Evaluating the Effectiveness of Various Aggregate Cleaning Methods

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Abstract

Aggregate used in passive mine water treatment systems can become fouled over time with metal solids that decrease chemical reactivity and hydraulic retention. Replacement of fouled stone is expensive. We evaluated the effectiveness of various physical methods for cleaning aggregate in oxic limestone beds. All the methods involved tumbling the stone in mine water which removed Fe and Al solids. We measured the effects of cleaning on chemical and hydraulic characteristics of the beds. All the methods restored aggregate porosity, increased hydraulic retention time, and increased alkalinity generation. Thus, cleaning aggregate is an effective alternative to replacement of fouled stone.

Keywords: Passive treatment, limestone aggregate

Introduction

Aggregate is commonly used in passive mine water treatment systems. Calcareous aggregates, such as limestone (calcite) and dolomite, are used to neutralize acidity and generate alkalinity. Non-calcareous aggregates, such as granite and sandstone, are used to promote surface-dependent reactions (e.g. Mn removal). The fouling and plugging of aggregate is a problem in systems where metal removal occurs within the bed. One way to deal with this problem is to avoid creating or maintaining redox conditions that inhibit the formation of solids. Anoxic limestone drains and vertical flow ponds (also known as reducing and alkalinity producing systems (RAPS)) are such systems (Hedin *et al* 1994; Younger *et al* 2002). However, for mine waters that contain metals whose solubility is not redox dependant (e.g. Al), metal removal within the aggregate cannot be avoided. Design features such as flushing systems can remove a portion of the accumulated metal solids, but long-term treatment plans should consider management of the solids that cannot be flushed. One solution for the long-term maintenance of these systems to replace the aggregate. In these cases, valuable chemical or physical characteristic of the aggregate are masked by the solids and useful aggregate is disposed of. An alternative action is removal of the solids and renewal of the useful attributes of the aggregate.

This project studied methods being used to clean aggregate in passive mine water treatment systems in the eastern U.S. We cleaned aggregate in 10 oxic limestone beds contained in passive treatment systems. We evaluated how the various cleaning methods affected factors that influence impact treatment effectiveness such as porosity, hydraulic retention time, and chemical reactivity. We evaluated how the various methods handled solids cleaned from the aggregate. This paper provides a review of the general results of our project.

Methods

The effects of aggregate cleaning were evaluated by measuring chemical and physical parameters before and after a cleaning event. The treatment effectiveness of the beds was evaluated by collecting water samples from influent and effluent locations. Flow rates were measured by the timed-volume method. Conductivity, pH, and temperature were measured in the field with a calibrated combination pH/conductivity electrode and meter. Alkalinity was measured by titration to pH 4.5 with sulfuric acid. Raw and acidified (nitric acid) water samples were collected and submitted to a laboratory for analysis of acidity, Fe, Al, Mn, and sulfate by standard methods. The samples were not filtered, and results represent total concentrations.

The porosity of aggregate beds was determined by measuring the amount of water needed to fill a known volume of aggregate. A water level transducer was installed in an effluent water level control structure. The bed was drained and then allowed to refill by a known flow of mine water while the transducer measured the water level. Construction plans were used to calculate the volume of the aggregate at various elevations. Porosity was calculated:

Porosity, % = Volume (L) / flow (L/min) / time (min) x 100 (1)

where volume is the amount of aggregate filled, flow is the inflow rate of mine water in, time is the number of minutes needed to fill the aggregate, and 100 converts the result to a percentage. The transducer reported water levels on ten-minute intervals. Bed dimensions were determined for each water level, allowing calculation of porosity for sections of the beds.

Porosity measurements were not conducted on the full depth of aggregate at all sites. In order to standardize comparisons within and between sites, porosity measurements presented in this paper represent the top 45 cm of the aggregate beds (unless otherwise indicated).

The theoretical hydraulic retention of water flowing through a bed, THRT, was calculated from the bed volume, porosity, and flow rate.

THRT (h) = bed volume (L) × porosity (%) / flow (L/h) (2)

This value represents the retention time if water travels through the bed without any preferential or short-circuiting flow paths. The actual hydraulic retention time, HRT, was determined through a tracer addition. The flow rate of mine water through the bed was measured. A calibrated Na-fluorescein sensor (Cyclops-7 Logger) was placed in effluent of the bed and set to make measurements every ten minutes. Uranine, a Na-fluorescein dye, was added to the influent. The tracer addition was calculated from limestone volume and Na-fluorescein concentration in the injection dye with a target concentration of 10 ppb in the pore spaces of the limestone bed.

