Appendix I

Treatability Study Report

March 2023
Former Reynolds Metals Reduction Plant – Longview

Treatability Study Report

Prepared for
Northwest Alloys, Inc.
c/o Alcoa Corp.
201 Isabella Street
Pittsburgh, Pennsylvania 15212-5858

Prepared by
Anchor QEA, LLC
6720 South Macadam Avenue, Suite 125
Portland, Oregon 97219

Project Number: 220002-04.02
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ABBREVIATIONS

µg/L	micrograms per liter
µm	micron
µS/cm	microsiemens per centimeter
1/n	Freundlich isotherm exponent related to sorption intensity
Axens	Axens Canada Specialty Aluminas Inc.
Axens AA	ActiGuard F 14×28 activated alumina obtained from Axens Canada Specialty Aluminas Inc.
BMP	Black Mud Pond
$CaCO_3$	calcite
cm	centimeter
C_e	equilibrium fluoride concentration
CEC	cation exchange capacity
Delta AA	AAFS50 28×48 activated alumina obtained from Delta Adsorbents
DO	dissolved oxygen
DOC	dissolved organic carbon
EGL	Environmental Geochemistry Laboratory
Final EDR	*Final Engineering Design Report, Version 2*
HCl	hydrochloric acid
HDPE	high-density polyethylene
K_f	Freundlich isotherm constant related to sorption capacity
L	liter
L/S	liquid to solid
LDPE	low-density polyethylene
M	moles per liter
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MgO	magnesium oxide
mL	milliliter
mm	millimeter
mV	millivolt
N/A	not applicable
NA	not analyzed
NaCl	sodium chloride
NaOH	sodium hydroxide
ORP	oxidation reduction potential
PDI Work Plan	*Pre-Design Investigation Work Plan*

PRB	permeable reactive barrier
R^2	the coefficient of determination (R-squared)
SC	specific conductivity
USEPA	U.S. Environmental Protection Agency

1 Introduction

This *Treatability Study Report* presents results of groundwater treatability testing for the former Reynolds Metals Reduction Plant in Longview, Washington. This report is an appendix to the *Final Engineering Design Report, Version 2* (Final EDR), prepared in accordance with the cleanup action as specified in the *Cleanup Action Plan* (Ecology 2018a) pursuant to Consent Decree No. 18-2-01312-08 (Ecology 2018b).

As part of the cleanup action, two areas of affected groundwater (i.e., the East and West Groundwater Areas) will be addressed through actions including the construction of permeable reactive barriers (PRBs) and reactive backfill with amendment to reduce the mobility of fluoride in groundwater. Laboratory treatability testing was performed to evaluate and select reactive amendments suitable for fluoride removal from site groundwater, and the findings of these investigations and recommendations are presented in this report.

1.1 Site Description

The site is located at 4029 Industrial Way near Longview, Washington, in unincorporated Cowlitz County. The property includes about 460 acres and is currently operated as a multimodal bulk materials handling facility. The site is approximately 10 feet above mean sea level and bounded by the Columbia River to the south; Consolidated Diking Improvement District drainage ditches to the north, west, and east; Industrial Way along the northern boundary; and private property to the east.

1.2 Background

Dissolved fluoride can be removed from groundwater by several different reactive amendments (Bhatnagar et al. 2011). Crushed limestone consists mainly of calcium carbonate minerals such as calcite ($CaCO_3$), which can remove fluoride by surface adsorption and precipitation of fluorite (CaF_2) (Reardon and Wang 2000; Turner et al. 2005). Calcite has been shown to remove fluoride from groundwater impacted by wastes derived from the aluminum smelting process (Turner et al. 2008). Calcium phosphates such as mineral apatite ($Ca_5[PO_4]_3[OH]$; e.g., rock phosphate) and biogenic apatite (e.g., bone meal and bone char) have been shown to have a high fluoride uptake capacity from aqueous solution (Bhargava and Killedar 1992; Gao et al. 2009). Fluoride ion exchanges with the hydroxyl in calcium phosphate minerals to form insoluble fluorapatite ($Ca_5[PO_4]_3F$). Siderite ($FeCO_3$), an iron carbonate, has also been shown to remove fluoride from water (Liu et al. 2010; Shan and Guo 2013). Alumina (Al_2O_3) is a strong adsorbent for fluoride (Hao and Huang 1986; Ku and Chiou 2002; Tang et al. 2009; Fletcher et al. 2006). Layered double hydroxides such as hydrotalcite are also known for their high anion exchange capacity and have been documented to remove fluoride from aqueous waste streams (Wang et al. 2007; Jiménez-Núñez et al. 2007; Batistella et al. 2011). Magnesium oxide is reactive toward dissolved fluoride and has been implicated as the phase responsible for the enhanced fluoride uptake by magnesium-bearing carbonates and hydrotalcite after partial calcination (Sasaki et al. 2013; Zhang et al. 2015).

1.3 Purpose

The objectives of this treatability study are to provide site-specific empirical bench-scale data on the fluoride removal performance of various reactive media to aid in selection of amendments for use in PRB and reactive backfill applications and develop information needed for the basis of design that supports the Final EDR. Fluoride removal performance of selected reactive media was evaluated in a series of laboratory batch tests with site groundwater to determine the extent of fluoride removal as a function of fluoride concentration, reaction time, and liquid to solid (L/S) ratio. Test results were compared and ranked in terms of fluoride removal rate, removal efficiency (i.e., percent fluoride removal), fluoride uptake capacity, and potential water quality impacts from the amendments. Reactive amendments that exhibited the best fluoride removal performance were then investigated by flow-through column tests to provide information on the expected media lifetime and evaluate irreversibility and long-term stability of the sequestered fluoride.

Treatability testing was performed at Anchor QEA's Environmental Geochemistry Laboratory (EGL) in Portland, Oregon, following procedures outlined in the *Pre-Design Investigation Work Plan* (PDI Work Plan; Anchor QEA 2019).

2 Materials

2.1 Reactive Media

Representative samples of reactive media were obtained from commercially available sources for the fluoride treatability testing. Bone meal, bone char, rock phosphate, and hydrotalcite were available from multiple sources. The full list of media tested and vendor sources is included in Table I1, and the visual appearance of the media is shown in Figure I1.

2.2 Site Groundwater

Representative site groundwater samples were collected by Anchor QEA staff from monitoring wells RL-2S and PZ-5 for use in treatability tests. These monitoring wells are located adjacent to the proposed locations of PRBs in the West Groundwater Area and reactive backfill in the East Groundwater Area, respectively. Historically, fluoride concentrations in RL-2S and PZ-5 ranged from approximately 30 to 70 and 2,000 to 2,500 milligrams per liter (mg/L), respectively. Prior to groundwater sample collection, groundwater was pumped until field parameters (including pH, oxidation reduction potential [ORP], dissolved oxygen [DO], specific conductivity [SC], and turbidity) had stabilized. Groundwater samples were collected in 20-liter (L) low-density polyethylene (LDPE) Cubitainers with zero headspace and packed in Mylar barrier bags containing oxygen-absorbent packets to minimize potential changes in redox conditions during transport to the EGL. Groundwater samples for batch tests were collected on May 19 and October 31, 2019, for column tests. Groundwater samples were collected from the same monitoring wells again on January 27, 2022, for additional batch and column tests with activated alumina obtained from Axens Canada Specialty Aluminas Inc. (Axens), the planned project source of the activated alumina.

Site groundwater samples collected on May 19, 2019, and January 27, 2022, were chemically characterized to support the design and interpretation of the treatability tests. On receipt of the site groundwater samples at the EGL, pH, ORP, DO, and SC were measured under nitrogen atmosphere. Groundwater samples were also submitted in duplicate to Apex Laboratories, LLC, for chemical analysis as described in the PDI Work Plan (Anchor QEA 2019). Groundwater characterization results are presented in Table I2.

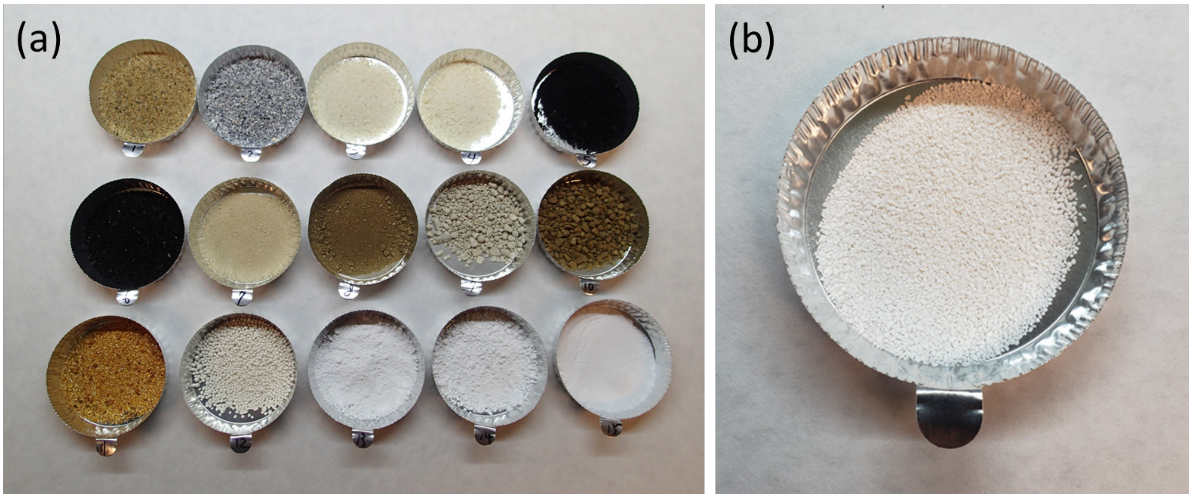
Table I1
Reactive Media Tested

Media	Formula	Vendor/Source	Initial Screening (Section 3.1)[1]		Second Screening Test (Section 3.2)		Batch and Column Tests (Sections 4 and 5)
			Tested	Retained for Further Testing	Tested	Retained for Further Testing	
Activated alumina	Al_2O_3	Delta Adsorbents (Delta Enterprises Inc.)			✓	✓	✓
		Axens[2]					✓
Bone meal	$Ca_5(PO_4)_3(OH)$	Down to Earth Distributors, Inc.	✓	✓	✓	✓	✓
		Bridgewell Agribusiness, LLC	✓				
Bone char	$Ca_5(PO_4)_3(OH)$	American Charcoal Company	✓	✓	✓	✓	✓
		Fedco Seeds, Inc.	✓				
Calcite	$CaCO_3$	Clark Corporation			✓		
Hydrotalcite	$Mg_6Al_2CO_3(OH)_{16}\cdot 4H_2O$	Kisuma Chemicals, DHT-4C	✓	✓	✓	✓	✓
	$Mg_{4.3}Al_2(OH)_{12.6}CO_3\cdot mH_2O$	Kisuma Chemicals, DHT-4V	✓				
	$Mg_{0.7}Al_{0.3}O_{1.15}$	Kyowa Chemical Industry Co., Ltd, KW-2000	✓				
Magnesium oxide	MgO	Martin Marietta Magnesia Specialties, LLC			✓		
Rock phosphate	$Ca_5(PO_4)_3(OH)$	Down to Earth Distributors, Inc. (from Florida)	✓				
		Fedco Seeds, Inc. (from Tennessee)	✓				
		Fedco Seeds, Inc. (from Minnesota)	✓				
Siderite	$FeCO_3$	Sidco Minerals, Inc.			✓		
Silica sand	SiO_2	Target Products Ltd.			✓		

Notes:

1. An initial screening test was performed to rank the fluoride removal efficiencies and select a preferred source for reactive media that were available in different grades or from multiple vendors (bone meal, bone char, rock phosphate, and hydrotalcite). For each reactive media, the best performing media was retained for the second screening test. All rock phosphate media were dropped due to their low fluoride removal efficiencies.
2. Following recommendation of activated alumina as the preferred reactive media (Section 4.4), Axens AA was selected as the specific material to be used for PRBs and reactive backfill based on availability. Additional batch and column tests were performed in 2022 to obtain site-specific performance data in support of design.

