Comparison of midwestern U.S. Conventional and hybrid vertical flow ponds to previous performance data

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Abstract

Acid mine drainage (AMD) discharging from abandoned coal mine sites in the Midwestern U.S. are often highly acidic. The AMD in this region is typically characterized by iron, aluminum, manganese, and sulfate concentrations that are considerably higher than typical coal mine drainage in Appalachia and many international locations. Although active AMD treatment is a more secure, limitations in site conditions and the availability of long-term funding have prompted the use of passive treatment in the region. Poor AMD quality has required three types of treatment: 1) vertical flow ponds (VFP) also known as reducing and alkalinity-producing systems (RAPS) or vertical flow reactors (VFR), 2) anaerobic wetlands, and 3) sulfate-reducing bioreactors. Oxidation ponds and aerobic (surface-flow) wetlands support these alkalinity production cells. High aluminum concentration in midwestern AMD requires an increased thickness of limestone-blended compost as compared to more conventional VFPs used in Appalachia. This ultimately forms a hybrid between limestone-based VFP technologies and compost-based sulfate-reducing bioreactors. This paper will present the performance of six hybrid VFP-based treatment cells and compare these with performance results of four conventional VFPs and two bioreactors constructed in the Midwestern U.S.A. The prime design goal of these systems is to produce sufficient alkalinity to buffer (maintain circumneutral) pH in the following oxidation ponds and/or aerobic wetlands to stimulate precipitation of most of the remaining iron. Manganese removal in these systems is typically minimal. Conversely, limited sulfate removal can be expected. These midwestern systems are also compared with performance results of earlier reviews of full-scale VFPs with the goal to increase the empirical dataset used in VFP design.

Keywords: Acid mine drainage, sulfate-reducing bioreactor, aerobic wetland, VFP, RAPS

Introduction

Vertical flow ponds (VFP) have been applied worldwide to treat acid mine drainage (AMD; Hedin et al, 1994a, 1994b, Skovran and Clouser, 1998). Another commonly used term for this technology, the reducing and alkalinity producing system (RAPS), is a better description of the treatment process (Watzlaf, 1997; Younger et al, 2002). AMD which has been exposed to the atmosphere and partially oxidized flows downward though a VFP's compost layer during anaerobic digestion. The resultant, partially treated, AMD is anoxic with most iron in the reduced ferrous iron (Fe^{2+}) state. Alkalinity and pH are increased by passage through the underlying limestone layer (Hedin et al., 1994a, 1994b). Additional alkalinity is provided by the dissolution of fine ground limestone blended in the compost layer as well as the bacterial sulfate reduction in this layer. At pH 6.0 +/-, ferrous iron within the VFP should remain mobile passing through the VFP. Upon discharge from the VFP, the alkalinity and pH enhanced AMD is re-aerated. As a result, most of iron is retained as hydroxide precipitate within follow-up oxidation ponds and/or aerobic wetlands. At abandoned mine sites in the Midwestern U.S., AMD is often characterized by elevated aluminum content (> 5 mg/L) and net acidity (>250 mg/L calcium carbonate equivalent – CCE; Behum and Kim, 2004). Due to these pollutants, the longevity of conventional VFPs is expected to be lower than typical applications with easier to treat waters (Rose, 2006). Moderately high concentrations of acidity (200-400 mg/L) are relatively easy to treat by employing sequential additions of alkalinity. In fact, one of the first application of VFPs was to remediate AMD with moderate acidity by employing two VFPs in series (Kepler and McCleary, 1994). This technology, known as successive alkalinity producing system (SAPS), uses a double dose of alkalinity to provide the necessary alkalinity; Kepler and McCleary (1994) reported acidity removal between 150-300 mg/L. High aluminum concentrations, however, remained problematic for VFP operation because hydroxide precipitates will form within the treatment media at the anticipated pH > 4.5. These aluminum hydroxide precipitates will normally coat and render ineffective the limestone fines and gravel and clog treatment media. Flushing of the VFPs has been advocated as a solution to reduce fouling of the treatment media, but in practice, has proven to produce varied results (Kepler and McCleary, 1997; Weaver et al., 2004; Hedin et al., 2010). Sulfate-reducing bioreactors have also been used to passively treat highly acidic and aluminum-bearing AMD (Gusek and Wildeman, 2002; Jong and Parry, 2006; McCauley et al., 2009; Behum et al. 2011; Lefticariu et al., 2015). Bioreactors, while effective, are costly to build and maintain (Gusek, 2002) and show a marked decline in performance during winter months (Branam, 2010; Behum et al., 2011, Lefticariu et al., 2012). In this paper, we will evaluate twelve vertical flow systems. Six of these are called a "hybrid VFP," which is a merger of two technologies – a conventional VFP and a sulfate-reducing bioreactor. Classical VFP design employ 0.15 – 0.61 m. compost underlain by 0.62–0.91 m. limestone layer (Fig. 1, Table 1; Jage et al, 2000; Hedin et al., 2010). Midwestern U.S.A. hybrid VFPs differ from conventional VFPs by increasing the thickness of compost to between 0.61 and 1.37 m; limestone thickness in these hybrid VFPs range from 0.61 to 0.76 m. Performance of hybrid systems were compared to four conventional VFPs and two sulfate-reducing bioreactors (Table 1). Most midwestern VFPs contain at least 15% fine ground limestone (aglime) to bolster alkalinity in the media. Rose (2004) found that VFPs with fine limestone added to the compost have double the AMD remediation performance and may be a solution for high-aluminum discharges.