After at least twice the estimated THRT had elapsed, the detector was retrieved and data downloaded into a spreadsheet. Tracer masses were calculated for each interval from the concentration, flow rate, and elapsed time. The total recovery of tracer was determined by summing the individual masses. The amount of tracer recovered varied from the injection, presumably due to adsorption onto solids in the bed and/or overestimation due to scattering from turbidity (Naurath *et al.*, 2011). The individual mass measurements were divided by the total recovered tracer, converted to percentages, and summed. The hydraulic retention time was determined as the time for 50% of the tracer recovery.

The HRT for bed varies depending on the flow rate at the time of testing. While we had several cases where pre-clean and post-clean HRTs were measured under similar flows and direct comparison of HRTs was reasonable, most comparisons occurred under different flow rates. To standardize for this variation, we calculated an efficiency value by comparing the HRT to the THRT

HRT efficiency (%) = HRT / THRT (3)

Cleaning methods

Aggregate was cleaned by four methods as outlined below.

Dozer: A bulldozer pushes aggregate from the flooded bed onto a berm and then back into the bed. The aggregate's tumbling action removes solids which either settle to the bottom of the bed flow out into a settling pond by gravity or pumps. Support with an excavator may be necessary.

Mix and Rinse: And excavator mixes aggregate within the flooded bed. A sump is dug in the bed in which aggregate is mixed with the excavator and sprayed with a pump. Clean stone is placed aside and the process repeated until logistics require establishment of a new cleaning sump. Solids washed off the aggregate are carried out of the bed by gravity flow and pumps or settle in the sump and are periodically excavated and disposed of outside the bed or left in the bed.

Screening bucket: This method utilizes a specialized attachment that replaces the bucket on an excavator. There are two primary types of screening bucket: basket and drum. The basket type has a screen that rotates on an axis parallel to the boom of the excavator. It is similar in appearance and function to the basket in a vertical axis clothes washer. The drum type has a barrel-shaped screen like a trommel screen that rotates on an axis that is perpendicular to the boom of the machine.

Both types of screening buckets are loaded like a standard excavator bucket. The loaded bucket is held in a partially curled position and rotated to tumble the aggregate. Dipping the screen in water while it rotates washes solids from the aggregate. Basket screening buckets are unloaded like a standard bucket while drum screening buckets are unloaded by reversing the drum rotation.

Cleaning can take place within the aggregate, but a preferred method utilizes a dedicated container to serve as a wash basin such as a stone boat or roll of container. Clean water is pumped into the wash basin while solids laden water is simultaneously pumped out of the wash basin during the cleaning work. Coarse solids tend to accumulate in the wash basin and must be removed periodically by either excavation or by tipping the basin over. Solids are then disposed of outside the limestone bed in either a settling pond or by burial.

Trommel: A trommel is a cylindrical rotating screen that allows fines to fall through the screen while clean aggregate is discharged out the end of the cylinder. For this project a mobile trommel unit was modified so that aggregate would be sprayed with water as it tumbled through the screen. Solids washed off the aggregate were captured in a pan beneath the screen and pumped away. The trommel used in this project was powered by a farm tractor and fed by an excavator.

Results and Discussion

Table 1 shows the characteristics of 10 aggregate beds included in this project. The size of the beds and flow rates of mine water varied widely. Nine of the beds received low pH water containing Fe, Al and Mn. One of the beds received an alkaline influent containing Fe. All the beds were constructed with high-calcite limestone aggregate and operated as oxic systems where the formation of Fe, Al, and Mn solids was encouraged. Seven of the systems contained operational automated flushing devices that drained the beds empty once/week. The draining removes a portion of the metal solids which prolongs the effectiveness of the beds (Wolfe *et al.* 2010). However, after several years of operation the aggregate in the beds requires rehabilitation or replacement to maintain effectiveness.

We observed two types of solids that form within aggregate beds. Suspended solids accumulate within the aggregate pores that appear to be Fe and Al oxides and hydroxides. These solids can be partially removed by flushing and are readily removed by washing. Solids also form scales attached to aggregate particles. These Fe and Al solids are not removed by flushing but can be removed with washing. Fig. 1 shows stone fouled with Al and Fe solids before and after cleaning. Mn oxide solids also form as attached coatings, but they are not readily removed by washing (evidenced by black coatings remaining on stones after cleaning).

Table 2 shows changes in alkalinity generation and hydrologic characteristics of the beds before and after cleaning. Water chemistry assessments were made for all beds. A primary goal of the cleaning was to increase alkalinity generation. All the cleaned beds discharged more alkalinity than pre-cleaning. All the effluents from the cleaned beds had pH 6–8 and contained <1 mg/L Fe and Al (data not shown).