Figure I1
Reactive Media Tested



Notes:
Top row left to right of image (a): silica sand (Target Products Ltd.), calcite (Clark Corporation), bone meal (Down to Earth Distributors, Inc.), bone meal (Bridgewell Agribusiness, LLC), and bone char (American Charcoal Company)
Middle row from left to right of image (a): bone char (Fedco Seeds, Inc.), rock phosphate (Down to Earth Distributors, Inc. [from Florida]), rock phosphate (Fedco Seeds, Inc. [from Tennessee]), rock phosphate (Fedco Seeds, Inc. [from Minnesota]), and siderite (Sidco Minerals, Inc.)
Bottom row from left to right of image (a): Delta AA, MgO (Martin Marietta Magnesia Specialties, LLC), hydrotalcite (Kisuma Chemicals [DHT-4C]), hydrotalcite (Kisuma Chemicals [DHT-4V]), and hydrotalcite (Kyowa Chemical Industry Co. [KW-2000])
Image (b): Axens AA

Table I2
Initial Groundwater Characterization Results

Parameter	Result[1]				Units
	RL-2S		PZ-5		
	May 19, 2019	January 27, 2022	May 19, 2019	January 27, 2022	
Fluoride	84.7 (2.4)	80.3 (0.5)	1,960 (40)	1,620 (10)	mg/L
Aluminum, total	416 (34)	281 (40)	<250	146 (0)	µg/L
Aluminum, dissolved	<250	190 (4)	<250	128 (4)	µg/L
Iron, total	7.97 (0.18)	8.99 (0.32)	70.2 (2.5)	64.0 (1.2)	mg/L
Iron, dissolved	8.23 (0.08)	9.05 (0.08)	68.5 (0.28)	63.0 (1.2)	mg/L
Manganese, total	44.6 (0.6)	51.0 (1.2)	25.6 (1.2)	24.6 (0)	µg/L
Manganese, dissolved	47.4 (4.5)	52.3 (7.0)	25.8 (0.5)	30.4 (2.5)	µg/L
Sodium, total	2,310 (10)	2,060 (100)	6,740 (60)	5,870 (710)	mg/L
Potassium, total	3.01 (0.09)	2.68 (0.07)	11.3 (0.0)	12.2 (0.3)	mg/L
Magnesium, total	4.00 (0.05)	1.95 (0.07)	<1.25	0.40 (0.01)	mg/L
Calcium, total	11.3 (0.2)	6.40 (0.14)	0.78 (0.01)	<1.50	mg/L
Chloride	43.0 (0.6)	35.6 (0.1)	57.0 (0.6)	64.0 (0.2)	mg/L
Nitrate-N	<0.25	<0.25	<2.50	<2.50	mg/L
Sulfate	198 (6)	187 (5)	255 (10)	173 (11)	mg/L
DOC	215 (8)	157 (4)	485 (9)	503 (5)	mg/L
Phosphate-P	18.1 (0.1)	17.7 (0.4)	22.0 (0.8)	24.8 (0.1)	mg/L
Total alkalinity	4,630 (10)	4,290 (20)	9,810 (270)	10,700 (100)	mg/L
Bicarbonate alkalinity	2,600 (60)	2,200 (20)	2,110 (20)	2,650 (10)	mg/L as $CaCO_3$
Carbonate alkalinity	2,030 (60)	2,100 (40)	7,720 (270)	7,960 (50)	mg/L as $CaCO_3$
Hydroxide alkalinity	<20	<20	<20	<20	mg/L as $CaCO_3$
pH	9.56 (0.02)	9.84 (0.01)	10.0 (0.0)	10.1 (0.0)	Standard unit
ORP	-46.8 (6.1)	-47.9 (0.4)	-403 (0)	-405 (6)	mV
SC	9,100 (50)	12,900 (100)	21,900 (400)	22,100 (600)	µS/cm
DO	0.15 (0.01)	0.17 (0.01)	0.04 (0.01)	0.04 (0.01)	mg/L

Note:

1. Averages of two replicate samples. Standard deviation in parentheses. Samples were field-filtered (0.45 micron [µm]) at the time of collection and filtered again prior to analysis for dissolved constituents.

3 Reactive Media Screening

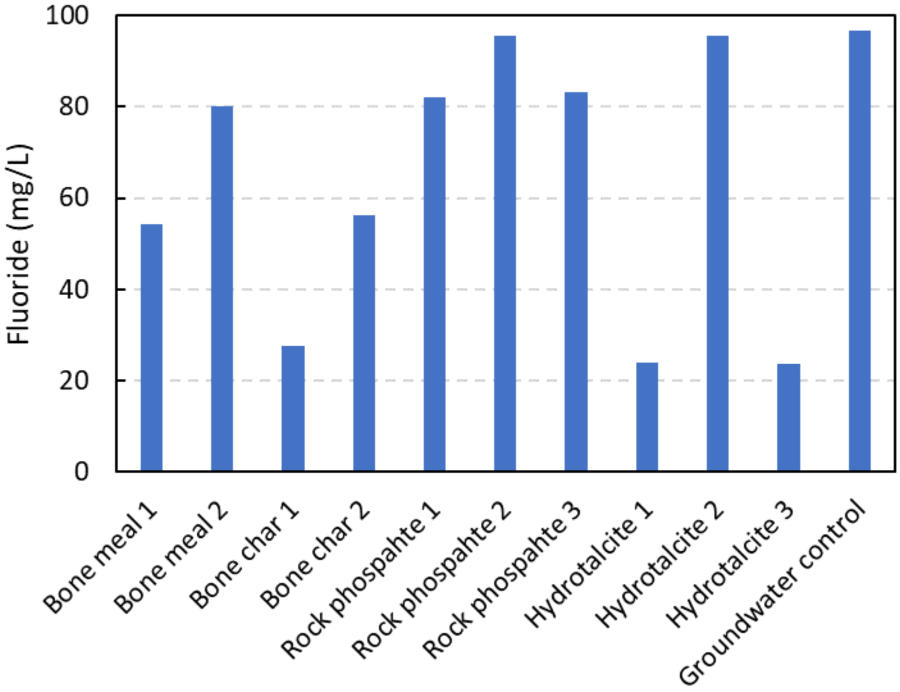
3.1 Initial Screening

An initial screening test was performed to rank the fluoride removal efficiencies and select a preferred source for reactive media that were available in different grades and/or from multiple vendors (bone meal, bone char, rock phosphate, and hydrotalcite).

Batch tests were prepared in 250-milliliter (mL) high-density polyethylene (HDPE) bottles with groundwater from monitoring well RL-2S at an L/S ratio (mass of test solution to dry mass of amendment) of 20 under nitrogen atmosphere. Test solutions were sampled after 24 hours of reaction and analyzed for dissolved fluoride and pH. Unless otherwise noted, dissolved fluoride concentrations were measured using a Thermo Scientific fluoride ion selective electrode connected to a Thermo Scientific Orion Star A211 potentiometer in accordance with SW-846 Test Method 9214.

The initial screening test results are summarized in Figure I2, and data are provided in Attachment I1, Table I1-1. A subset of the better performing reactive media was carried forward for further testing as shown in Table I1. The rock phosphate media tested did not show any appreciable fluoride removal; therefore, rock phosphate was not retained for further testing.

Figure I2
Initial Screening Test Results



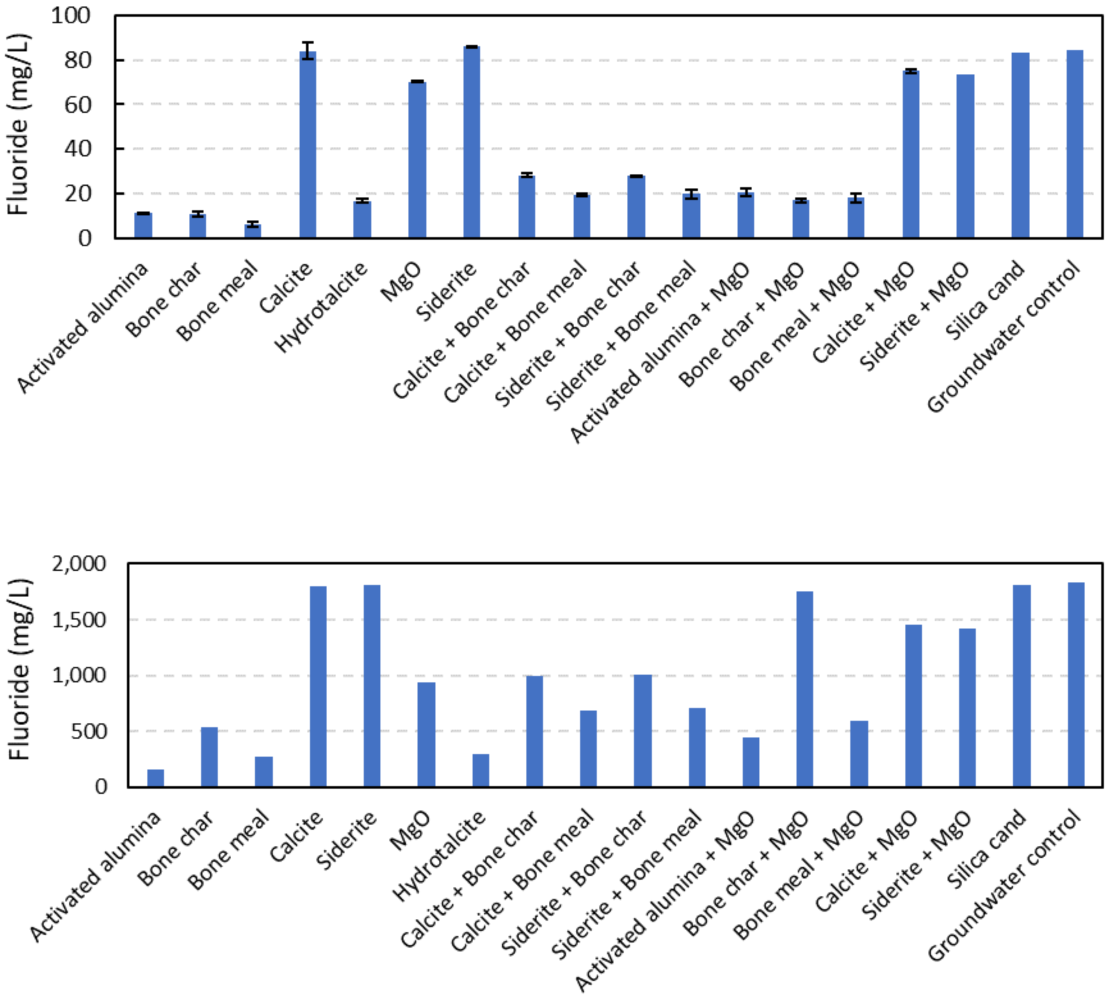
Note:
Bone meal 1: Bridgewell Agribusiness, LLC; Bone meal 2: Down To Earth Distributors, Inc.; Bone char 1: American Charcoal Company; Bone char 2: Fedco Seeds, Inc.; Rock phosphate 1: Down to Earth Distributors, Inc. (from Florida); Rock phosphate 2: Fedco Seeds, Inc. (from Tennessee); Rock phosphate 3: Fedco Seeds, Inc. (from Minnesota); Hydrotalcite 1: Kisuma Chemicals (DHT-4C); Hydrotalcite 2: Kisuma Chemicals (DHT-4V); Hydrotalcite 3: Kyowa Chemical Industry Co., Ltd. (KW-2000)

3.2 Screening of Reactive Media and Mixtures

A second screening test was performed to evaluate fluoride removal by single media versus combinations of media. The objective of this test was to rank the fluoride removal efficiency of the media from groundwater in the East and West groundwater areas and assess synergistic effects of combinations of reactive media in order to screen out amendments and mixtures with low fluoride removal efficiency.

Batch tests were set up in 250-mL HDPE bottles with groundwater from monitoring wells RL-2S and PZ-5 at L/S ratios of 20 and 4, respectively. Test solutions were sampled after 24 hours of reaction and analyzed for dissolved fluoride, pH, and SC. Screening batch test results are summarized in Figure I3, and the data are provided in Attachment I1, Table I1-2.

Figure I3
Single Media and Mixture Screening Test Results for Groundwater from Monitoring Wells RL-2S (top) and PZ-5 (bottom)



Notes:
Error bars indicate standard deviation (n = 2, RL-2S only).
Delta AA was used in the screening tests.

For the tests with single amendments, bone meal, bone char, activated alumina, and hydrotalcite showed the highest fluoride removals for both groundwaters. Magnesium oxide also removed fluoride to some extent but was not as effective. Calcite and siderite did not remove fluoride as observed in other studies (Turner et al. 2008; Liu et al. 2010; Shan and Guo 2013), likely due to the low solubility and hence reactivity of carbonate minerals at the elevated pH of site groundwater. Silica sand alone also did not remove fluoride.

Specific combinations of media were also screened in 50/50 mixtures by mass to assess whether fluoride removal could be improved for poorer performing media by incorporating a second component. Magnesium oxide was tested in combination with bone meal, bone char, or activated alumina. Although the combinations performed significantly better than magnesium oxide alone, none of the mixed media achieved higher fluoride removals than the better performing component of the mixture when tested alone. The three combinations were nevertheless retained for further batch testing to evaluate kinetics of removal.

Calcite and siderite were also tested in combination with bone char, bone meal, or magnesium oxide. The combinations of either calcite or siderite with magnesium oxide showed modest fluoride removal. Combinations of calcite or siderite with bone meal or bone char achieved somewhat better fluoride removal than calcite or siderite alone, but none of the mixtures achieved better fluoride removals than bone char or bone meal alone. Based on these results, calcite and siderite were not retained for further testing.

