin Code, Appendix 1						
	Category 1	Category 2&3	Category 4	Replicate 1		Replicate 2	
Water Leach Test (ASTM D3987)							
Parameter	mg/l	mg/l	mg/l	mg/l		mg/l	
Aluminum	1.5	--	--	1.58		1.54	
Antimony	0.0012	0.012	--	0.005	U	0.005	U
Arsenic	0.005	0.05	--	0.01	U	0.01	U
Barium	0.4	4	--	0.21		0.23	
Beryllium	0.0004	0.004	--	0.0005	U	0.0005	U
Cadmium	0.0005	0.005	0.025	0.0005	U	0.0005	U
Chromium, Tot	0.01	0.1	--	0.001	U	0.001	U
Copper	0.13	--	--	0.0025	U	0.0025	U
Total Cyanide	0.04	--	--	0.0015	U	0.0015	U
Fluoride	0.8	--	--	0.39		0.39	
Iron	0.15	1.5	3	0.01	U	0.01	U
Lead	0.0015	0.015	0.075	0.01	U	0.01	U
Manganese	0.025	0.25	--	0.0018	J	0.0018	J
Mercury	0.0002	0.0002	0.01	0.0001	U	0.0001	U
Nickel	0.02	--	--	0.0025	U	0.0025	U
Selenium	0.01	0.1	--	0.02	U	0.02	U
Sulfate	125	--	--	18.4		21	E
Thallium	0.0004	--	--	0.048		0.017	J
Zinc	2.5	--	--	0.006	J	0.007	J

Exceeds Category 1, but satisfies all other categories

"J" flagged; the analyte was positively identified. The associated numerical value is an estimated quantity.

"U" flagged; The analyte was analyzed for, but was not detected above the reported sample quantitation limit.

WDNR aquifer criteria & SPLP leaching of soil like media

Metal	WI Ground Water Quality Standard.[1]	Blast Furnace Slag	Top Soil	Potting Soil 2	Wood Mulch 2	Bentonite	Kaolinite	Limestone	RCA	MV
Units	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Aluminum (Al)	0.200	3.72	11.70	7.93	0.279	109	11.0	0.182	0.71	0.389
Antimony (Sb)	0.006	0.0069	<0.0345	<0.0345	<0.0345	<0.0345	<0.0345	<0.0345	<0.0345	<0.0345
Arsenic (As)	0.010	<0.010	<0.0632	<0.0632	<0.0632	<0.0632	<0.0632	<0.0632	<0.0632	<0.0632
Barium (Ba)	2.00	0.173	0.0869	0.0834	0.0347	0.467	0.0662	0.0192	0.218	<0.001
Beryllium (Be)	0.004	0.0005	0.0013	<0.00106	<0.00106	0.00399	0.00148	<0.00106	<0.00106	<0.00106
Cadmium (Cd)	0.005	<0.0005	<0.00169	<0.00169	<0.00169	<0.00169	<0.00169	<0.00169	<0.00169	0.00201
Chromium (Cr tot)	0.100	0.0064	0.0141	0.0148	<0.00727	<0.00727	0.0141	<0.00727	0.0362	0.641
Copper (Cu)	1.30	0.0257	0.0304	0.0479	0.0164	0.0279	<0.0119	<0.0119	0.0251	16.2
Iron (Fe)	0.300	0.279	10.40	4.26	0.327	37.0	1.96	<0.08	<0.08	61.8
Lead (Pb)	0.015	<0.010	<0.0136	<0.0136	<0.0136	0.0368	<0.0136	<0.0136	<0.0136	<0.0136
Manganese (Mn)	0.300	0.303	0.0857	0.0602	0.0277	0.19	0.017	<0.00732	<0.00732	10.9
Mercury (Hg)	0.002	--	<0.00015	<0.00015	<0.00015	<0.00015	0.00026	<0.00015	<0.00015	<0.00015
Nickel (Ni)	0.100	<0.0025	0.0146	<0.0123	<0.0123	<0.0123	<0.0123	<0.0123	<0.0123	0.241
Selenium (Se)	0.050	<0.0200	<0.105	<0.105	<0.105	<0.105	<0.105	<0.105	<0.105	2.69
Silver (Ag)	0.050	<0.0013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013
Thallium (Tl)	0.002	<0.0041	<0.0339	<0.0339	0.0384	<0.0339	<0.0339	<0.0339	<0.0339	<0.0339
Tin (Sn)	NR	--	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.0445
Vanadium (V)	0.030	0.0198	0.0191	<0.00888	<0.00888	0.0124	0.0729	<0.00888	<0.00888	0.0168
Zinc (Zn)	5.00	0.0516	0.0592	0.072	0.0971	0.151	<0.0278	<0.0278	<0.0278	13.0