A second goal of this paper is comparing midwestern VFP performance data with data from early VFPs constructed in Pennsylvania, compiled by Rose and Dietz (2002), Rose (2004) and Rose (2006). Importantly, VFP performance data from these studies was used to develop a widely used, empirical VFP design criteria (the Rose and Dietz Method). We suggest that, by adding newer and long-term empirical data from sites outside of the Appalachian Coal Basin to this older dataset, future passive treatment designs could be improved. Early VFP systems were reported to produce high alkalinity neutralizing 51 g/m2/day (Nairn et al., 1999) to 61.8 g/ m^2/day acidity (Dietz and Stidinger, 1996). However, research has shown that long-term performance of VFP-type systems may be overestimated if based on successful treatment during early operation (Skovran and Clouser, 1999; Jage et al., 2000). In 2002, Rose and Dietz conducted a comprehensive review of the performance of 29 early VFP installations. Net alkalinity in these VFPs ranges from 7 to 686 mg/L with a median 160 mg/L CCE [net acidity = (-)160 mg/L CCE]. Rose and Dietz developed regression equation relating influent acidity loading vs. effluent alkalinity which indicated (r2=0.55) that an average areal acidity loading of less than 40 g/m2/day, typically produced net alkaline effluent. Within the Pennsylvania dataset, twelve VFPs, which ranged from 25 to 50 g/m2/day, were selected to represent VFPs operating a peak performance. These 12 VFPs were used in developing a conservative design criterion of 25 g/m2/day areal acidity loading rate. This empirical VFP design criterion has since served as an alternative to retention time-based method suggested by the U.S. Bureau of Mines for construction of anoxic limestone drains (ALD; Hedin et al., 1994b; Cravotta, 2003). Rose (2004) reassessed the 2002 study by adding two additional years of performance data. He found that the rates of acidity removal were lower as the systems aged with an average acidity loading of 34 rather than 40 g/m2/day. If the designer employed the calculated non-Mn acidity, then the sizing parameter to produce a net alkaline effluent was recommended to be 35 g/m^2/day. Rose (2006) expanded his VFP review and addressed factors which could lead VFP performance decline during operation. These include: 1) accumulation of iron hydroxides and hydrous sulfate minerals on top of the compost layer, 2) plugging of the treatment media with aluminum hydroxide minerals whenever inlet aluminum concentration is greater than 20 mg/L, 3) short-circuiting if AMD through the treatment media by inadequate design, and 4) undersized design, a problem in some early VFPs based on limestone media retention time of 15 hours (Rose, 2006). Rose (2006) reiterated that VFP designs should be limited to inlet acidity loading of less than 35 to 40 g/m^2/day.