4 Batch Tests

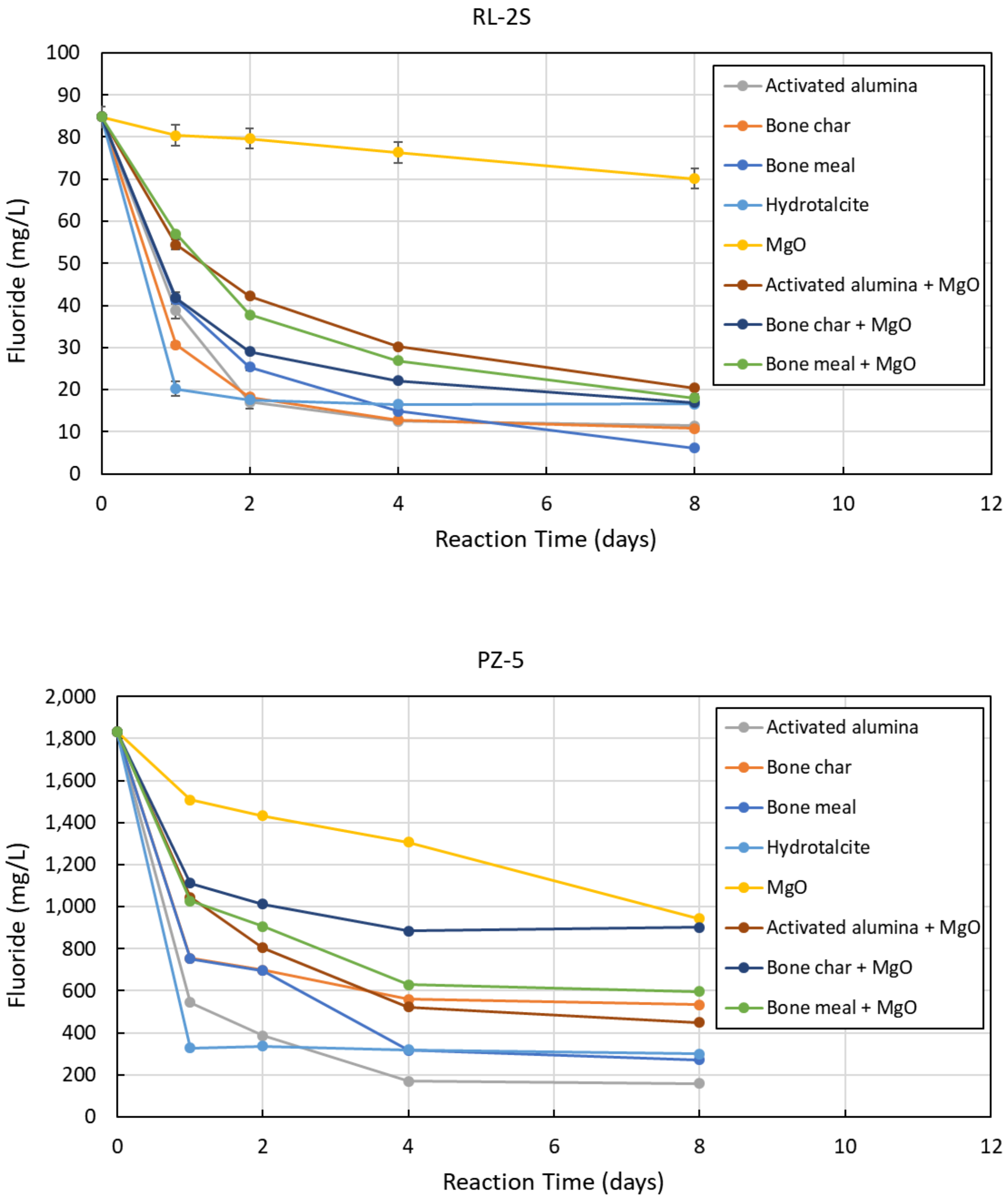
4.1 Kinetic Tests

Kinetic batch tests were performed for the selected single/mixed amendments to evaluate the rates of fluoride uptake from site groundwater. The tests were set up in 250-mL HDPE bottles with groundwater from monitoring wells RL-2S and PZ-5 at L/S ratios of 20 and 4, respectively. Test solutions were periodically sampled after 1, 2, 4, and 8 days of reaction and analyzed for dissolved fluoride, pH, and SC. The results of the kinetic batch tests are presented in Figure I4, and the data are tabulated in Attachment I1, Tables I1-3a and I1-3b.

Most of the kinetic batch tests with either RL2-S or PZ-5 groundwater appear to have approached equilibrium in 8 days or less as indicated by leveling of fluoride concentrations (Figures I5a through I5c) and relatively stable pH and SC (data in Attachment I1, Tables I1-3a and I1-3b). Hydrotalcite, activated alumina, bone char, and bone meal generally showed the highest fluoride removal rates. Fluoride removal rates were slowest in tests with magnesium oxide alone, and combinations of magnesium oxide with other amendments (activated alumina, bone char, or bone meal) also generally exhibited slower removal rates than the same amendments without magnesium oxide. Similar trends were observed in final fluoride concentrations (i.e., magnesium oxide alone or in combinations with other amendments did not achieve as high fluoride removal efficiencies after 8 days as activated alumina, bone char, bone meal, or hydrotalcite alone).

Based on these results, magnesium oxide was not retained for further testing, and activated alumina, bone char, bone meal, and hydrotalcite were carried forward for isotherm testing.

Figure I4
Fluoride Concentrations as a Function of Reaction Time for Groundwater from Monitoring Wells RL-2S (top) and PZ-5 (bottom)



Notes:
Error bars indicate standard deviation (n = 2, RL-2S only).
Delta AA was used in the kinetic tests.

4.2 Isotherm Tests

Isotherm batch tests were performed to evaluate the fluoride uptake capacity of selected reactive media from site groundwater. The batch tests were set up in either 125-, 250- or 1,000-mL HDPE bottles with groundwater from monitoring wells RL-2S and PZ-5. The selected media (activated alumina, bone char, bone meal, and hydrotalcite) were added to individual test bottles in varying amounts to achieve L/S ratios ranging between 2 and 100. Test solutions were sampled after 8 days of reaction, which was considered sufficient for equilibrium to be achieved, and analyzed for dissolved fluoride, pH, and SC.

Following initial ranking of reactive media in 2021 (Section 4.4), additional isotherm tests were performed in 2022 for ActiGuard F 14×28 activated alumina obtained from Axens (Axens AA; the selected source that will be used in PRBs and reactive backfill), as well as representative sand and fill samples sourced from a local quarry that will be used to supply aggregate for PRBs and backfill, respectively, to evaluate fluoride uptake capacity of these media. The results of the fluoride batch isotherm tests are presented in Figures I5a through I5c, and the data are summarized in Attachment I1, Table I1-4.

Figures I5a through I5c show isotherm plots for each of the media with fluoride concentrations in the solid phase plotted as a function of equilibrium fluoride concentration in solution. To estimate and compare the sorption capacity of the different media, the isotherm data were fit to the Freundlich isotherm equation (Equation I1), and the isotherm parameters for each of the media tested are summarized in Table I3.

Equation I1

$$q_e = \mathrm{K}_f (C_e)^{1/\mathrm{n}}$$

where:

q_e = equilibrium concentration of fluoride on the solid (mg/kg)
K_f = isotherm constant related to sorption capacity
C_e = equilibrium concentration of fluoride in solution (mg/L)
$1/\mathrm{n}$ = isotherm exponent related to sorption intensity

Table I3
Site-Specific Freundlich Isotherm Parameters for Media Tested and Predicted Fluoride Uptake

Media	K_f	1/n	R^2	Fluoride Uptake (mg/kg) at C_e 4 mg/L	40 mg/L	400 mg/L	2,000 mg/L
Axens AA	436	0.53	0.97	909	3,080	10,440	24,490
Delta AA	311	0.50	0.81	622	1,967	6,220	13,910
Bone char	485	0.36	0.86	799	1,830	4,193	7,484
Bone meal	474	0.40	0.84	825	2,073	5,207	9,913
Hydrotalcite	256	0.57	0.97	564	2,096	7,788	19,490
Quarry sand (PRB)	1.56	0.80	0.90	4.7	30	188	682
Quarry fill (reactive backfill)	1.25	0.80	0.83	3.8	24	151	547

Table I3 also shows the predicted fluoride uptake capacity for different treatment target fluoride concentrations (C_e). For a target fluoride concentration of 4 mg/L, activated alumina, bone meal, and bone char have the highest uptake capacity. At target fluoride concentrations of 40 mg/L or higher, activated alumina and hydrotalcite have a higher uptake capacity. Axens AA showed the highest fluoride uptake capacity across the range of target fluoride concentrations. Although the fluoride uptake capacity of quarry sand and fill material is small relative to that of the reactive media, it is not zero and is expected to contribute to overall fluoride removal because these materials will constitute a high proportion of the matrix within the PRBs and reactive backfill.

4.3 Quarry Sand and Fill Characterization

The quarry sand and quarry fill were analyzed for their cation exchange capacity (CEC) and extractable iron and aluminum oxide concentrations. CEC and extractable iron and aluminum oxide data were used to assign cation exchange and sorption capacity (concentrations of iron and aluminum binding sites) parameters in the PRB and Reactive Backfill models. The CECs of the quarry sand and quarry fill are 37.1±0.9 and 37.8±0.8 milliequivalents per kilogram, respectively. The data are provided in Attachment I1, Tables I1-5 and I1-6.