Notes:

WI = Wisconsin

SPLP: = Synthetic Precipitation Leaching Procedure

"<" represents analytical results not detected at detection limit. Equivalent to "U" in lab report.

NR = Not regulated; -- = Not tested.

Color coding: Yellow: = SPLP concentrations above Wisconsin Groundwater Standards.

RCA = SHA Recycled Concrete Aggregate

MV = Multivitamin

Ecotoxicity Testing Results

Table 1 PHx_Ecotox_67 Summary of Acute Results C. dubia	
Sample Concentration (%)	Percent Survival (at Test Termination)
Control	100
6.25	80
12.5	95
25.0	90
50.0	100
100	95

Table 2 PHx_Ecotox_67 Summary of Acute Results P. promelas	
Sample Concentration (%)	Percent Survival (at Test Termination)
Control	100
6.25	100
12.5	100
25.0	100
50.0	97.5
100	100

- ACBF slag leachate on second flush (first flush removes fines)
- C. Dubia (water fleas) test duration 48 hours
  - Initial pH in 100% ACBF slag was 8.8, dropped to 7.5 by end of test
- P. Promelas (fathead minnows) test duration 96 hours
  - Initial pH in 100% ACBF slag was 8.8, dropped to 7.1 by end of test
- Both tests pass min. 90% survival rate

BF Slag PO4 Batch Immobilization Experiments

- **Motivation**
  - Bracket PO4 uptake kinetics of BF slag based on expected PAVEDRAIN system residence times and anticipated PO4 levels.
- **Testing Program**
  - <3/8-inch; AASHTO 67, AASHTO 3 sizes
  - PO4 stock solutions: 1, 5, 10 mg/L
  - Contact times: 5, 10 min; 1, 4, 8, 24 and 72 hours
  - L:S ratio 1:1 (in-situ ratio)
  - <3/8 minus & AASHTO 67 on ZHE TCLP tumbler
  - AASHTO 3 on Orbital shaker at 30 RPM