Methodology

To complete this evaluation, we compiled midwestern VFP performance data from field and laboratory testing. VFP construction details and hydrologic data are shown in Table 1. The three Arkansas systems were designed as conventional VFPs but were constructed with a thicker compost layer than listed. Therefore, the Arkansas systems were evaluated as hybrid systems. Pertinent water quality data is presented in Table 2. All water quality data was collected post-construction. Laboratory data is derived from state or contract facilities that are U.S Environmental Protection Agency (EPA)-certified. This includes Illinois Department of Natural Resources, Office of Mines and Minerals, Benton, IL Laboratory; Pace Analytical Services, LLC, Madisonville, IN; Indiana Geological and Water Survey, Bloomington, IN; Engineering Surveys and Services Testing Laboratories, Columbia, MO; Arkansas Department of Environmental Quality, North Little Rock, AR; and ACZ Laboratories, Inc., Steamboat Springs, CO. Commercial and state laboratory testing are supplemented by OSMRE in-house testing for dissolved Fe, Fe^{2+}, Mn, and Al, along with SO4 and total alkalinity using Hach Company (Loveland, CO) colorimetric and titrimetric methods. Field measurements included pH, specific conductivity (SC), dissolved oxygen, oxidation and reduction potential (ORP) and temperature with Hach HQ40 meters. Ferric iron (Fe^{3+}) was determent by subtracting ferrous iron from the total dissolved iron content. Dissolved ferrous iron, ferric iron, manganese, and aluminum along with pH are used to calculate acidity from the formula:

$$\text{Acidity} = 50*((2*[Fe^{2+}]/55.85) + (3*[Fe^{3+}]/55.85) + (2*[Mn]/54.94) + (3*[Al]/26.98) + (1000*10^{-pH}))$$

Calculated acidity values are reported as calcium carbonate equivalent (CCE). System performance is based on comparisons of net acidity where:

Net acidity = calculated acidity – total alkalinity.

In most cases, calculated acidity could be determined from field and laboratory values. If metal data is unavailable, lab (measured) acidity values were applied (lab acidity ~ net acidity = calculated acidity – total alkalinity; Hedin, 2006). Discharge was generally measured by observing flow through a weir installed at VFP inlet or outlet or by bucket and stopwatch methods.

Findings – Comparing Midwestern VFP Types

The severity of AMD treated by vertical flow cells in this study varied widely (Table 2). AMD with higher acidity and aluminum concentration is treated by two bioreactors IL1 and IN3. IL1, the full-scale Tab-Simco Bioreactor in Carbondale, Illinois, is treating AMD with acidity of 1830 mg/L CCE and aluminum concentration of 122.3 mg/L (Behum et al., 2011; Lefticariu, et al., 2015).

Table 1 Design details, construction date, hydrologic and operational data for Midwestern VFPs