Figure I5a
Fluoride Uptake Isotherms for Activated Alumina

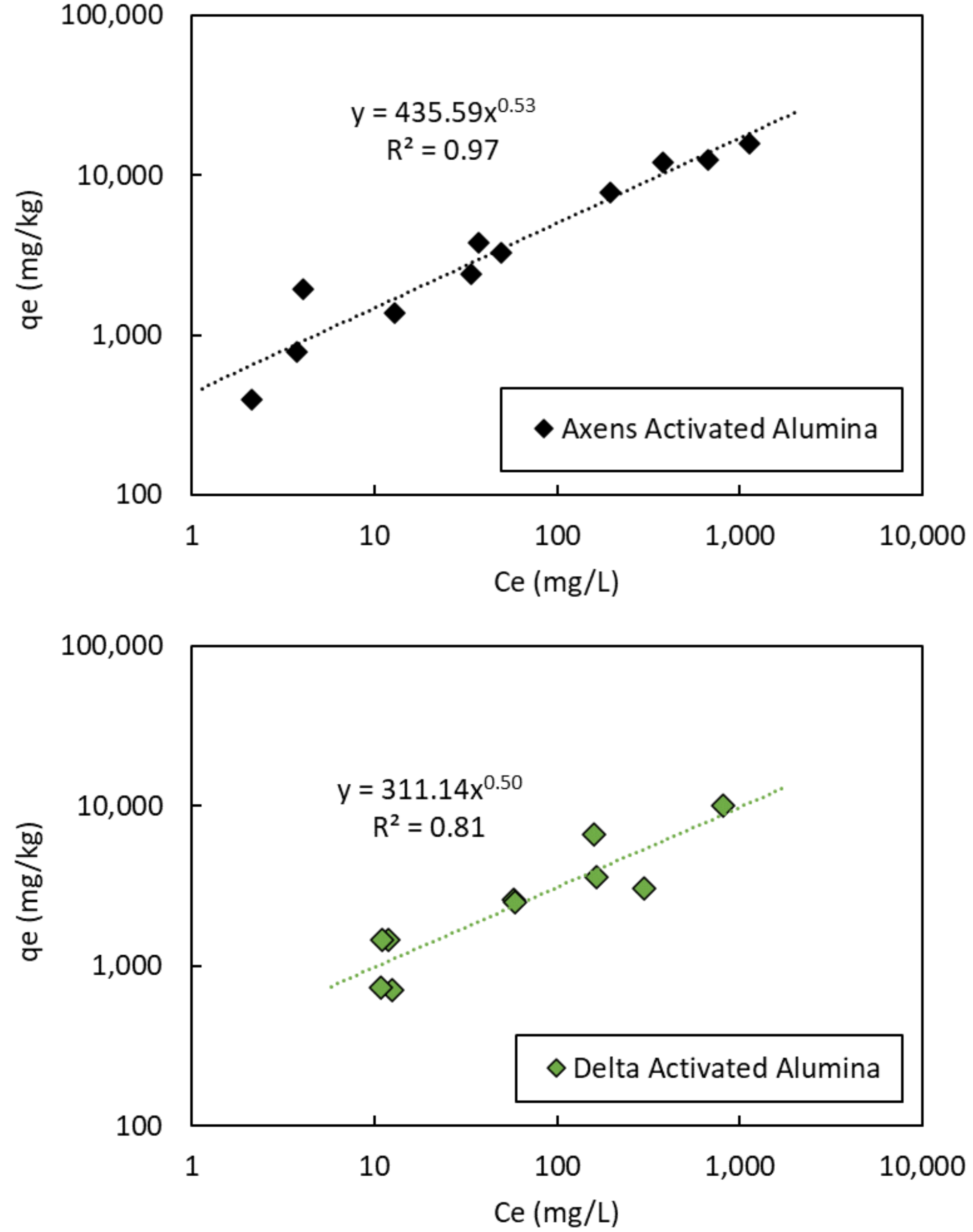


Figure I5b
Fluoride Uptake Isotherms for Bone Char and Bone Meal

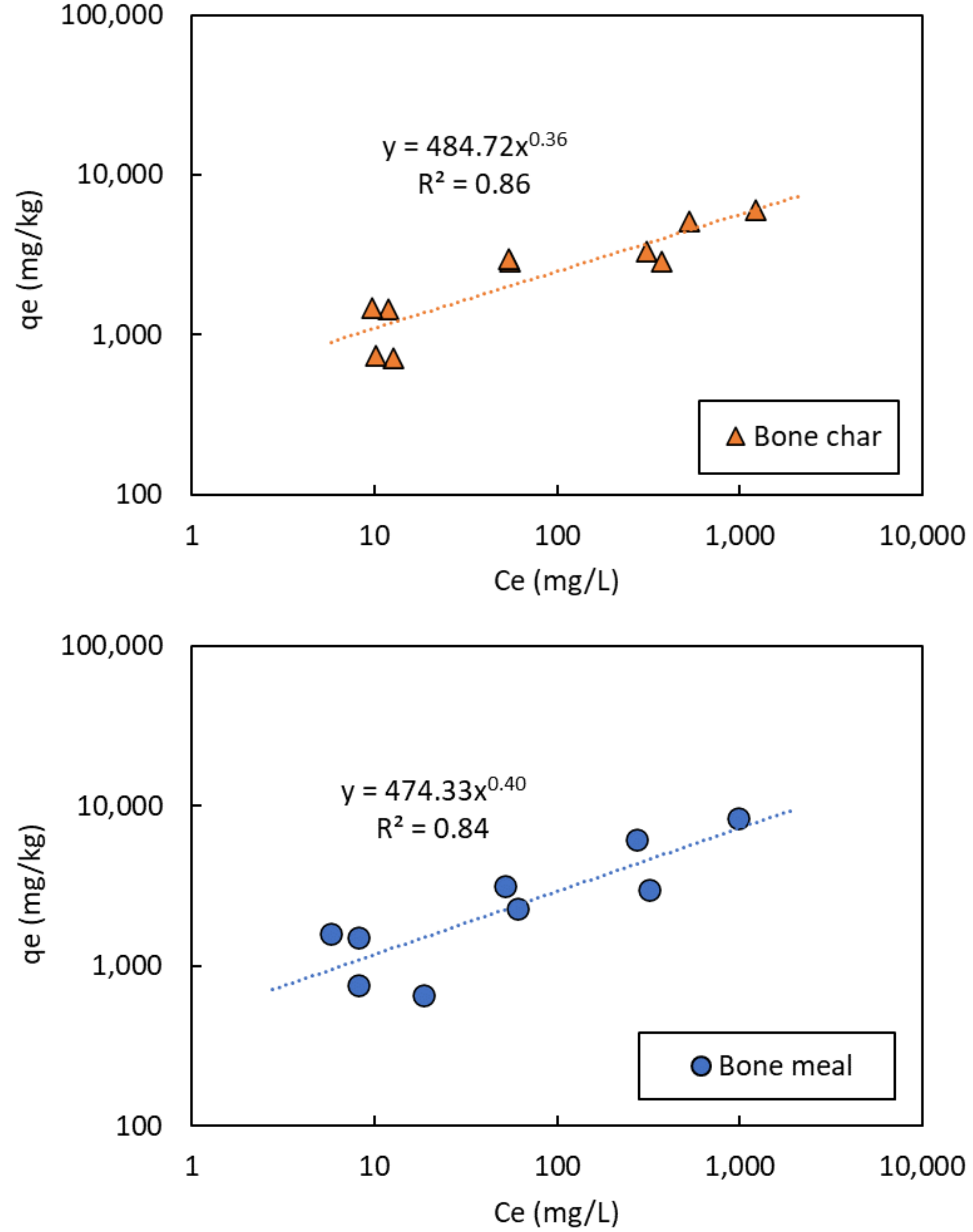
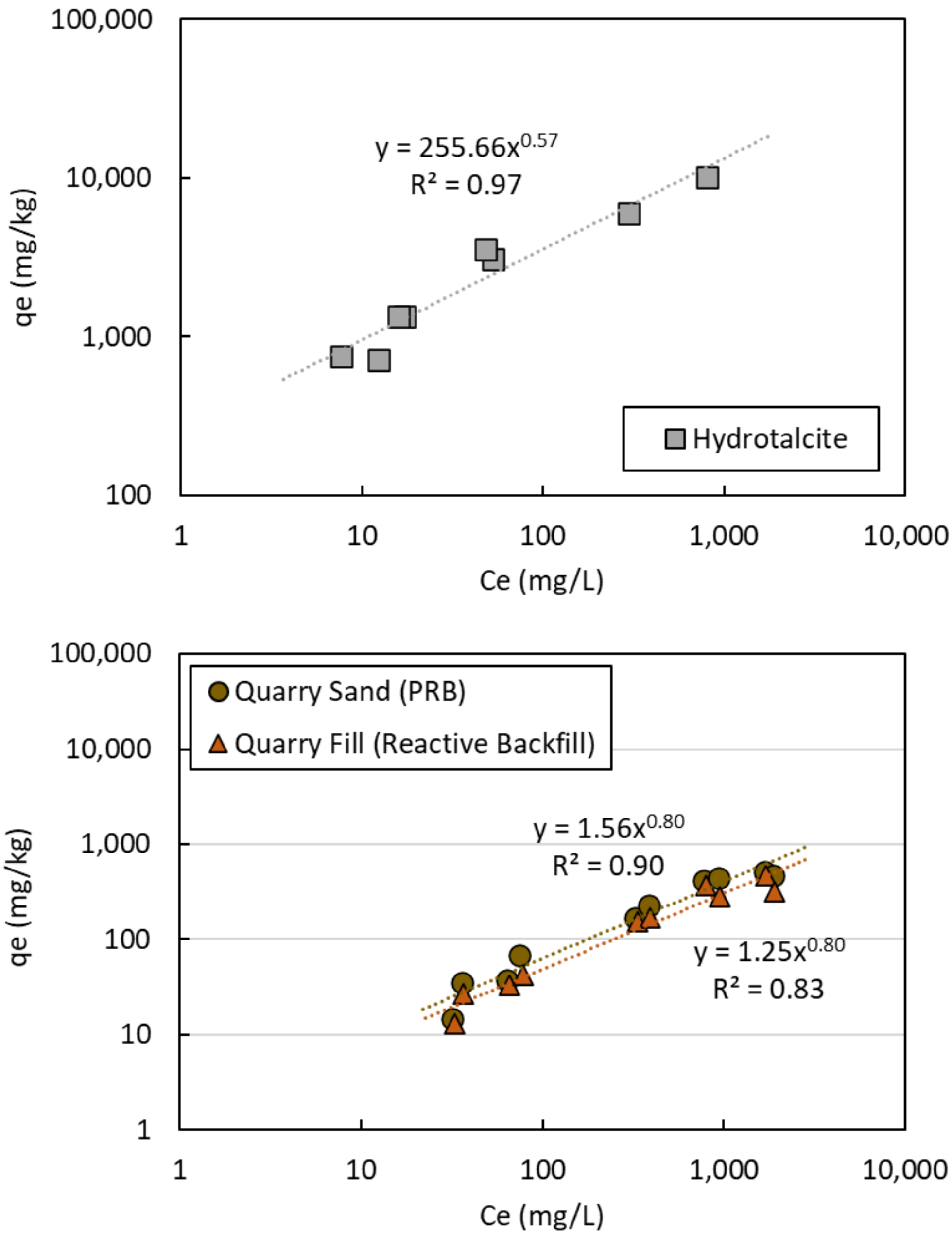


Figure I5c
Fluoride Uptake Isotherms for Hydrotalcite, Sand for PRB, and Soil for Reactive Backfill



4.4 Water Quality Effects from Reactive Media

Select test solutions from the PZ-5 batch tests at an L/S ratio of 2 were also sampled and submitted to Apex Laboratories for chemical analysis. Dissolved aluminum, calcium, phosphate-P, ammonia-N, and dissolved organic carbon (DOC) were analyzed to evaluate release of these constituents from the media and assess the potential for secondary groundwater quality impacts that could result from field application. The results are summarized in Table I4. Axens AA was not tested for secondary groundwater quality impacts, but results are expected to be similar to AAFS50 28×48 activated alumina obtained from Delta Adsorbents (Delta AA).

Table I4
Select Water Quality Data for Reactive Media Batch Tests with Site Groundwater

Media[1]	Aluminum (mg/L)	Calcium (mg/L)	Phosphate-P[2] (mg/L)	Ammonia-N (mg/L)	DOC (mg/L)	pH
Activated alumina (Delta AA)	3.17	NA	NA	146	226	9.85
Bone char	NA	1.49	163	149	154	9.93
Bone meal	NA	2.88	227	347	1,880	9.63
Groundwater (control)	<0.25	0.872	22.1	278	495	10.37

Notes:

1. Analyses are for filtered samples from batch test bottles for media with PZ-5 groundwater at L/S=2 after 8 days' reaction. The test solution for the hydrotalcite L/S=2 batch test could not be sampled because water was completely absorbed by media.
2. Phosphate was analyzed using Standard Method 4500-P E.

Due to the elevated pH of PZ-5 groundwater, dissolved aluminum was detected at 3.17 mg/L in the activated alumina batch test solution. Calcium concentrations in the bone char and bone meal test solutions (1.49 and 2.88 mg/L, respectively) were not appreciably different from that of groundwater (0.87 mg/L), but phosphate concentrations increased by up to an order of magnitude (163 and 227 mg/L) relative to groundwater (22.1 mg/L). The bone meal test solutions also had higher ammonia-N (347 mg/L) and DOC concentrations (1,880 mg/L) than PZ-5 groundwater (278 mg/L ammonia-N and 495 mg/L DOC), indicating dissolution of organic residues present in the bone meal. In contrast, both bone char and activated alumina removed ammonia-N and DOC from groundwater. Potential for water quality impacts is considered in media ranking and discussed further in Section 4.4.

4.5 Summary and Ranking of Reactive Media

Table I5 summarizes the ranking of the reactive media for PRB and reactive backfill application based on fluoride removal performance, relative cost, and potential water for quality impacts. Despite good fluoride removal, bone meal was ranked lowest due to potential for secondary water quality effects.

Table I5
Ranking of Reactive Media for PRB and Reactive Backfill Applications

Media	Particle Size (mm)	Fluoride Removal	Relative Cost	Potential for Water Quality Impacts	Notes	Ranking	
						PRB	Reactive Backfill
Activated alumina	0.3–0.6 (Delta AA)[1] 0.7-1.41 (Axens AA)[1]	Very good	Moderate	Low	Removes phosphate, ammonia-N, and DOC from groundwater. May release aluminum to groundwater depending on pH.	1	1
Bone meal	0.2–2.0[2]	Good	Low	High	Releases phosphate, ammonia-N, and DOC to groundwater.	4	4
Bone char	0.6–3.4[1]	Good	Moderate	Moderate	Releases phosphate to groundwater. Removes ammonia-N and DOC from groundwater.	2	3
Hydrotalcite	0.0004 (average)[1]	Good	High	N/A	Only readily available in powder form, which makes it unsuitable for PRB applications.	3	2

Notes:

1. From the vendor-provided specification sheets
2. Determined from material used in treatability testing

For PRBs proposed to be installed in the West Groundwater Area, where fluoride concentrations are typically less than 100 mg/L and the performance target is to reduce concentrations to be protective of surface water (4 mg/L), activated alumina was ranked highest. Bone char was ranked lower than activated alumina due to potential water quality impacts from phosphate. Hydrotalcite is not considered suitable for PRB applications due to the very fine grain size of commercially available hydrotalcites (average particle size is 0.4 micron [µm]). The granular PRB medium will be a coarse sand-fine gravel gradation with pore sizes much larger than the hydrotalcite particles. This would likely result in the hydrotalcite being washed out from the PRB after emplacement and could also result in clogging the silty-sand aquifer medium downgradient of the PRB. These issues could result in early failure of a PRB; therefore, hydrotalcite was ranked lower than activated alumina and bone char.

For reactive backfill applications, especially in the East Groundwater Area, where initial fluoride concentrations are expected to be much higher, activated alumina was also ranked highest, followed by hydrotalcite and bone char.

Activated alumina was therefore selected and retained for further testing.

