The engineering of truly passive mine water treatment systems using recycled concrete aggregate

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Abstract

Treatment of acidic and metalliferous drainage (AMD) from mines using globally available recycled concrete aggregate (RCA) is passive, simple, long-term, cheap, and sustainable. RCA contains up to 20% by weight alkaline calcium minerals, mainly portlandite ($Ca(OH)_2$) and calcite ($CaCO_3$), which are available by dissolution and diffusion from the concrete particle matrix to treat metal-containing water that contacts it. Testing has demonstrated that RCA can remove > 95% of dissolved metals of concern (including antimony, arsenic, cadmium, copper, iron, mercury, manganese, nickel, lead, and zinc from AMD by slowly passing it through a large bed of crushed concrete particles and generally has no waste products.

However, to date the actual application of this technology in the field has been largely unsuccessful, due to limited performance. A five-year evaluation of this technology has been conducted by the author to identify the reasons why the promise of this sustainable material for AMD treatment has not yet been realized. This research shows that the reasons include: 1) the AMD has been passed through the RCA too rapidly; 2) the particle size of the RCA has been too large; and 3) the hydraulics of the treatment systems are too complex and active.

The research quantifies the requirements for successful site-specific long-term passive RCA treatment systems: 1) Small RCA particle size to allow the timed-release of alkalinity from the RCA, which is in the order of 5–10 mm; 2) Large RCA void volume to allow AMD retention required for treatment and filtration, which is in the order of 1 to 15 days for this particle size; and 3) sufficiently simple upflow treatment hydraulics, ideally without pumps or pipes.

This paper provides the support for these guidelines, and sets out instructions for successfully testing, designing, and engineering a truly passive, long-term, and sustainable AMD treatment system at any site using RCA as the treatment, sequestration, and filtration medium.

Keywords: Passive mine water treatment, recycled concrete aggregate, acidic and metalliferous discharge treatment

Introduction

Treatment of acidic and metalliferous drainage (AMD) from mines using globally available recycled concrete aggregate (RCA) is passive, simple, long-term, cheap, and sustainable (Brown 2018). RCA contains up to 20% by weight of alkaline calcium minerals, mainly portlandite ($Ca(OH)_2$) and calcite ($CaCO_3$), which are available by dissolution and diffusion from the concrete particle matrix to treat metal-containing water that comes into contact with it. Testing has demonstrated that RCA has the potential to remove > 95% of dissolved metals of concern (including antimony, arsenic, cadmium, copper, iron, mercury, manganese, nickel, lead, and zinc) from AMD by slowly passing it through a large bed of crushed concrete particles. This treatment captures and immobilizes the metals of concern in the RCA matrix, and so in general has no waste products.

However, to date actual application of this promising technology in the field has been largely unsuccessful, due to limited performance (Johnson et al. 2000; Regmi et al. 2011; Wang et al. 2013; Wang et al. 2016;

Jones and Cetin 2017). To identify how the promise of the AMD treatment capacity of this sustainable recycled medium can be realized, a five-year program of laboratory and field evaluation of this technology has been conducted by the author.

This paper describes the work performed to unlock the AMD treatment potential of RCA. It uses the results of that work to describe successful testing, designing, and engineering a truly passive, long-term, and sustainable AMD treatment system at any site using RCA as the treatment, sequestration, and filtration medium.

Approach

The approach taken to unlocking the AMD treatment potential of RCA has been empirical: to simply pass AMD water from various mines through RCA from local sources and observe what it takes to passively remove metals of concern (MOCs), which for this study antimony, arsenic, cadmium, copper, iron, lead, mercury, manganese, nickel, silver, and zinc.

In each test, the fundamental activity is to bring AMD into contact with RCA for a known time and observe the change in the concentration of the dissolved constituents in the treated fluid. I used three approaches:

1. *Batch Testing:* AMD is suddenly added to saturate a bucket containing ≈ 20 kg of washed RCA, and the water quality is monitored over time until the MOCs are substantially removed, which required up to 15 days. A total of 17 tests were performed using a variety of local AMD and RCA samples. The results of these tests were encouraging (Brown 2018), but regulatory reviewers were concerned that they over-estimated the long-term treatment performance of RCA.
2. *Column Testing:* AMD is passed through a laboratory column containing between 1 kg and 5 kg of RCA and the quality of the treated fluid is monitored. The test is conducted with relatively rapid flow until between 200 and 400 pore volumes of AMD have been treated, after which the flow rate is reduced stepwise until the MOCs are removed. Typical tests last for one to three months. A total of 22 tests were performed using a variety of local AMD and RCA samples. The results of these tests were also encouraging, but obtaining the large quantities of AMD needed for the tests prevented the tests reaching exhaustion.
3. *Field Testing:* AMD from a mine is passed through an on-site column or pilot treatment facility containing between 20 kg and 500 kg of RCA, and the quality of the treated fluid is monitored. The test is again conducted with relatively rapid flow until between 200 and 500 pore volumes of AMD have been treated, after which the flow rate is reduced stepwise until the MOCs are removed. Typical tests last for six to twelve months, after which the remaining RCA was leached with clean water to determine if the MOC sequestration was permanent and sampled to measure how much of the removed MOCs remained in the RCA. A total of 13 tests were performed using a variety of local AMD and RCA samples. These tests were in general reliable and successful. Results from a typical field test are shown in Tables 1 and 2.

Results

Example water quality results of the most complete test of the treatment of AMD using RCA that I have conducted to date are presented for water quality of the treated in Table 1, and the corresponding RCA elemental abundance results in Table 2.

Empirical Results

The empirical insights that I have drawn from the testing which are germane to the engineering of passive AMD treatment systems using RCA are offered below.

RCA successfully removes MOCs from AMD.

All the testing performed in this study shows that there is always a treatment rate that removes MOCs. RCA treatment of AMD is slow and removal of MOCs generally requires a contact time between 1 to 15 days. While this is tedious from a testing perspective, it is beneficial from a treatment perspective, as it demonstrates the slow, timed-release of

Table 1 *Water quality results of long-term RCA treatment of AMD*

ACTION		TREATMENT TESTING		POST-TEST EXTRACTION	
Fluid		Raw AMD	Treated AMD	Extractant	Extract
Fluid source		Zinc Mine	Test cell	Tap water	Test cell
Solid		RCA	RCA	RCA	RCA
Solid source		Denver CO	Denver CO	Denver CO	Denver CO
Mass of solid	kg	25	25	25	25
Start of step		2022-12-20	2022-12-20	2023-07-06	2023-07-06
End of step		2023-01-04	2023-01-04	2023-07-07	2023-07-07
Treated to Date	Pore Volumes	--	220	--	458
Flow rate	PV/day	--	0.288	--	7.0
Retention Time	hours	--	187	--	3
ANALYTE		EM-IN-230104	C18-CX-230104	EM-IN-230707	C18-CX-230707
pH		6.2	8.1	8.4	8.2
Al	mg/L	0.09	<0.05	0.054	<0.05
Sb	mg/L	<0.03	<0.03	<0.03	<0.03
As	mg/L	0.298	<0.04	<0.04	<0.04
Cd	mg/L	0.0469	<0.008	<0.008	<0.008
Ca	mg/L	348	462	20.5	43.9
Cu	mg/L	0.164	<0.01	<0.01	<0.01
Fe	mg/L	47.5	1.58	<0.06	0.086
Pb	mg/L	<0.03	<0.03	<0.03	<0.03
Mg	mg/L	226	142	5.65	6.73
Mn	mg/L	15.5	3.78	<0.01	0.419
K	mg/L	10.8	15.6	1.51	2.55
Si	mg/L	7.1	4.96	3.25	5.8
Na	mg/L	7.89	9.89	20.9	20.9
S	mg/L	566	517	14.6	29.5
Zn	mg/L	23.8	0.608	<0.02	0.171

Note: All analyses were conducted on unfiltered samples preserved with nitric acid onsite.