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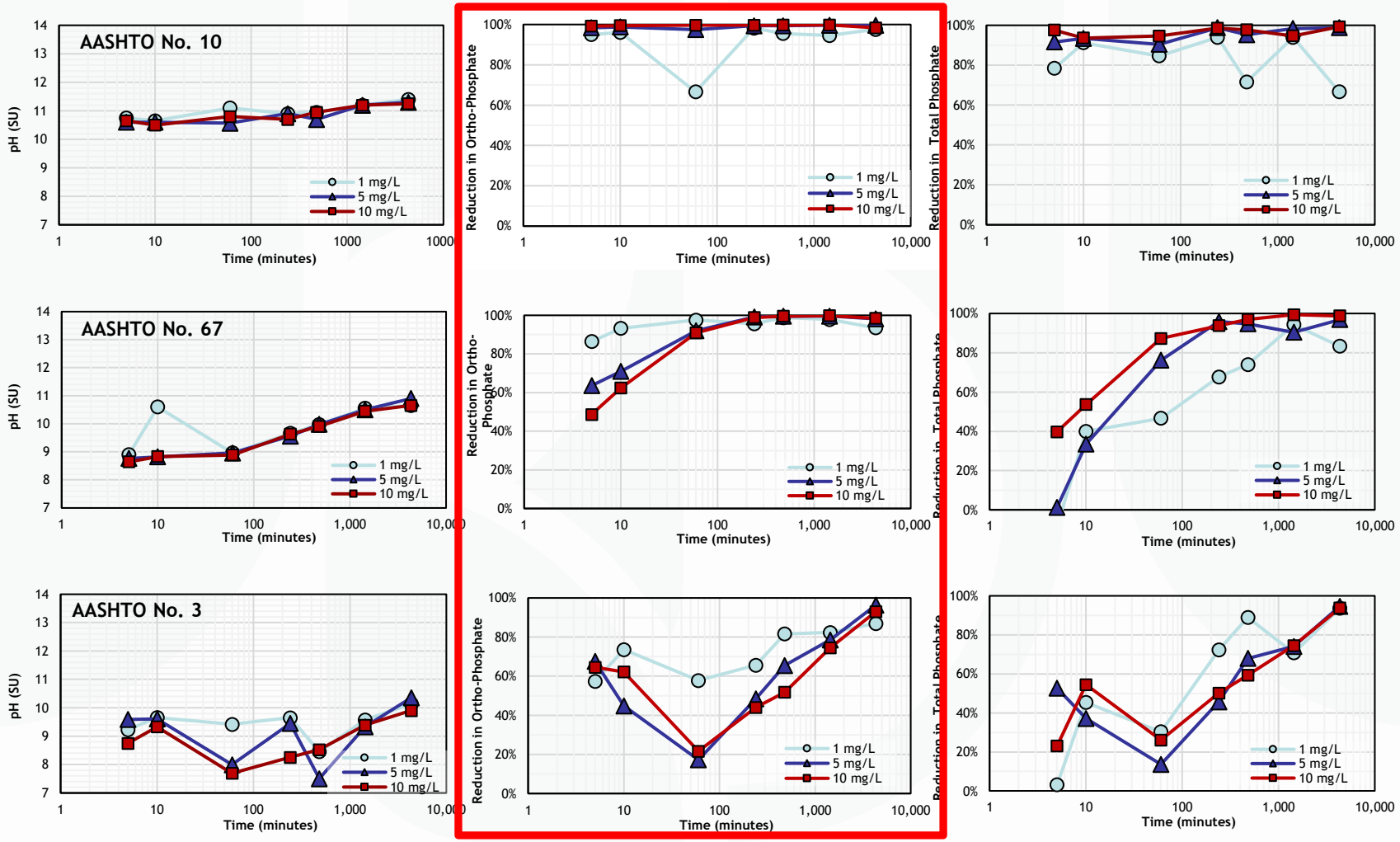
Post-Extraction Test Eluate pH (left), ortho- (center) and total (right) Phosphate Concentration Reductions for AASHTO No. 10 (top), No. 67 (middle), and No. 3 (bottom) ACBF Slag (LS=1)