5 Column Tests

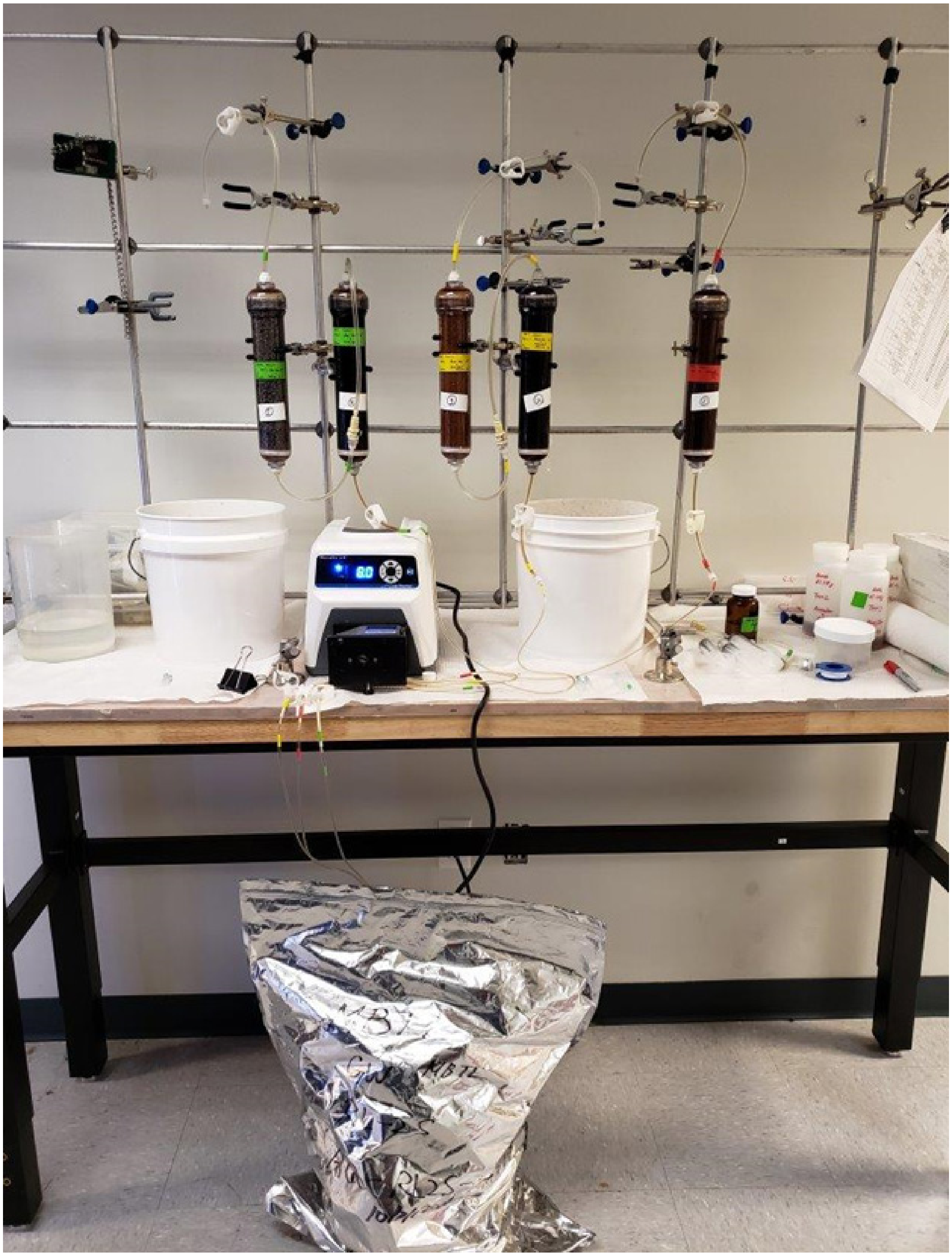
Column testing was performed to evaluate fluoride removal performance under flow conditions and provide data for PRB design modeling. Initial testing was performed with Delta AA. Following submittal of the *Revised Engineering Design Report* in 2021 (Anchor QEA 2021), Alcoa Corp. began a search for a vendor that could supply the quantities of activated alumina that would be needed for PRBs and reactive backfill during construction and entered discussions with Axens. A sample of Axens AA was also obtained for testing with site groundwater to confirm fluoride removal performance. Isotherm tests (Section 4.2) showed that Axens' product had better performance than the Delta AA previously tested. Additional column tests were performed with the Axens AA in 2022. The column tests, which are described in Sections 5.1 and 5.2, provided the site-specific media performance data needed to calibrate models that were used for full-scale design of PRB and reactive backfill (Appendices G and J of the Final EDR, respectively).

5.1 Initial Column Test

The initial column test evaluated fluoride breakthrough for Delta AA using groundwater from West Groundwater Area monitoring well RL-2S as column influent.

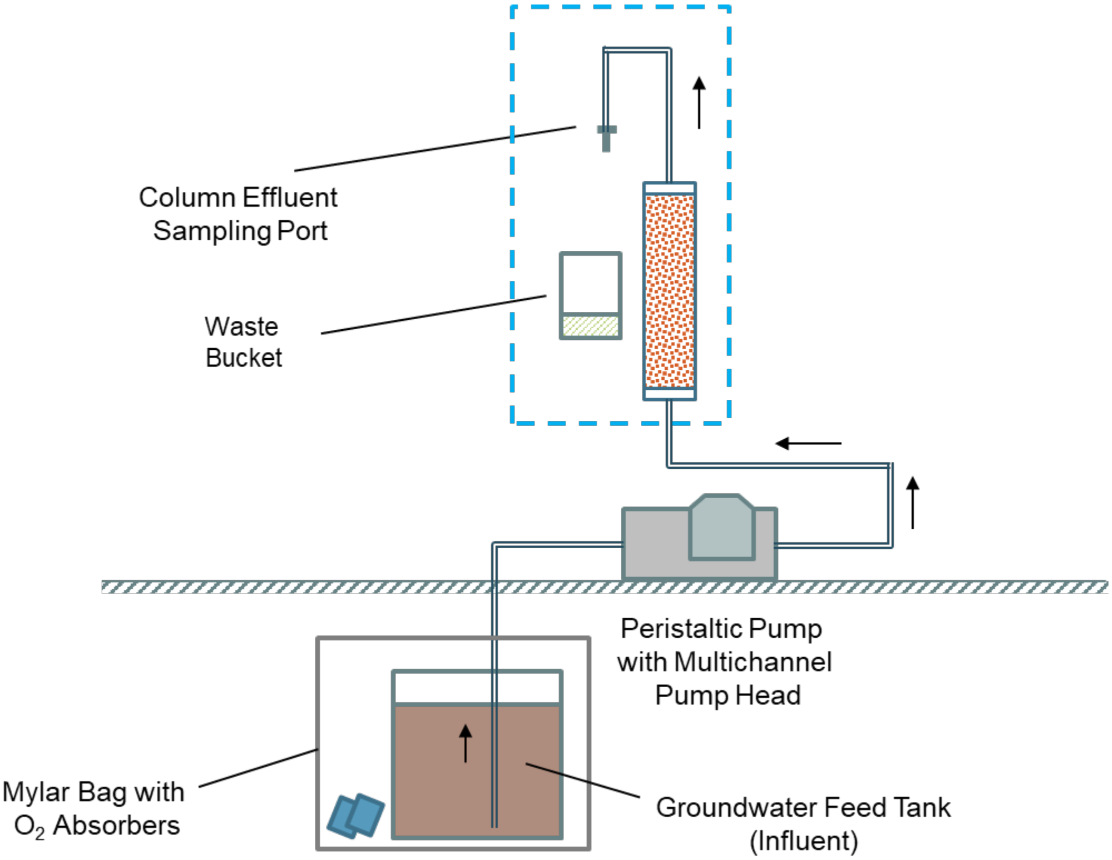
The laboratory column setup is shown in Figure I6, and a detailed schematic is provided in Figure I7.

Figure I6
Column Test Equipment Setup



Note:
The column farthest to the right was packed with Delta AA mixed with clean quartz sand (Accusand) in a 50:50 mass ratio.

Figure I7
Schematic of Column Test Setup



Note:
The column was packed with Delta AA mixed with clean quartz sand (Accusand) in a 50:50 mass ratio.

The column test was carried out using a 25-centimeter (cm) long polycarbonate column. Delta AA was mixed with clean quartz sand (Accusand) in a 50:50 mass ratio, and the mixture was packed into the column to achieve a total depth of 22 cm. Site groundwater was pumped using a peristatic pump in an up-flow direction through the column at a flow rate of approximately 0.3 mL per minute for a total of 4 weeks. The flow rate was regularly checked and adjusted as needed to maintain a constant flow rate. Column operating conditions are summarized in Table I6. The total volume of groundwater treated was approximately 120 column pore volumes.

Table I6
Column Test Operating Conditions

Parameter	Value	Unit
Reactive media depth	22.0	cm
Column Inside diameter	4.2	cm
Flow rate	0.30	mL per minute
Empty bed contact time	16.9	hours
Porosity	30	%
Hydraulic residence time	5.9	hours
Darcy flux	9.3	cm per day
Linear velocity	31	cm per day
Column test duration	28.9	days

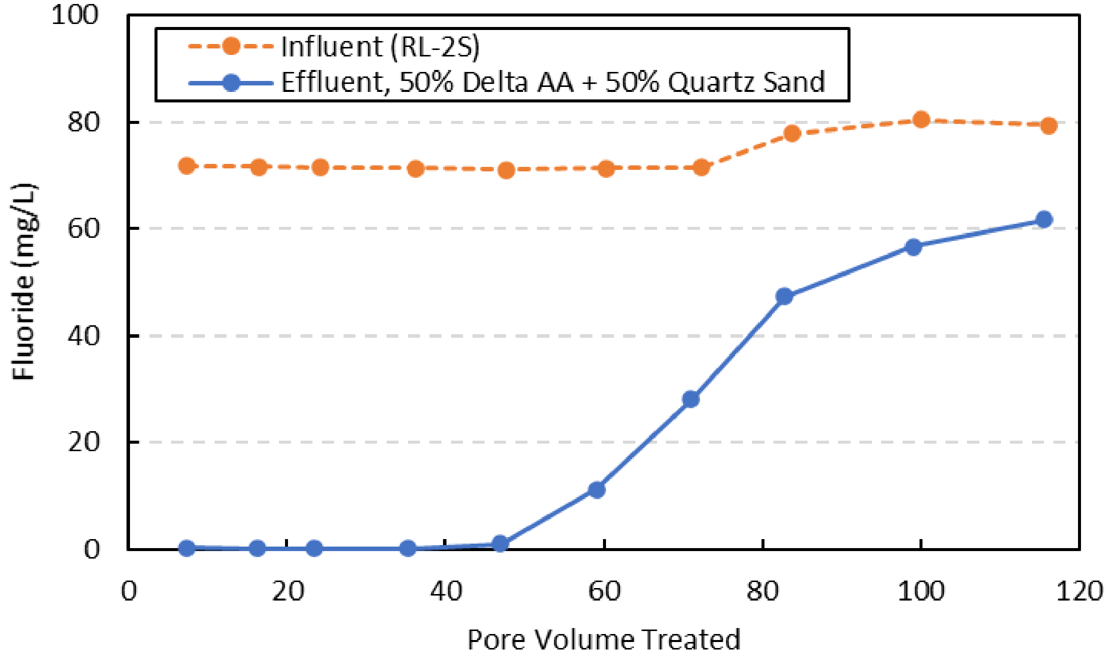
The column influent and effluent were sampled periodically (two to three times weekly) over the duration of the test. Samples were filtered using 0.45-µm nylon syringe filters and analyzed for fluoride, phosphate, pH, and SC. Fluoride was determined by ion-specific electrode, and phosphate was determined by the ascorbic acid method using a Hach DR3800 spectrophotometer. This method is accepted by the U.S. Environmental Protection Agency (USEPA) for reporting for wastewater and drinking water analysis (Standard Method 4500-P E and USEPA Method 365.1),

The laboratory column test was operated at a significantly higher linear velocity (89 cm per day) than the groundwater flow conditions in the vicinity of the PRB alignment along the northern and western edges of the Closed Black Mud Pond (BMP) Facility. Groundwater velocities are expected to be less than 10 cm per day based on modeling conducted during the remedial investigation/feasibility study (Anchor QEA 2015). As a result, the hydraulic residence time in the columns was also shorter than would be available in a full-scale PRB. Therefore, the fluoride removal performance measured in the column is a conservative estimate of the expected fluoride removal performance from site groundwater in a full-scale field PRB application with a similar dose of Delta AA.

5.1.1 Column Test Results

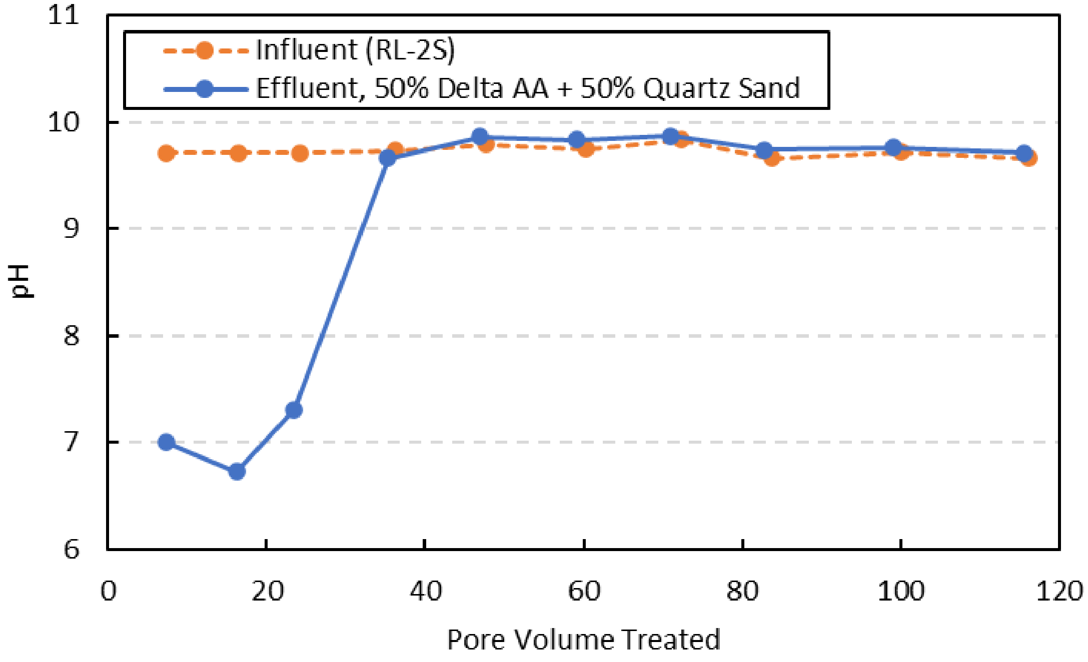
The column test data are tabulated in Attachment I1, Table I1-7. Influent and effluent fluoride concentrations are shown in Figure I8. Influent fluoride concentrations remained stable for the duration of the tests at approximately 80 mg/L. Effluent fluoride concentrations started to increase after about 50 pore volumes, reaching 50% of influent after approximately 80 pore volumes.