Measurements were made of porosity and hydraulic retention time at five sites. Fresh well-sorted aggregate typically has a porosity between 40% and 45%. The porosity of fouled aggregate was as low as 10–12%. Cleaning increased porosity, generally to values consistent with fresh aggregate. Fig. 2 shows porosity values measured at the Kentucky Hollow site where aggregate was cleaned by the screening bucket method and porosity was increased from 33% to 44%.

Hydraulic retention time was measured by tracer additions. Fig. 3 shows tracer test results for the Scootac Site-1 bed where cleaning by the mix/rinse method increased HRT from 10 hr to 17 hr. Cleaning increased

HRT at all sites. This change can be attributed to the increased void space (porosity) and the elimination of preferential flow paths. The increased retention time provides more times for limestone dissolution and increased alkalinity where its generation is limited by contact time. Cleaning did not eliminate hydraulic inefficiency (HRT/THRT). Many of the beds have design features that promote the creation of "dead spots" or preferential flow paths. Cleaning the aggregate will not correct these problems.

All the methods tested improved the treatment effectiveness of the systems. The methods vary in how they handle solids produced during cleaning. The dozer and mix/rinse methods clean the aggregate *in situ*. While a portion of the solids produced may be removed by piping/pumping turbid water to a settling pond, solids also settle and are retained in the bed. These solids decrease the bed volume and porosity, especially in the bottoms of the beds (Hedin Environmental, in review). Eventually the accumulation of these solids would be expected to impair the effectiveness of the system. The screening bucket and trommel methods collect solids in a box or pan and provide the opportunity to remove solids permanently from the bed. This practice likely allows more sustainable treatment by the system.

Conclusions

The treatment effectiveness of oxic limestone beds containing fouled aggregate was evaluated restored through cleaning of the aggregate. Four cleaning methods were tested and all were effective. Cleaning increased aggregate porosity, increased the hydraulic retention time of the mine water in the beds, and increased the generation of alkalinity from limestone dissolution. The main differences between the methods were that the dozer and mix/rinse methods uses standard construction equipment but the washed off solids were retained in the limestone bed compared to the screening bucket and trommel methods which required specialized equipment but removed the washed off solids from the limestone bed.

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Figure 1 A) Aggregate fouled with AMD solids; B) aggregate after cleaning Both photos from the Kentucky Hollow oxic limestone bed.

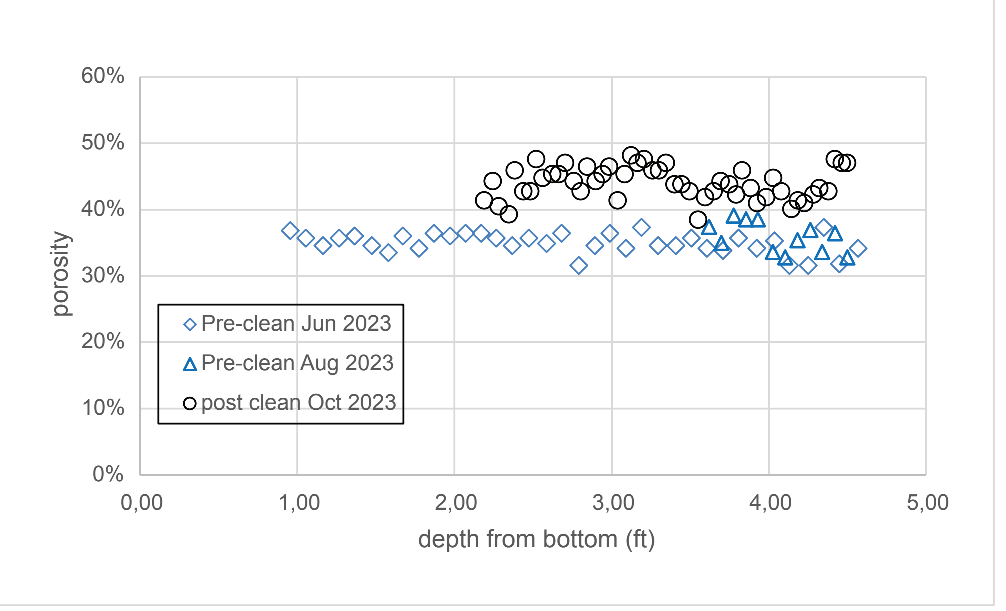

Figure 2 Porosity measurements made at the Kentucky Hollow oxic limestone bed which was cleaned via the screening bucket method.