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Design Considerations

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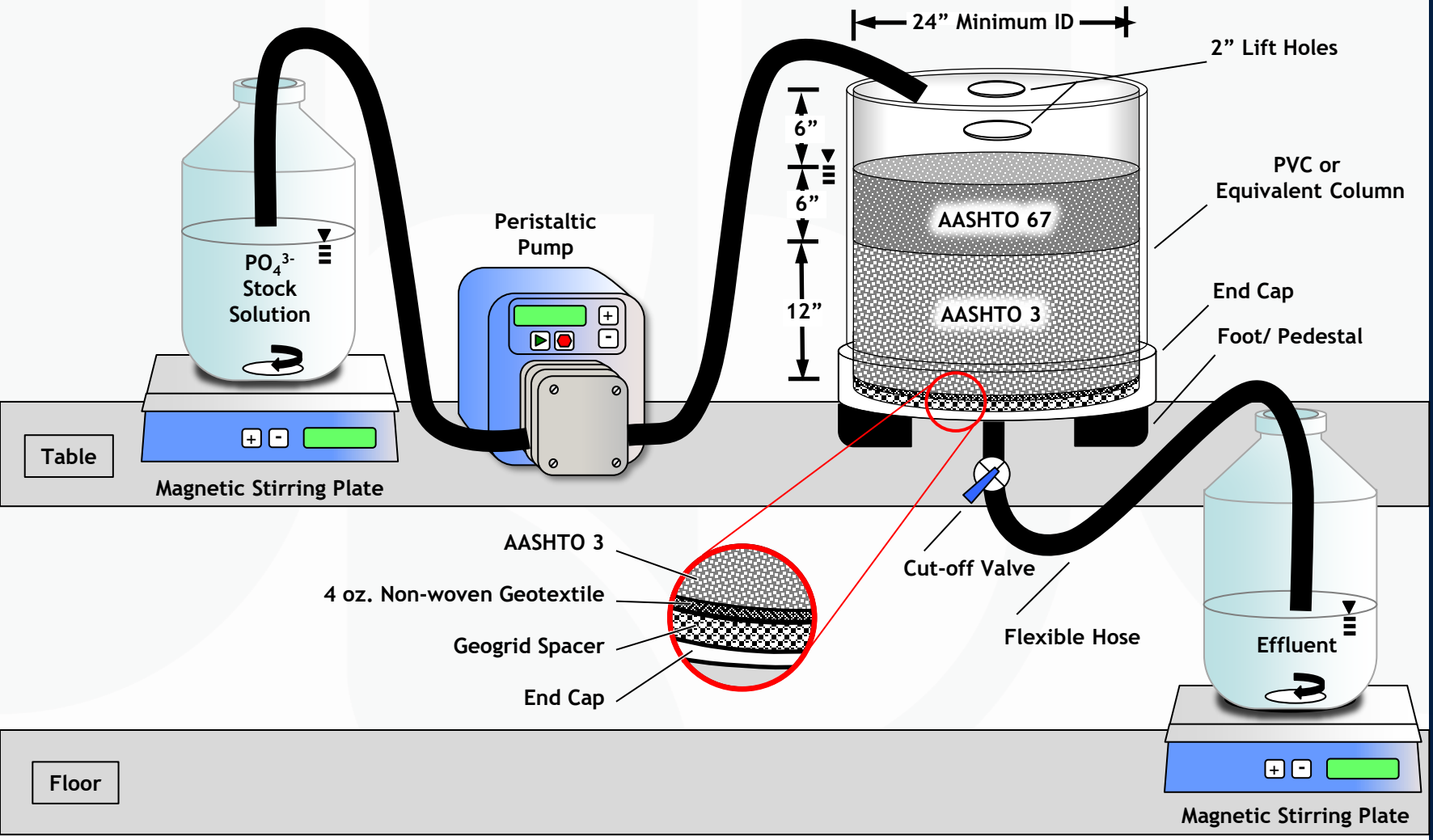
Life Cycle Simulations