Figure I8
Fluoride Breakthrough Curve



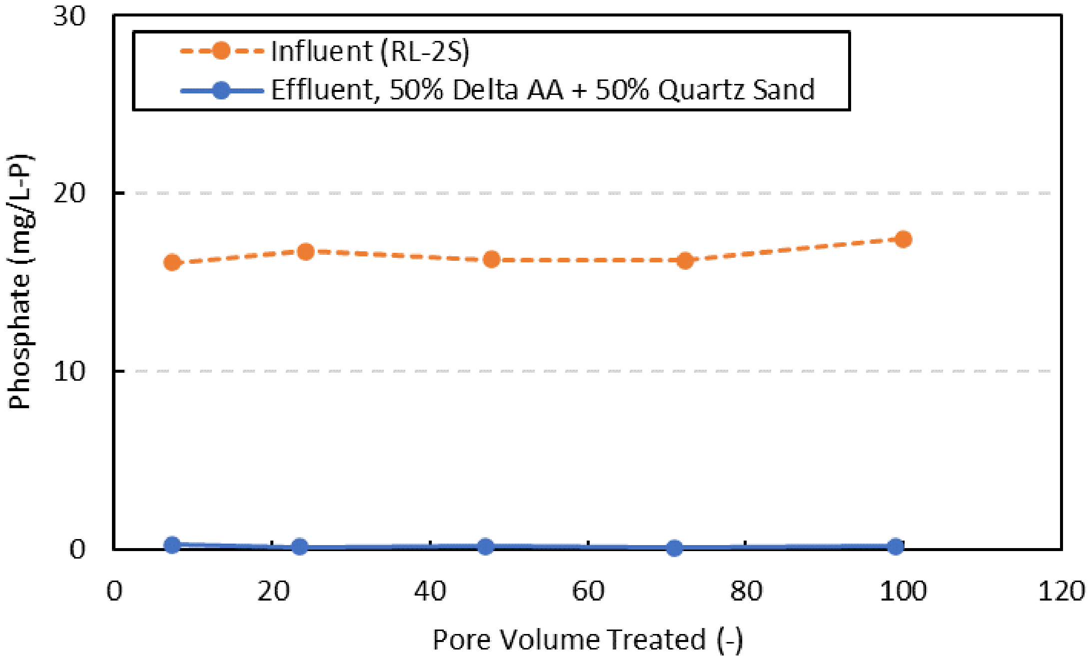
Influent and effluent column pH are shown in Figure I9. Influent pH was near 10. Delta AA neutralized pH for approximately 25 pore volumes but had no effect at later times. Fluoride uptake by activated alumina is primarily through the formation of strong complexes with alumina surface binding sites, which is pH-dependent and decreases with increasing pH above 7 (Tang et al. 2009). Alumina is insoluble under these conditions, and the observed pH neutralization is mainly due to release of protons initially present on the hydrated alumina surface sites.

Figure I9
Breakthrough Curve for pH



The activated alumina column also removed phosphate, which was present at a level of approximately 17 mg/L in the influent groundwater, to very low levels for the duration of the column test (Figure I10). This is an added benefit of using activated alumina in the PRBs, which is expected to contribute to improved water quality in the Consolidated Diking Improvement District ditch in the long term.

Figure I10
Phosphate Breakthrough Curve



5.2 Supplemental Column Tests

Following completion of the initial column test with Delta AA, Northwest Alloys selected Axens as the supplier of activated alumina for full-scale implementation, and a local quarry source (CalPortland) for aggregate (sand for PRBs and fill for reactive backfill areas) was identified. Additional column tests were performed with Axens AA mixed with either sand or fill to produce representative data for the media that will actually be used at the site.

5.2.1 Column Test Design

The column tests were designed to measure fluoride breakthrough for Axens AA mixed with either quarry sand with influent groundwater from monitoring well RL-2S to simulate a PRB or fill material with influent groundwater from monitoring well PZ-5 to simulate reactive backfill. A total of six column tests were performed varying the dose of activated alumina as summarized in Table I7.

The column test setup was similar to the initial column tests. Operating conditions of the supplemental column tests are summarized in Table I8.

Table I7
Supplemental Column Test Setup

Column Test	Axens AA (%)	Sand (%)	Fill Soil (%)	Groundwater	Flow Rate (mL per minute)
S1	15	85	--	RL-2S	0.30
S2	30	70	--	RL-2S	0.30
S3	5	--	95	PZ-5	0.15
S4	15	--	85	PZ-5	0.15
S5	15	--	85	PZ-5	0.30
S6	30	--	70	PZ-5	0.30

Note:
--: not included in column

Table I8
Supplemental Column Test Operating Conditions

Parameter	Value						Unit
	Column S1	Column S2	Column S3	Column S4	Column S5	Column S6	
Reactive media depth	22.0	22.0	22.0	22.0	22.0	22.0	cm
Column inside diameter	4.2	4.2	4.2	4.2	4.2	4.2	cm
Flow rate	0.30	0.30	0.15	0.15	0.30	0.30	mL
Empty bed contact time	16.9	16.9	33.8	33.8	16.9	16.9	hours
Porosity	30	30	32	32	32	32	%
Hydraulic residence time	5.11	5.11	10.9	10.9	5.45	5.45	hours
Darcy flux	9.30	9.30	4.96	4.96	9.92	9.92	cm per day
Linear velocity	31.0	31.0	15.5	15.5	31.0	31.0	cm per day
Column test duration	25.0	25.0	11.0	11.0	14.0	14.0	days

Column tests were carried out in 25-cm-long polycarbonate columns. The Axens AA-sand or soil mixtures were packed into the columns to achieve a total depth of 22 cm. Site groundwater was pumped using a peristatic pump with a multichannel head in an up-flow direction through the columns at a constant flow rate of either 0.15 or 0.3 mL per minute for a total of 11 (Columns S5 and S6), 14 (Columns S3 and S4), or 25 (Columns S1 and S2) days. Flow rates were regularly checked and adjusted as needed to maintain a constant flow rate. Column operating conditions are summarized in Table I6. The total volume of groundwater treated by each of the columns corresponded to approximately 120 volumes for Columns S1 and S2, 30 pore volumes for Columns S3 and S4, and 50 pore volumes for Columns S5 and S6.

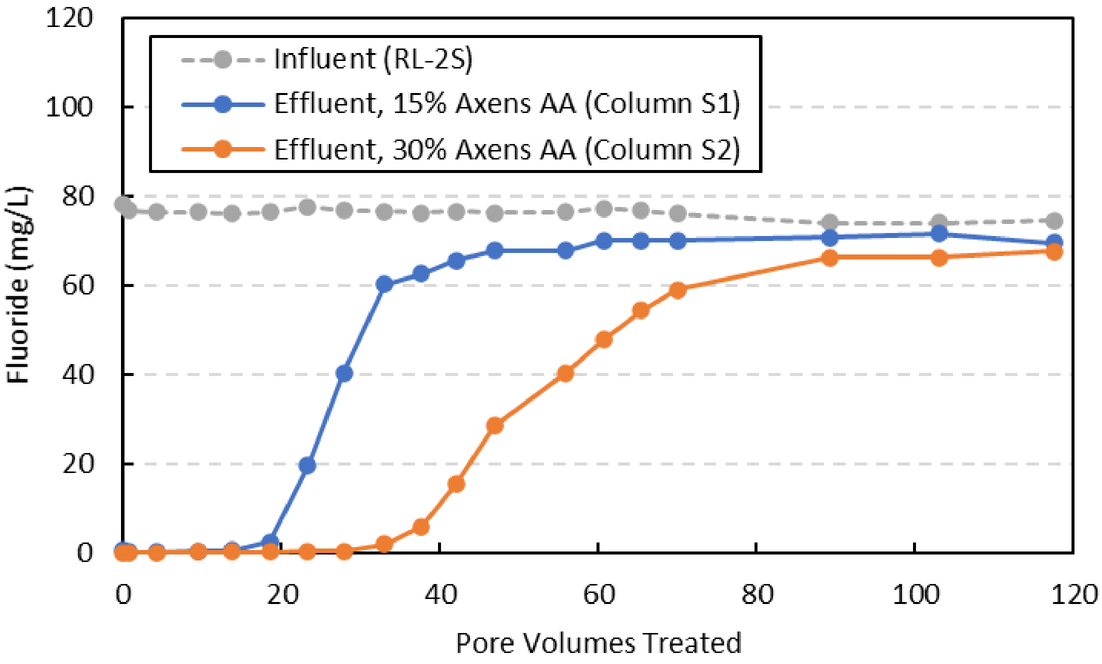
The influent reservoirs and column effluents were periodically sampled. Water samples were filtered using 0.45-µm nylon syringe filters and analyzed for dissolved fluoride, phosphate, pH, and SC. Fluoride was determined by ion-specific electrode, and phosphate was determined by the molybdovanadate method using a Hach DR3800 spectrophotometer.

5.2.2 PRB Column Test Results

The supplemental column test data are tabulated in Attachment I1, Table I1-8. Influent and effluent fluoride concentrations for the PRB columns are shown in Figure I11. Influent fluoride concentrations were approximately 78 mg/L and remained relatively constant throughout the tests.

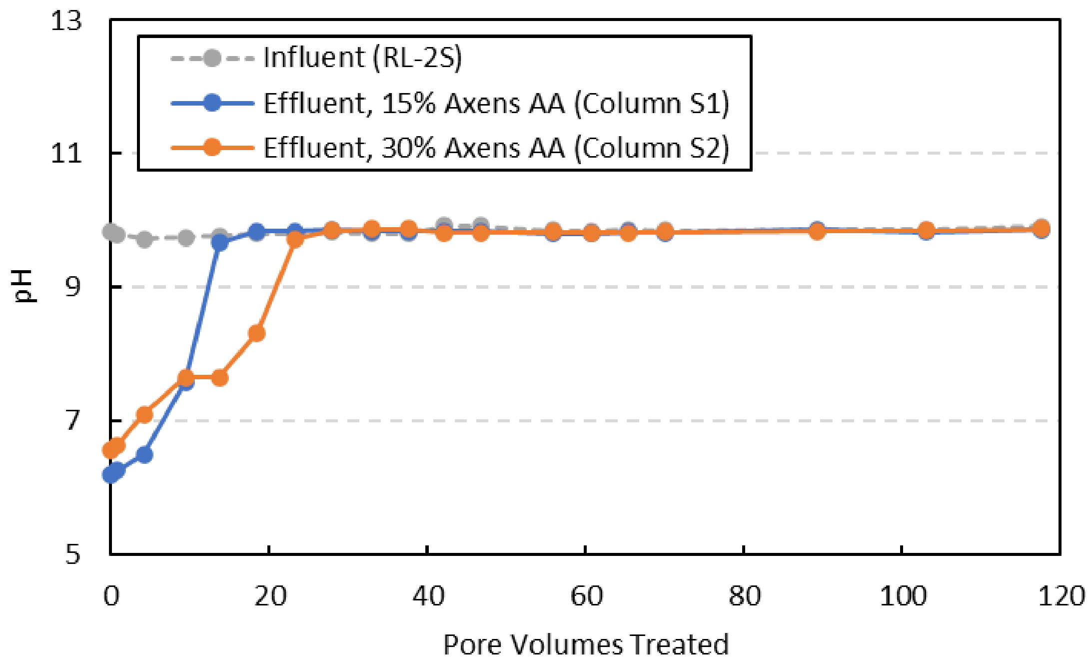
In the 15% Axens AA column (Column S1), fluoride breakthrough started at approximately 20 pore volumes and reached 50% of influent concentration after approximately 25 pore volumes. In the 30% Axens AA column (Column S2), effluent fluoride breakthrough started at approximately after 35 pore volumes and reached 50% of influent concentration after approximately 50 pore volumes. The fluoride removal performance of the Axens AA columns is comparable to the Delta AA column test (Section 5.1.1).

Figure I11
Dissolved Fluoride Breakthrough Curves



Influent and column effluent pH for the columns are shown in Figure I12. Influent pH was approximately 9.8. Early effluents (up to 14 and 24 pore volumes for Column S1 and S2, respectively) had lower pH values than the influent but were not different than the influent at later times. The pH neutralization by activated alumina is due to release of protons initially present on the surface sites, similar to the behavior observed in the Delta AA column test (Section 5.1.1).