Cell ID	Water Layer* (cm)	Compost Layer* (cm)	Limestone Layer* (cm)	Hydraulic Head (cm)	Build Date ** (mo./yr.)	Flow (LPM)	Pool Area (m^2)	Water (HRT) (Hr.)	Compost HRT (Hr.)	Limestone HRT (Hr.)
IL1	30.0	180.0	60.9	255.9	12/2007	85.05	3521	202.8	316.0	110.5
IN1	90.0	90.0	60.9	225.9	12/2005	599.4	4016	95.0	25.3	19.7
IN2	90.0	90.0	60.9	225.9	12/2005	599.4	5487	130.9	35.4	27.4
IN3	30.0	152.4	0.0	167.4	12/2008	70.41	2394	161.8	152.7	0.0
MO1	76.2	45.7	83.8	205.8	8/2001	82.44	918	52.1	7.86	14.9
MO2	76.2	45.7	91.4	213.4	8/2001	82.44	1154	66.2	10.2	21.4
MO3	30.5	137.2	76.2	243.8	5/2016	18.33	1728	464.8	470.8	221.9
MO4	38.1	45.7	76.2	160.0	4/2017	30.85	1103	216.9	70.2	125.8
MO5	15.2	45.7	76.2	137.1	4/2017	112.9	1838	40.9	34.7	64.8
AR1	30.5	60.9	68.6	160.0	3/2009	27.06	2875	526.8	293.6	375.9
AR2	30.5	60.9	76.2	167.7	5/2015	164.7	3776	114.2	65.5	92.8
AR3	30.5	60.9	76.2	167.7	5/2015	77.17	3833	247.4	139.0	199.1

*All are constructed as downflow systems with a water layer on top, a compost layer in the middle and a limestone layer on the bottom; the thickness of water + compost + limestone = the hydraulic head of the system; porosity of the compost = 30% and porosity of the limestone = 38%; IN3 used woodchips instead of limestone as pipe bedding. MO1 followed by MO2 form a SAPS with supporting oxidation and wetland cells.

**All systems have continuous operations from construction date to a paper preparation date December 2023.

Located in Augusta, Indiana IN3, the pilot-scale Midwestern Bioreactor, is also treating poor-quality AMD (Table 2). Conventional VFPs evaluated in this study included two series-connected VFPs at the Old Bevier Passive Treatment System (PTS) in Bevier, Missouri (MO1-SAPS 1 followed by MO2-SAPS 2, Tables 1 and 2). SAPS1 inlet AMD is pre-treated by limestone in a large highwall drain. Because of this, the Old Bevier PTS inlet AMD aluminum concentration is relatively low (1.73 mg/L; Behum et al, 2002). Two small conventional VFPs were also constructed in 2017 at the Germantown AML site in Montrose, Missouri (MO4 and MO5). These systems, termed by Missouri as "organics-limestone-aglime" (OLA) cells treat AMD with moderate acidity (121.4 and 158.5, respectively) and low aluminum (Table 2).

Aside from MO3, a small hybrid VFP/bioreactor, all hybrid-type VFPs evaluated in this study ae relatively large ranging from 2875 to 5487 m^2. Constructed in 2016, MO3 treats AMD with moderate acidity and relatively low aluminum content. Located within a large area of graded mine spoil at the Germantown AML site, the L-Pit hybrid VFP design overestimated the amount of mine drainage collected by the PTS (Table 1); MO3, therefore, is overdesigned. IN1 and IN2 are large hybrid VFPs arranged in parallel to treat a large AMD discharge from the Enos coal waste (gob) pile, a facility in Enos Corner, Indiana that is undergoing remining. Originally designed as VFPs, IN1 and IN2 also received a thicker than normal compost layer during construction and compost replacement efforts (Behum et al., 2012; Table 1). Dilution water with excess alkalinity is first added to pretreat the Enos Gob Pile drainage in a large aerobic wetland. Therefore, hybrids IN1 and IN2 treat AMD with relatively low acidity and aluminum content (Table 2). The three Arkansas VFPs treat AMD derived from underground mine pool discharges with large seasonal variations. Built to treat high flow events, they are oversized during low flow conditions. Operational problems with these Arkansas hybrid systems, constructed with a thicker (> 30 cm) compost, layer have altered treatment conditions from the original design parameters. Hybrid VFP AR1 is located at the Mine No. 6 PTS near Huntington, Arkansas. Here both a large vertical anoxic limestone drain (VALD) and follow-up oxidation pond pre-treats the AMD prior to secondary treatment by AR1, (Behum and Kim, 2004; LaBar and Nairn, 2008). As a result, the AR1 inlet AMD has a low acidity and aluminum concentration (7.45 mg/L CCE and 0.79 mg/L, respectively, Table 2); the amount of AMD treated at the Mine 6 PTS is much lower than anticipated due to agricultural use of the mine pool water by the landowner and problems with the VALD discharge pipeline. Similarly, AR2 and AR3 at the Hartford PTS, Hartford, Arkansas has been plagued by repeated plugging of AMD treatment pipelines which has reducing the amount of AMD treated. Inlet AR 2 and AR3 iron load is mitigated by pretreatment by low-pH iron oxidation in 4 large oxidation ponds.