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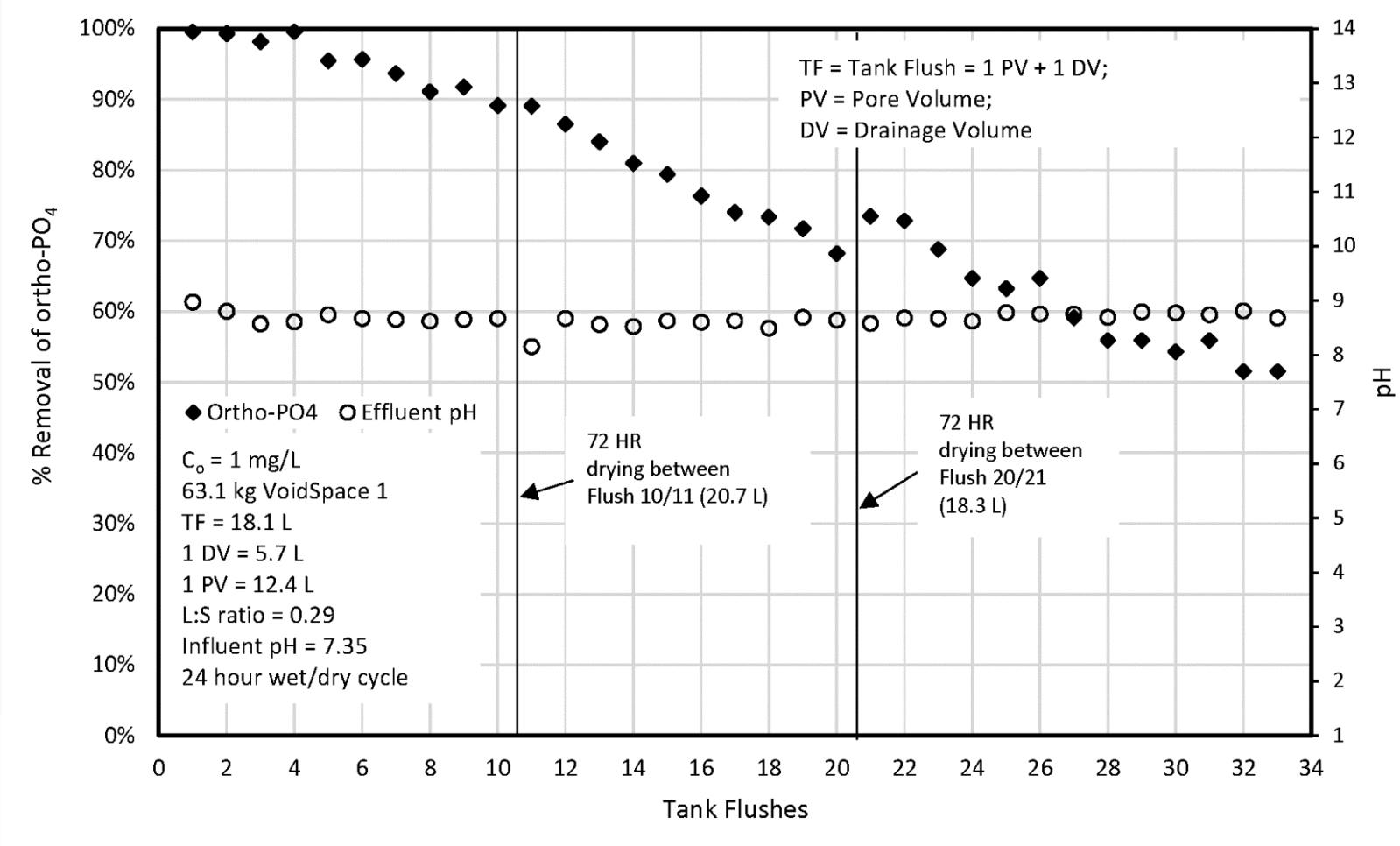
Capacity Test Results (%Removal PO4)



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WinSLAMM Analysis

- Evaluated three specific land use conditions for five Great Lakes cities
- Local rainfall files used for annual pollutant loads and runoff volume
- Focused on total and ortho-phosphorus