Table 2 *Elemental abundance in RCA used for long-term treatment of AMD*

ELEMENT	PRE-TEST mg/kg	POST-TEST mg/kg	CHANGE mg/kg	%CHANGE %
Al	49,600	60,300	10,700	22%
Sb	-153	-152	-1	-1%
As	-1,020	-202	-818	-80%
Cd	-41	-40	0	-1%
Ca	71,100	42,100	-29,000	-41%
Cu	-51	-51	-1	-1%
Fe	17,800	17,700	-100	-1%
Pb	384	-152	-232	-60%
Mg	2,690	6,620	3,930	146%
Mn	393	654	261	66%
K	32,200	29,500	-2,700	-8%
Si	299,000	295,000	-4,000	-1%
Na	15,300	18,200	2,900	19%
S	2,530	2,060	-470	-19%
Zn	-102	1,580	1,478	1449%
C	6,000	6,000	0	0%
O(calc)	496,925	515,300	18,375	4%

Note: Total digestion using EPA Method 3052 (HF digestion) alkalinity from the RCA and timed absorption of metals from the AMD that is necessary for successful long-term passive treatment.

AMD treatment requires small particles of RCA.

Optimal treatment requires ≈ 10 mm particles. Finer is too fast, and coarser is too slow. To arrive at this conclusion, I batch- and column-tested the same fluids with different sized RCA. The required retention time varies with about the square of the average particle diameter.

AMD treatment works best with upflow through the RCA.

Upflow is beneficial because it minimizes plugging, exposure to the atmosphere, and oxidation of metals during treatment. When I tested using downflow, iron hydroxide precipitated on the surface of the test material, which clogged the material and generated acid, reducing the treatment life of the RCA.

RCA treatment of AMD does not clog the RCA medium.

All the tests performed caused visible precipitation of process products and degradation of the particles making up the treatment mass. Surprisingly none of the tests displayed a meaningful increase in resistance to flow at the treatment rates which were effective. This appears to be the result of a balance between formation of precipitates and dissolution of the cement in the RCA, leaving the silicious concrete aggregate which creates a porous matrix for flow.

RCA treatment of AMD does not substantially blind the RCA medium.

The visible precipitation of process products on the RCA particles should blind the RCA and reduce or prevent treatment. While the tests showed a reduction in treatment rate over the long term, it appears that the cause was slowing of diffusion as the MOC concentrations in the particles increased over time.

RCA treatment of AMD does not create deleterious short-circuit flow pathways.

The dissolution of cement creates visible flow passages through the RCA, but again surprisingly they do not appear to affect treatment performance at the extremely slow flow rates corresponding to successful treatment.

RCA treatment of AMD retains treatment products within the treatment matrix.

For the low flow rates of successful removal of MOCs the RCA concrete aggregate particles filter precipitates (surprisingly), so the water discharged from the successful tests is in general clear.

RCA treatment of AMD in general produces alkaline discharge.

RCA contains up to 25% by weight of alkaline calcium compounds, mainly portlandite ($CaO.H_2O$) and calcite ($CaCO_3$), which treat the AMD. High pH is expected, and occurs early in the tests, but at the successful treatment rates in the long-term discharge pH is between 7 and 9.

RCA treatment of AMD permanently sequesters extracted MOCs in the treatment matrix in non-hazardous form.

Post-test leaching of the RCA shows that MOCs are permanently retained. The solids have non-hazardous concentrations of MOCs, so the treatment residue can be left in position. Table 2 shows a typical solid phase analysis of RCA from before testing and after long-term testing, showing that the materials are not in general hazardous wastes, before or after testing.

RCA does not add MOCs to the treated fluid.

Concrete contains constituents which might be deleterious if released by treatment, particularly aluminum, arsenic, iron, manganese, and zinc. None of these constituents were released in the treated fluid at concentrations elevated above the influent concentration. Indeed, almost all the constituents were reduced by treatment, as shown in typical fluid concentrations Table 2.

Design

Quantity of RCA Required for AMD Treatment System

The design process for sizing passive RCA systems for treatment of AMD is straightforward:

1. Determine the flow rate (Q) of AMD that requires treatment; obtain and analyze samples.
2. Determine the RCA that will be used for passive treatment; obtain and analyze samples.
3. Perform batch or (better) field tests to determine:
    a. Retention time (t) required for your RCA to treat your AMD to remove MOCs.
    b. Porosity (n) of your RCA by measuring the volume of AMD to flood the RCA.
    c. Dry density (ρ) of your RCA by dividing the mass by the volume of test solids.
4. Calculate the amount of RCA that is required for your passive treatment system using the data that you have just obtained.

$$Total\ volume\ of\ RCA\ (V) = \frac{Treatment\ flow\ rate\ (Q)\times Retention\ time\ (t)}{Porosity\ of\ RCA\ (n)}$$