Several of the systems treating high net acidic discharges (bioreactors IL1 and IN3 and hybrid VFP MO1; Table 2). Four additional vertical flow systems (VFPs MO2/SAPS2, MO4 and MO5 and hybrid MO3) are treating AMD with moderate acidity (> 100 mg/L CCE). Bioreactors IL1 and IN1 and VFP MO1/SAPS1 and MO3 produce net acidic drainage. This reflects the difficulty in passive treatment of moderate to high acidity drainage and the degradation of alkalinity from the compost layer over time (Hedin et al, 2010; Behum et al, 2011; Lefticariu et al, 2015). Our research suggests that the longevity of treatment of higher acidity and aluminum content discharges will require more frequent compost replacement. In the case of the MO1/SAPS 1 discharge, additional treatment is provided by design with MO2/SAPS2. A better indicator of vertical flow cell longevity is provided by calculating the loading rate of the vertical treatment cell (Table 3, Fig. 1B). In this case, aerial loading rate is calculated using the pool area of the VFP (m2), inlet AMD flow rate (LPM) and the pollutant concentration (mg/L, Tables 2 and 3). As an example, using the net acidity of the AMD at the VFP inlet:

Acidity Loading (g/m^2/day) = [1.44 * Net Acidity (mg/L) * Flow (LPM)]/Pool Area (m^3)]

Average acidity load for this study ranged from 2.62 to 62.25 g/m^2/day and average acidity removal was between 2.14 and 58.71 g/m^2/day (Table 3). Bioreactors IL1 and IN3 and MO1, the initial VFP of a 2-stage SAPS system, received the greatest acidity load with commensurate elevated metal loads. Several vertical flow systems produced slightly net acidic drainage [acidity load > acidity removal; bioreactors IL1, IN3, VFP MO1 (SAPS1), and hybrid VFPs MO4, MO5]. In a SAPS system, the initial VFP is expected to produce net acid water as oxidation in the intervening oxidation ponds and/or aerobic wetland will produce lower pH drainage that assists in limestone dissolution in the follow-up VFP (SAPS2). With conventional VFPs, there is no mechanism to produce

***Table 2** Comparative Performance of Passive Vertical Flow Treatment Cells Treating Net Acidic Coal Mine Drainage – Area-based[1]*

Cell ID	Type**	Acidity In mg/L*	Fe In mg/L	Mn In mg/L	Al In mg/L	Fe Out mg/L	Mn Out mg/L	Al Out mg/L	Net Acidity Out mg/L*
IL1	Bioreactor	1830	495.9	37.34	122.3	127.7	32.78	0.756	92.7
IN1	Hybrid	57.2	14.8	2.32	0.96	4.43	2.44	0.143	-87.8
IN2	Hybrid	57.2	14.8	2.32	0.96	4.27	2.43	0.140	-109.2
IN3	Bioreactor	482.5	110.5	10.95	8.05	2.61	6.78	0.250	32.0
MO1	SAPS1	385.2	154.5	8.08	1.73	154.0	8.00	0.222	177.3
MO2	SAPS2	163.0	15.1	8.62	0.79	36.08	7.67	0.147	-60.9
MO3	Hybrid	102.2	52.0	19.71	1.82	8.45	6.24	0.115	-218.2
MO4	VFP	121.4	129.2	2.02	0.033	62.64	18.74	0.095	69.5
MO5	VFP	158.5	39.93	7.39	0.79	2.98	15.23	0.151	-7.3
AR1	Hybrid	7.45	3.14	2.02	0.033	0.54	1.77	0.027	-82.6
AR2	Hybrid	56.9	2.16	7.39	0.79	9.60	7.70	0.150	-110.8
AR3	Hybrid	56.9	2.16	7.39	0.79	0.90	5.70	0.195	-122.3