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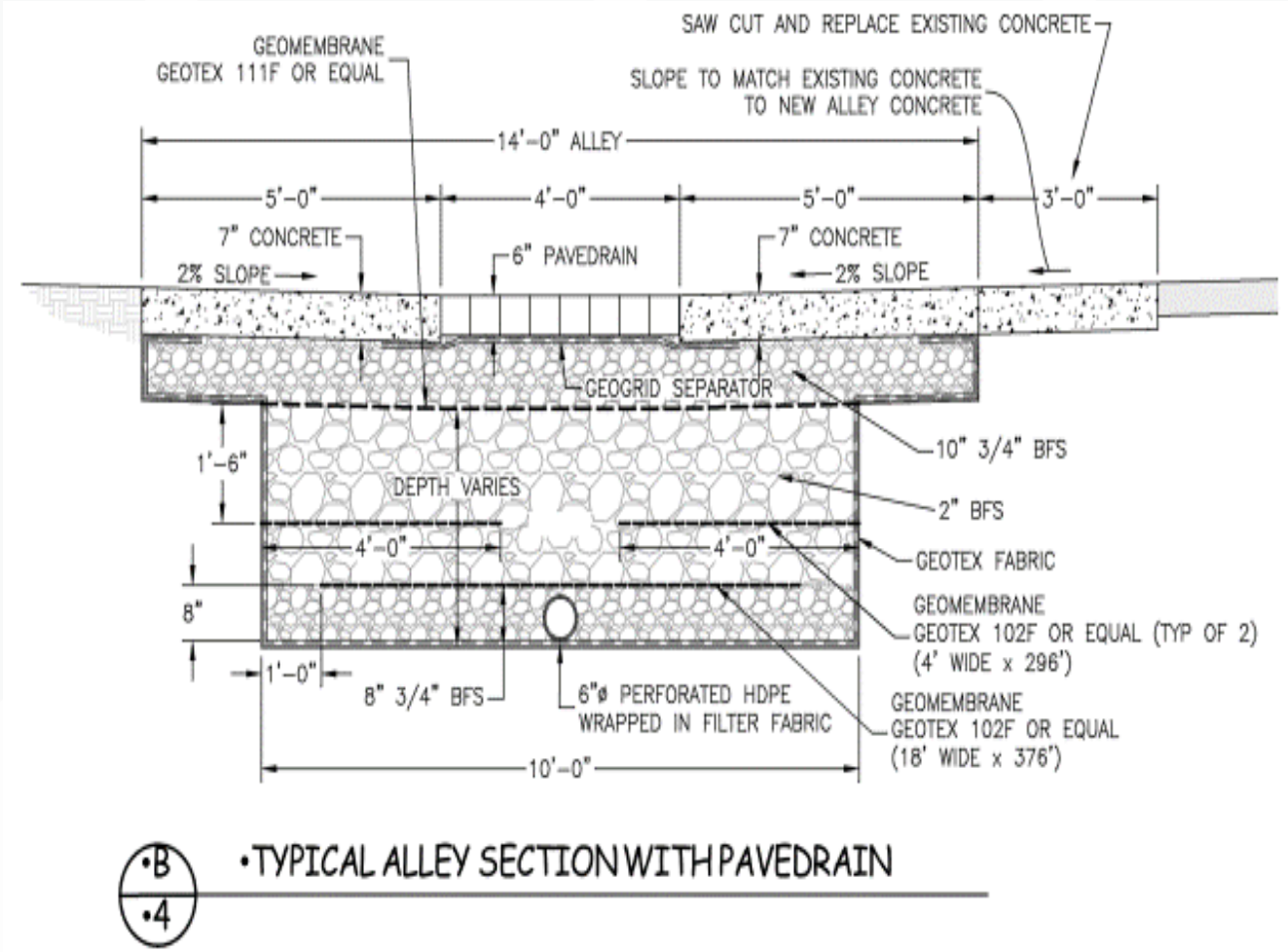
Estimated Design Life of ACBF Slag Media