To put this equation into perspective, consider a typical mining AMD treatment system using RCA. Based on testing as described above, the treatment system has the following characteristics:

Treatment Flow Rate (Q) : 1,000 m3/day (≈ 200 USgpm)
Critical Retention Time (t) : 4 days
Porosity of RCA (n) : 45%

The critical volume of RCA required to treat this AMD is computed using the above equation:

$$Critical\ volume\ of\ RCA\ (V) = \frac{1000\ (m^3/day)\times 4\ (days)}{45\ (\%)} = 9{,}000\ (m^3)$$

This is a large treatment facility. However, from a mining perspective moving and placing 9,000 cubic meters (about 12,500 t) of inexpensive recycled material to provide unattended treatment of a substantial flow of acid and metalliferous water for the long term is a small earthmoving task. It can be readily accomplished with standard mining equipment and personnel at a cost that is less than construction of a standard AMD plant to treat the same flow to the same standard.

Life of RCA Treatment System

The maximum life of the critical mass of RCA for treatment the AMD fluid can be estimated based on the availability of the principal treatment element, calcium, and its consumption and release during treatment using the following equations:

$$Estimated\ RCA\ life\ (t_{RCA}) = \frac{Mass\ of\ calcium\ in\ RCA\ (M_{Ca})}{Mass\ rate\ of\ calcium\ consumption\ (R_{Ca})}$$

$$\begin{aligned} &Mass\ of\ calcium\ in\ RCA\ (M_{Ca}) \\ &\qquad = Volume\ of\ RCA\ (V)\times Density\ of\ RCA\ (\rho_{RCA}) \\ &\qquad \times Concentration\ of\ Ca\ in\ RCA\ ([Ca_{RCA}]) \end{aligned}$$

$$\begin{aligned} &Mass\ rate\ of\ calcium\ consumption\ (R_{Ca}) \\ &\qquad = Treatment\ flow\ rate\ (Q)\times Density\ of\ water\ (\rho_W) \\ &\qquad \times Change\ in\ concentration\ of\ Ca\ in\ fluid\ ([\Delta C_{Ca}]) \end{aligned}$$

Again, these equations are applied to the RCA treatment system for the AMD in the above example to determine its expected life. Based on the batch testing above, the critical mining AMD treatment system using RCA has the following characteristics:

Volume of RCA (V) : 9,000 m^3
Bulk Density of RCA (ρ_{RCA}) : 1.41 t/ m^3
Concentration of Ca in RCA ([CaRCA]) : 7.1%
Treatment Flow Rate (Q) : 1,000 m^3/day (≈ 200 USgpm)
Density of water (ρ_W) : 1 t/ m^3
Change in concentration of Ca in fluid ([ΔCCa]) : +100 mg/L

The estimated life of the critical mass of RCA for treating this AMD is computed using the above equations:

$$Estimated\ RCA\ life\ (t_{RCA}) = \frac{9000\ (m^3)\times 1.41\ (t/m^3)\times 7.1\ (\%)}{1000\ (m^3/d)\ \times 1\ (t/m^3)\times 100\ (mg/L)} = 25\ years$$

This is a long treatment time, typical of the result for these facilities. If a longer life is required, the volume of RCA can be increased as needed. From a mining perspective this facility would replace a manned treatment plant, which would cost at least $US 1 million per year to run. The operating cost of the RCA treatment system once constructed is close to zero.

Conclusion

Long-term truly passive treatment of acid and metalliferous drainage (AMD) by treatment systems using recycled concrete aggregate (RCA) is feasible, provided the following guidelines are adopted:

1. *Small RCA particle size* to create constant timed-release of alkalinity from the RCA, which requires grainsizes in the range of 2–20 mm.
2. *Long contact between the AMD and the RCA* to allow time for treatment and filtration, which requires 1 to 10 days retention time.
3. *Large RCA mass* to provide long-term reagent for AMD treatment, which requires thousands of tonnes of RCA for typical AMD discharge flows.
4. *Minimal contact of the treated fluid with the atmosphere during treatment* to prevent acid generation and formation of oxidized metal precipitates, which requires that the treatment process be enclosed and flooded until discharge.
5. *Free-flowing treatment system hydraulics* to allow long-term unattended passive treatment, which requires upflow in the treatment system and minimization of pumps, valves, and pipes.

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