1.Median values; loading calculations based on discharge and VFP surface area values shown in Table 1.

*Calcium carbonate equivalent (CCE).

**Hybrid = Hybrid bioreactor/vertical flow pond.

relevant alkalinity within the follow-up oxidation ponds. Therefore, these systems must produce sufficient alkalinity to yield net alkaline drainage (MO2/SAPS2, MO4 and MO5). However, with the thicker compost in bioreactors and hybrid VFPs, sulfide ions are expected to discharge into a follow-up oxidation pond. Subsequent sulfate reduction in the depths of these ponds will likely reduce sulfate and generate additional alkalinity above the values shown in Table 3.

Excluding alkalinity generated in the follow-up oxidation ponds, this study indicates that there is little difference in acidity removal between conventional and hybrid VFPs (14.18 and 14.93 g/m2/day, respectively). Operational issues due to curtailment of AMD supply somewhat skew the dataset. However, when charted as a separate dataset there is considerable differences in the Rose (2004) Appalachian dataset and our midwestern dataset. To better conduct these comparisons, a much larger dataset is needed to overcome the effects of operational issues of individual systems and to include the inevitable decline in performance during long-term operation. Performance of several system was improved during operation by replacement of compost media. Limestone-amended IL1 compost was replaced in October 2013. Compost was also replaced in IN2 in October 2009 and IN3 in October 2012. Both compost and limestone were replaced in SAPS MO1 and MO2 in March 2021 after 20 years of operation.

Findings – Comparing Midwestern to Appalachian VFPs

The second goal of this paper is to compare midwestern VFP performance data with Pennsylvania data published by Rose and Dietz (2002) and Rose (2004; Figs. 1A and 1B). Because the Rose and Dietz data was used to develop a common empirical design criterion, we suggest that adding newer datasets will improve future passive treatment designs. Rose (2002) found that the rate of acidity reduction in 29 Northern Appalachian VFPs was comparable to the results for the regression of acidity loading (g/m^2/day) verses effluent alkalinity (mg/L CCE). How does the performance of Midwestern U.S. hybrid VFP's compare to Appalachian VFPs? Figs. 1A and 1B replots the Rose 2004 dataset along with the results of our VFP assessment (midwestern VFP data in orange). Would our data improve to the empirical design criteria? Midwestern VFP's and hybrid VFPs are found

***Table 3** Comparative Performance of Passive Vertical Flow Treatment Cells Treating Net Acidic Coal Mine Drainage -Volume-based; inlet values unless noted[1]*