Location/LU	Life Cycle (yrs)				
	BFS Storage Gallery = 10% of watershed	BFS Storage Gallery = 20% of watershed	BFS Storage Gallery = 30% of watershed	BFS Storage Gallery = 35% of watershed	BFS Storage Gallery =5% of watershed
Buffalo / HD Residential	15.9	33.8	50.8	59.2	8.38
Buffalo / LD Residential	15.9	33.8	50.7	59.1	8.36
Buffalo / Industrial	25.8	54.9	82.4	96.1	13.60
Chicago/ HD Residential	9.1	19.3	29.0	33.8	4.78
Chicago / LD Residential	9.3	19.9	29.3	34.1	4.93
Chicago / Industrial	17.7	37.6	56.4	65.8	9.31
Duluth / HD Residential	10.9	23.2	34.8	40.6	5.75
Duluth / LD Residential	11.2	23.8	35.8	41.7	5.91
Duluth / Industrial	21.0	44.8	67.2	78.4	11.09
Erie / HD Residential	8.5	18.1	27.2	31.7	4.48
Erie / LD Residential	8.5	18.1	27.2	31.7	4.48
Erie / Industrial	17.7	37.8	56.7	66.1	9.35
Green Bay / HD Residential	13.2	28.1	42.2	49.2	6.97
Green Bay / LD Residential	13.1	28.0	42.0	49.0	6.93
Green Bay/ Industrial	21.7	46.1	69.2	80.7	11.42

Cudahy - Green Alley



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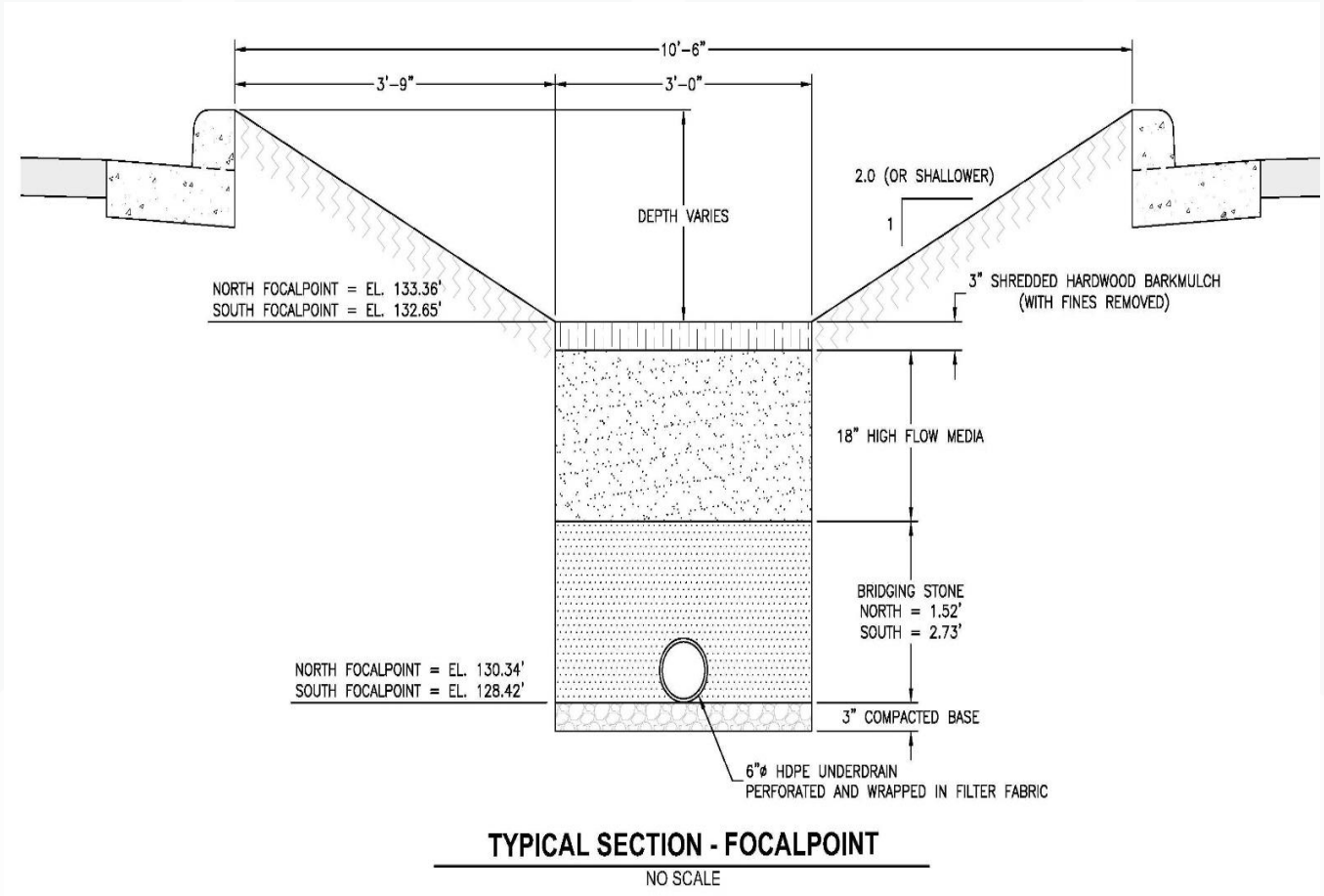
Cudahy - Squires Ave Parking Lot