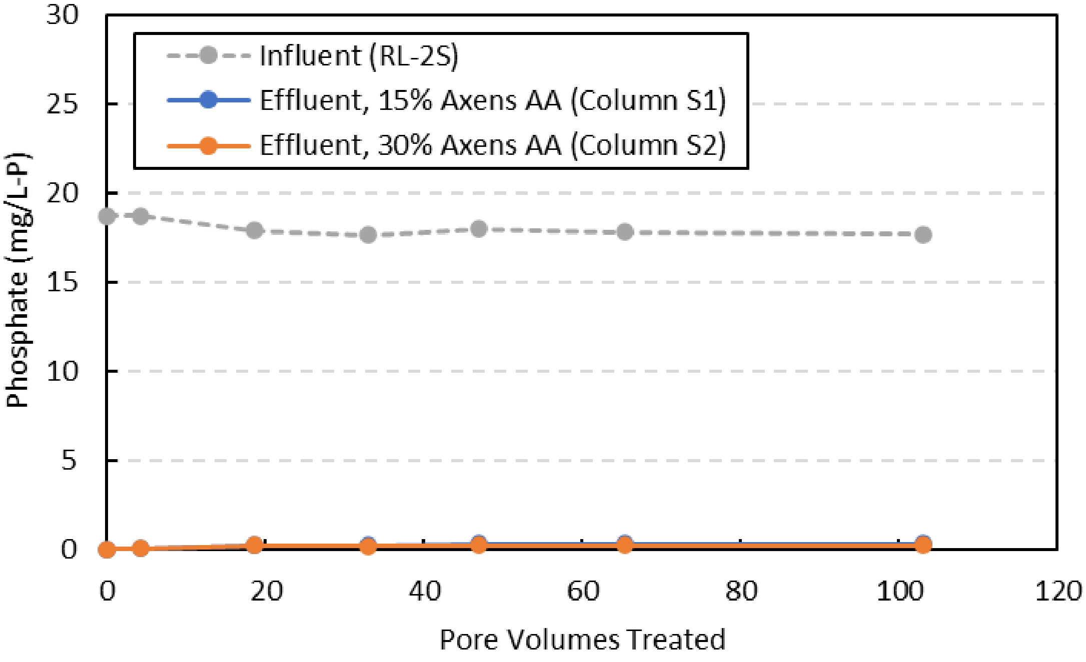
Figure I12
Breakthrough Curves for pH



Column influent and effluent phosphate concentrations are shown in Figure I13. The influent phosphate concentration was approximately 18 mg/L. As with the initial column test, the Axens AA columns also completely removed phosphate from influent groundwater for the duration of the column tests.

The column test results are used in conjunction with modeling to forecast the long-term sustainability of the PRBs at the site, including the effective PRB media lifetime and associated need for periodic media replacement.

Figure I13
Phosphate Breakthrough Curves



5.2.3 *Reactive Backfill Column Test Results*

The supplemental reactive backfill column test data are tabulated in Attachment I1, Table I1-8. Influent and effluent fluoride concentrations for the columns are shown in Figure I14. Influent fluoride concentrations were approximately 1,720 mg/L and remained relatively constant.

In the 5% Axens AA column (Column S3), fluoride breakthrough started after about 2.1 pore volumes and reached 50% of influent concentration after approximately 4.0 pore volumes. In the 15% Axens AA columns (Columns S4 and S5), fluoride breakthrough started after 4.0 pore volumes and reached 50% of influent concentration after approximately 8.4 and 8.8 pore volumes, respectively. In the 30% Axens AA column (Column S6), fluoride breakthrough started after 5.0 pore volumes and reached 50% of influent concentration after approximately 13.9 pore volumes.

Influent and column effluent pH for the columns are shown in Figure I15. Influent pH was approximately 10.2. Early effluents (up to 5 pore volumes) had lower pH values than the influent but were similar to influent at later times. This behavior was also observed in the other activated alumina column tests.

Column influent and effluent phosphate concentrations are shown in Figure I16. The influent phosphate concentration was approximately 20 mg/L. The Axens AA mixed media columns completely removed phosphate from influent groundwater throughout the column tests.

Figure I14
Fluoride Breakthrough Curves

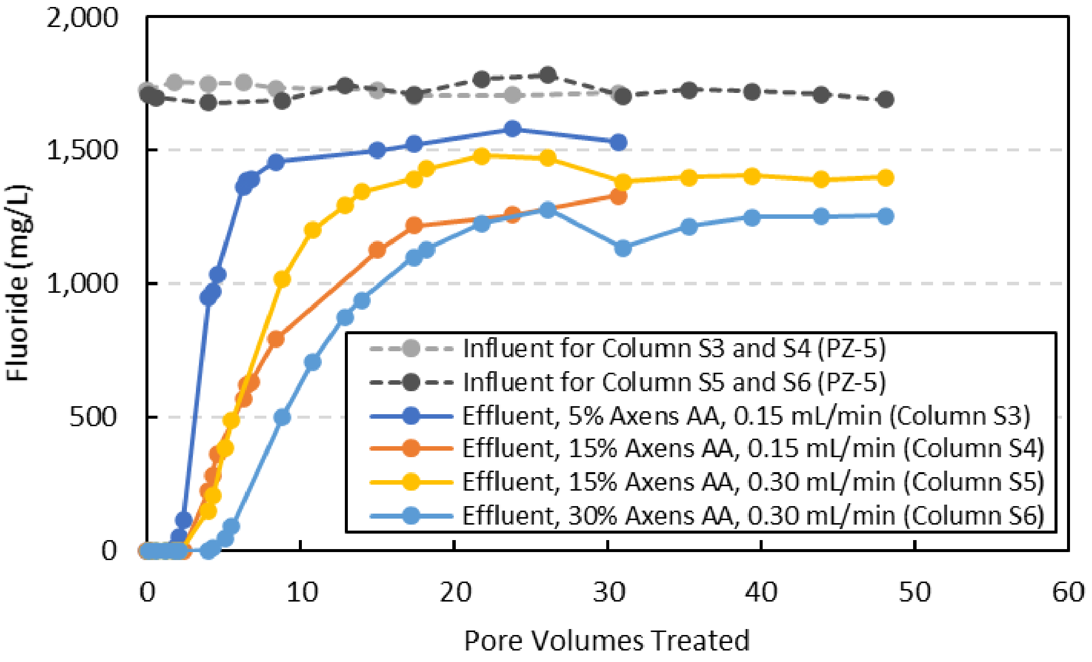


Figure I15
Breakthrough Curves for pH

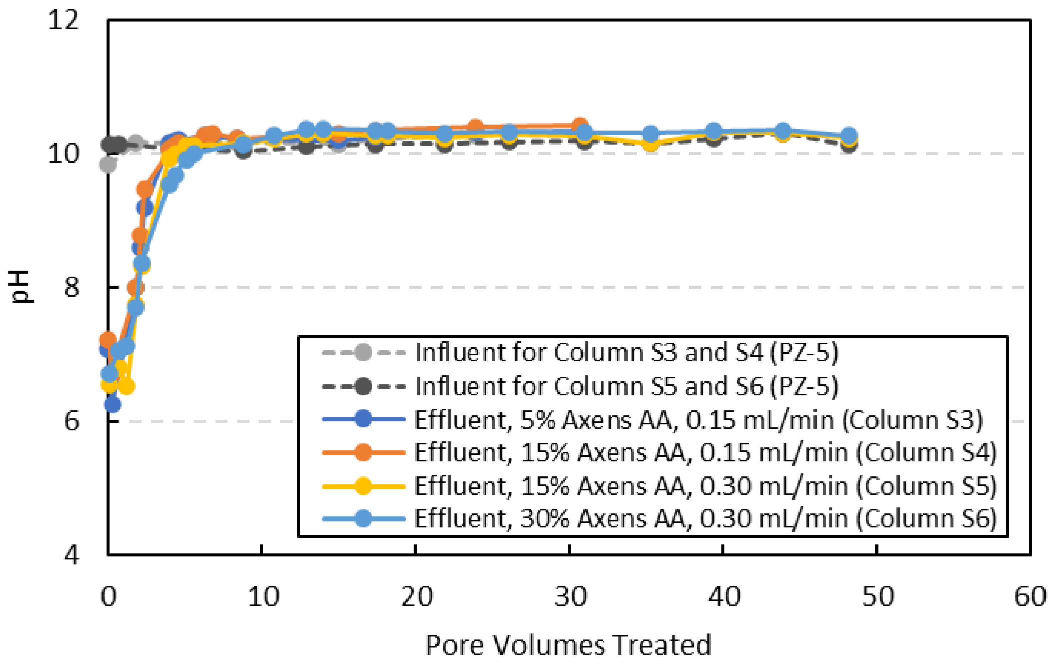
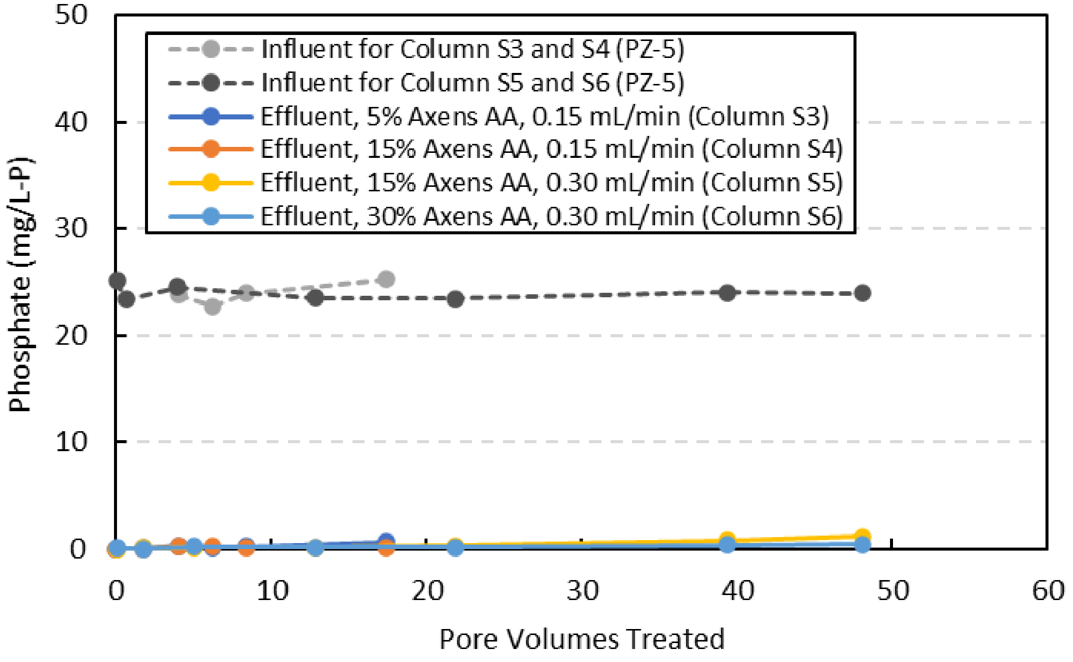


Figure I16
Phosphate Breakthrough Curves



5.2.4 *Stability of Sequestered Fluoride*

Following completion of the supplemental column tests, the reacted column media from Columns S1 through S6 (Axens AA mixed with quarry sand or soil) were recovered to evaluate the reversibility of fluoride removal and long-term stability of sequestered fluoride to remobilization. This involved measuring the amount of fluoride released by the column media in a series of leaching tests at different initial pH values.

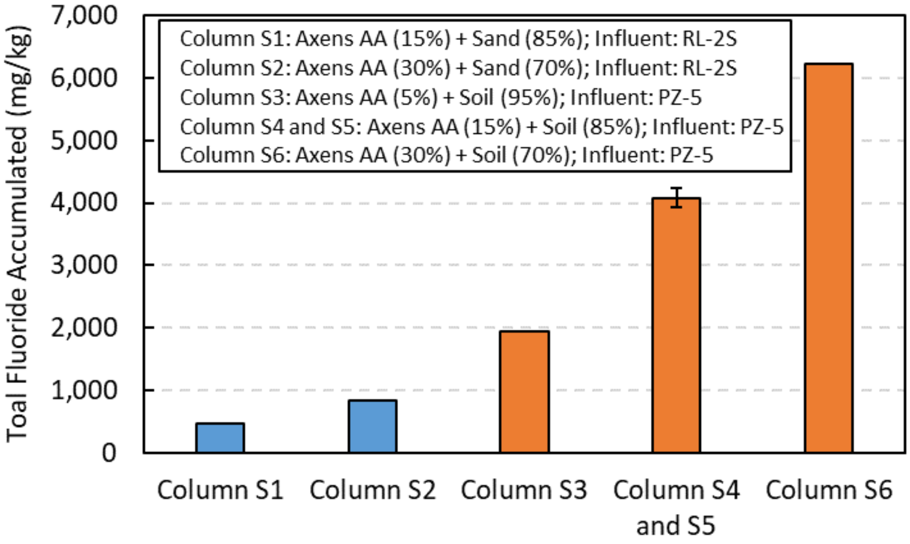
The recovered column media were thoroughly homogenized and split into three aliquots, which were extracted using the following extraction fluids:

- Acidic (pH 2): 0.01 moles per liter (M) hydrochloric acid (HCl)
- Neutral (pH 7): 0.01 M sodium chloride (NaCl)
- Basic (pH 12): 0.01 M sodium hydroxide (NaOH)

Extractions were performed at an L/S ratio of 50 for 24 hours. Briefly, 2 grams (dry-weight basis) of solid material were placed into a 125-mL LDPE reaction bottle, to which 100 mL of the extraction fluid was added. The reaction bottles were placed on a shaker table for 24 hours, at the end of which time the supernatant was sampled, filtered (0.45-µm nylon membrane filter), and analyzed for fluoride by ion-selective electrode. The total accumulated fluoride concentrations in the column media were calculated by mass balance (Figure I17), and the fluoride concentrations in the extraction solutions were converted to their equivalent dry-weight solid concentrations and compared to the total accumulated fluoride concentrations (Figure I18). The data are also provided in Attachment I1, Table I1-9. The final pH values of the extraction fluids changed from the initial pH values following reaction with the solids (Figure I18). In particular, the pH values of the 0.01 M NaCl extraction solutions shifted from approximately 7 to a range of 8.4 to 9.1; therefore, the 0.01 M NaCl extractions were more representative of extractability under basic conditions than neutral. More than 65% of the accumulated fluoride was not extractable from the spent PRB column media (Columns S1 and S2, Figure I18), and much less was extractable under either acidic condition. The pH dependence of fluoride extraction from the spent column media is consistent with the known pH dependence of fluoride adsorption-desorption by alumina (Farrah et al. 1987; Ku and Chiou 2002; Bahena et al. 2002) but also indicates that most of the fluoride is irreversibly bound to activated alumina. These results have implications for the long-term stability of fluoride sequestered by the PRBs at the site. The pH of groundwater entering the PRBs is currently alkaline but is expected to return to near-neutral values representative of background conditions as the residual impacted groundwater is flushed out from beneath the Closed BMP Facility. Most of the fluoride sequestered by the PRBs will be irreversibly bound, and no remobilization due to future changes in pH is anticipated.