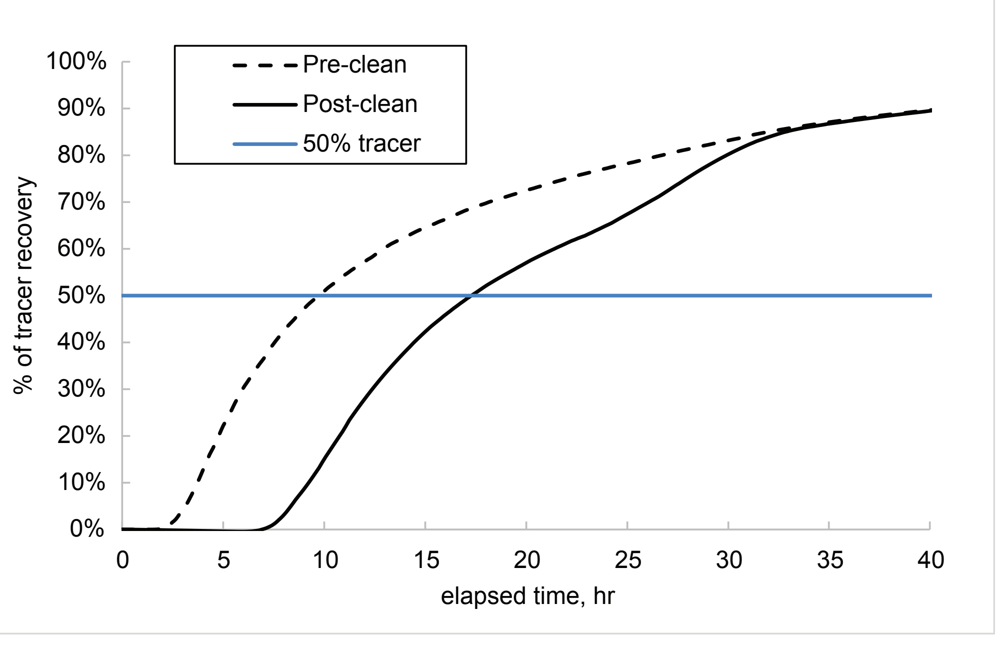

Figure 3 Tracer recovery at the Scootac Site-1 site. HRT is determined at 50% tracer recovery. Both tests done at flow rate of 150 L/min.

Table 1 Characteristics of sites included in the study. Flow and chemistry are average values.

	Bed size t	Installed a	flow L/min	pH s.u.	Acid mg/L	Fe mg/L	Al mg/L	Mn mg/L	SO4 mg/L	Cleaning method
KH-W	680	2019	128	3.5	85	0.9	7.8	0.9	397	SB[a]
Mud MR-4	635	2014	191	4.5	30	0.2	2.6	4.5	174	SB
Scootac	900	2010	219	4.0	85	0.2	10.2	23.1	880	mix/rinse
FB DLB1	3,000	2015	857	3.6	78	0.3	8.1	10.4	475	Dozer
Gib FLB-1	3,400	2018	184	3.5	39	1.2	3.2	2.7	139	trommel
Sterrett-S	1,600	2015	219	3.4	95	9.2	8.5	16.8	447	Dozer
Sterrett-N	1,600	2015	202	3.4	95	9.2	8.5	16.8	447	mix/rinse
Mor MR-8	360	2016	78	3.7	128	2.7	9.3	6.5	226	trommel
BT DLB-1	540	2005	23	2.6	520	196	6.3	4.6	597	SB
BTDLB-2	540	2005	28	7.6	-46	2.7	0.2	3.2	540	SB

[a]screening bucket

Table 2 Effects of aggregate cleaning on alkalinity generation and hydraulic characteristics.

	Effluent Alkalinity		Bed size	Porosity		Hydraulics – Pre				Hydraulics – post			
	Pre mg/L	Post mg/L	m³	Pre %	Post %	Flow L/min	HRT h	TRT h	HRT/THRT %	Flow L/min	HRT h	TRT h	HRT/THRT %
KH-W	110	162	375	33	44a	79	24	26	92	68	34	40	83
Mud MR-4	78	112	405	30	37	25	48	81	59	25	76	102	74
Scootac	122	190	601	10b	31b	151	10	7	146	151	15	21	75
Gib FLB-1	49	53	1,258	42	48a	93	95	94	101	178	68	57	119
FB DLB-1	0	79		32	22		10	8					
Sterrett-Sc	33	183	709		40					83	25	57	44
Sterrett-N	39	174											
Mor MR-8	28	70											
BT DLB-1	62	123											
BT DLB-2	82	105											

[a]5–45 cm depth; [b]0–30 cm depth; [c]Sterrett-S porosity and HRT measurements made 2 years after cleaning