TYPICAL SECTION - FOCALPOINT

NO SCALE

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Cudahy Project

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Cudahy Monitoring

Pre-Construction Sampling	Ortho P (mg/L)	Total P (mg/L)	TSS (mg/L)	Chloride (mg/l)	Lead (ug/l)	Nitrate (mg/l)	Ph
August 8th, 2018	-	0.02	26	0.00	0.00	0.16	7.69
August 20th, 2018	0.036	0.11	190	7.80	9.20	0.59	9.41
Post Construction Sampling	**Ortho P (mg/L)**	**Total P (mg/L)**	**TSS (mg/L)**	**Chloride (mg/l)**	**Lead (ug/l)**	**Nitrate (mg/l)**	**Ph**
November 5, 2018	0.000	0.011	52	0.00	0.00	0.26	7.47

Squire Avenue Parking Lot and Green Alley							
Pretreatment Sample	**Ortho P (mg/L)**	**Total P (mg/L)**	**TSS (mg/L)**	**Chloride (mg/l)**	**Lead (ug/l)**	**Nitrate (mg/l)**	**Ph**
June 6, 2020	0.14	0.74	150	11.00	ND	1.70	6.21
August 2, 2020	ND	0.67	130	8.30	16.00	1.10	6.43
Post Treatment Sample	**Ortho P (mg/L)**	**Total P (mg/L)**	**TSS (mg/L)**	**Chloride (mg/l)**	**Lead (ug/l)**	**Nitrate (mg/l)**	**Ph**
June 6, 2020	0.040	0.081	14	ND	ND	1.00	6.55
August 2, 2020	ND	0.039	ND	ND	ND	0.56	6.70

Summary

- **BF Slag Characterization**
  - BF slag is not toxic to the environment.
  - Few metals detected, even less leachable.
  - Well suited for PO4 immobilization applications
  - Long term leaching as base/subbase negligible from environmental perspective.
- **PO4 Uptake**
  - BF slag removes substantial PO4 concentrations in short timeframes
  - 3/8”-minus removes 99% ortho PO4 in 5 min for PO4 = 1 mg/L
  - AASHTO 67 removes 86% ortho PO4 in 5 min for PO4 = 1 mg/L
  - AASHTO 3 removes 57% ortho PO4 in 5 min for PO4 = 1 mg/L
- **Sustainability**
  - BF slag is 100% recycled material.
  - BF slag does not need to be landfilled.
  - Buk dry unit weight is more than 10 lb/ft3 less than limestone.

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Contact Information

Todd Weik, PLA, CPESC
262.219.2938 cell
toddweik@cbceng.com