Cell ID	Type**	n =	Acid. Load g/m^2/day	Fe Load g/m^2/day	Mn Load g/m^2/day	Al Load g/m^2/day	Cumulative Metal Load g/m^2/day	Acidity Removal g/m^2/day
IL1	Bioreactor	70	62.25	16.86	1.27	4.17	22.46	58.71
IN1	E. Hybrid	56	9.75	3.18	0.489	0.205	3.93	34.79
IN2	W. Hybrid	56	7.13	2.33	0.358	0.150	2.88	20.95
IN3	Bioreactor	42	20.43	4.68	0.464	0.341	5.49	19.08
MO1	SAPS1	20	49.82	20.95	1.07	0.223	22.24	15.44
MO2	SAPS2	20	8.95	1.55	0.888	0.081	2.519	14.09
MO3	Hybrid	11	2.62	0.795	0.107	0.030	0.931	2.14
MO4	VFP	8	15.33	5.20	1.04	0.240	6.59	12.53
MO5	VFP	8	14.02	3.53	0.032	0.161	5.44	14.67
AR1	Hybrid	14	1.01	0.426	0.274	0.004	0.704	13.07
AR2	N. Hybrid	7	5.90	0.561	0.422	0.069	1.052	12.93
AR3	S. Hybrid	7	2.72	0.259	0.195	0.032	0.486	5.70
	VFP Average		22.03	7.808	0.758	0.176	9.197	14.18
	Hybrid Average		4.86	1.258	0.307	0.082	1.663	14.93
	Bioreactor Average		41.34	10.771	0.866	2.256	13.973	38.90

1.Median values; loading calculations based on discharge and VFP surface area values shown in Table 1.

*Calcium carbonate equivalent (CCE).

**Hybrid = Hybrid bioreactor/vertical flow pond.

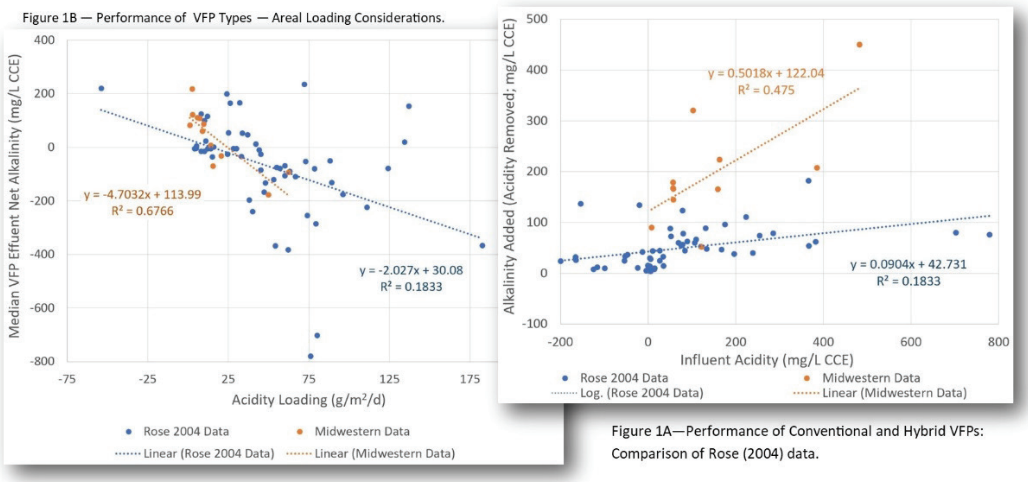

Figure 1 *Performance of VFPs: Alkalinity production compared to inlet acidity*

to be comparable with the data presented by Rose and Dietz (2004) and Rose (2006) when considering acidity loading rates (Fig. 1B).

To summarize, in the Midwestern U.S. VFP's and bioreactors are typically required to passively treat AMD with moderately to high acidity. Higher aluminum discharges are often treated by hybrid VFPs with thicker limestone-amended compost following the suggestions of Rose (2006). Flushing of VFPs could be an alternative to the use of thicker compost but has been avoided due to increased maintenance at sites distant from state reclamation offices. Plotting an extended dataset of Northern Appalachian data resulted in a similar linear equation but at an improved r2 value (Figs. 1A and 1B). Performance data from midwestern sites were derived from median performance over a long operation period of 6.8–21.8 years and compared this with historic Appalachian data collected over a much shorter operation term where higher performance is expected. Because construction of many Pennsylvania VFPs predated most midwestern VFPs, the latter installations benefited from lessons learned such as the need to increase compost thickness and the necessity of limestone addition to the compost layer.

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