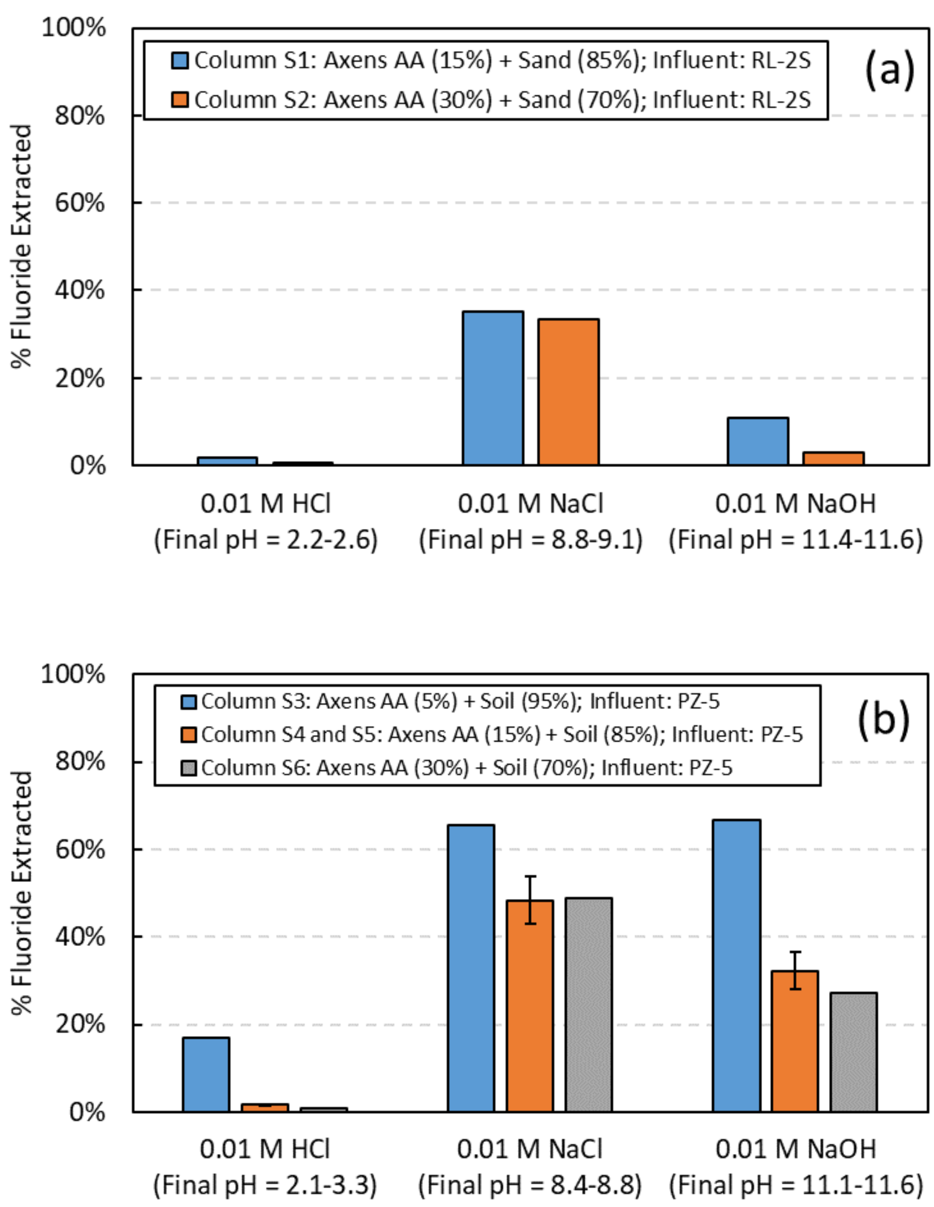
Similar trends were observed in extractability of fluoride from the spent reactive backfill column media with pH, although in general a smaller portion of the accumulated fluoride was not extractable compared to the PRB column media (Figure I18). This may be due to the higher fluoride loading and higher pH of the groundwater used in the reactive backfill column tests. However, after breakthrough the effluent fluoride concentrations in all of the reactive backfill columns appear to have stabilized at concentrations less than the influent concentration (Figure I14). This suggests that an additional fluoride removal mechanism, such as surface precipitation of fluoride minerals (e.g., aluminum hydroxyfluoride hydrate [Ntuk et al. 2015]) occurred under the higher fluoride conditions in these columns. Regardless of the mechanisms involved, the extraction results demonstrate that fluoride uptake by activated alumina is not reversible and the stability of sequestration increases with decreasing pH.

Figure I17
Total Accumulated Fluoride Concentrations in Axens Activated Alumina Column Media



Notes:
Blue bars indicate that the PRB columns (Columns S1 and S2) reacted with groundwater from monitoring well RL-2S. Orange bars indicate that the reactive backfill columns (Columns S3 through S5) reacted with groundwater from monitoring well PZ-5.
Error bar indicates standard deviation (n = 3, Column S4, S4 duplicate, and S5).

Figure I18
Percentage of Extractable Fluoride in Axens Activated Alumina Column Media



Note:
Error bars indicate standard deviation (n = 3, Column S4, S4 duplicate, and S5).

6 Summary and Recommendations

The findings of the groundwater treatability study and recommendations are summarized as follows:

- Batch and column treatability tests were performed to evaluate and rank reactive media for fluoride removal from site groundwater in PRB and reactive backfill applications. Performance criteria evaluated included fluoride removal rates, removal efficiency, uptake capacity, stability of the sequestered fluoride, and potential secondary water quality effects of the media. Media tested included activated alumina, calcium phosphates (bone meal, bone char, and rock phosphate), carbonates (calcite and siderite), hydrotalcite, and magnesium oxide.
- Activated alumina was found to have the best fluoride removal performance overall for the range of site groundwater chemistry tested. Bone meal, bone char, and hydrotalcite also showed good fluoride removal.
- Bone meal released significant concentrations of ammonia, DOC, and phosphate to groundwater and is not recommended for use in either PRBs or reactive backfill due to potential for secondary groundwater quality impacts.
- Bone char released phosphate but removed ammonia and DOC from groundwater.
- Hydrotalcite is not recommended for PRB application due to its very fine grain size.
- Column tests with activated alumina mixed with either sand or fill soil were performed to provide data to be used to develop design doses for activated alumina in PRBs and reactive backfill, respectively. The column tests also showed excellent phosphate removal from groundwater which is over time expected to contribute to improved water quality in surface water adjacent to the PRBs.
- Fluoride is strongly sequestered by activated alumina due to the formation of strong surface complexes and potentially surface precipitates, and the potential for remobilization under reasonably anticipated future site conditions is very low.
- The optimal PRB media mix and configuration was determined during the engineering design phase by modeling, which takes into account field conditions and PRB width to determine the media loading needed for the service life of the PRBs (Appendix J of the Final EDR).
- The reactive backfill mix was also optimized during engineering design (Appendix G of the Final EDR).
- Alcoa has identified Axens as a potential supplier of activated alumina for the project and is currently in negotiations to ensure the necessary quantities will be available and will be delivered as dictated by the construction schedule. In the event that Axens is unable to fulfill these requirements and a different supplier of activated alumina is selected, the fluoride uptake isotherm of the final selected alumina will be determined to ensure it meets or exceeds the performance of the Axens AA material.

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Attachment I1

Screening, Batch, and Column Test Results

Table I1-1
Initial Screening Test Results

Reactive Media	Source	Fluoride (mg/L)	pH
Bone meal 1	Down to Earth Distributors, Inc.	54.4	9.75
Bone meal 2	Bridgewell Argibusiness, LLC	80.0	9.59
Bone char 1	American Charcoal Company	27.8	9.82
Bone char 2	Fedco Seeds, Inc.	56.2	9.79
Rock phosphate 1	Fedco Seeds, Inc. (from Minnesota)	82.0	9.74
Rock phosphate 2	Fedco Seeds, Inc. (from Tennessee)	95.4	9.85
Rock phosphate 3	Down to Earth Distributors, Inc. (from Florida)	83.1	9.76
Hydrotalcite 1	Kisuma Chemicals (DHT-4C)	23.9	10.18
Hydrotalcite 2	Kisuma Chemicals (DHT-4V)	95.4	9.96
Hydrotalcite 3	Kyowa Chemical Industry Co. (KW-2000)	23.7	13.14
Groundwater control	Well RL-2S	96.6	9.62

Note:
mg/L: milligrams per liter

Table I1-2
Single Media and Mixture Screening Test Results

Groundwater	Reactive Media	Fluoride (mg/L)	pH	SC (µS/cm)
RL-2S	Activated alumina	11.4 (0.7)	9.06 (0.06)	10,380 (20)
	Bone char	10.8 (1.5)	9.57 (0.04)	8,450 (30)
	Bone meal	6.1 (0.5)	9.06 (0.21)	8,450 (450)
	Calcite	83.9 (0.2)	9.68 (0.03)	8,900 (20)
	Hydrotalcite	16.6 (1.1)	9.75 (0.02)	8,000 (130)
	MgO	70.1 (1.2)	10.36 (0.01)	9,080 (10)
	Siderite	86.1 (3.6)	9.64 (0.06)	8,820 (20)
	Calcite + Bone char	28.2 (1.0)	9.65 (0.01)	8,660 (10)
	Calcite + Bone meal	19.3 (0.3)	9.40 (0.08)	8,510 (70)
	Siderite + Bone char	27.7 (0.2)	9.66 (0.02)	8,640 (10)
	Siderite + Bone meal	19.8 (1.0)	9.37 (0.03)	8,520 (50)
	Activated alumina + MgO	20.5 (0.8)	10.81 (0.02)	10,000 (20)
	Bone char + MgO	16.9 (0.4)	10.73 (0.01)	9,160 (20)
	Bone meal + MgO	18.0 (2.0)	10.44 (0.00)	8,840 (60)
	Calcite + MgO	75.0 (1.6)	10.24 (0.01)	9,130 (50)
	Siderite + MgO	73.2 (0.9)	10.31 (0.01)	9,030 (20)
	Silica sand	83.4 (1.9)	9.79 (0.02)	8,790 (0)
	Groundwater control	84.2 (0.9)	9.76 (0.03)	8,840 (10)
PZ-5	Activated alumina	159	9.68	23,990
	Bone char	533	10.21	16,740
	Bone meal	271	9.80	15,680
	Calcite	1,800	10.31	21,680
	Hydrotalcite	299	10.52	16,380
	MgO	942	12.61	23,240
	Siderite	1,810	10.25	21,340
	Calcite + Bone char	999	10.30	19,460
	Calcite + Bone meal	681	10.11	17,680
	Siderite + Bone char	1,010	10.26	19,180
	Siderite + Bone meal	703	10.07	17,820
	Activated alumina + MgO	448	11.71	22,980
	Bone char + MgO	1,750	11.59	19,850
	Bone meal + MgO	596	11.38	17,960
	Calcite + MgO	1,450	10.85	21,410
	Siderite + MgO	1,430	10.55	21,180
	Silica sand	1,810	10.48	21,670
	Groundwater control	1,830	10.38	21,750

Notes:
AAFS50 28×48 activated alumina obtained from Delta Adsorbents was tested.
Parentheses indicate standard deviation for duplicate tests.
µS/cm: microsiemens per centimeter
mg/L: milligrams per liter
MgO: magnesium oxide
SC: specific conductance

Table I1-3a
Kinetic Batch Test Results for Groundwater Collected from Well RL-2S

Reactive Media	Reaction Time (days)	Fluoride (mg/L)	pH	SC (µS/cm)
Initial	0	84.8	9.56	9,095
Activated alumina	1	38.8 (2.0)	9.41 (0.00)	10,380 (30)
	2	17.1 (1.7)	9.10 (0.04)	10,260 (10)
	4	12.5 (0.1)	9.12 (0.01)	10,840 (30)
	8	11.4 (0.4)	9.10 (0.03)	10,360 (10)
Bone char	1	30.7 (0.5)	9.65 (0.01)	8,390 (30)
	2	18.2 (0.1)	9.59 (0.02)	8,330 (20)
	4	12.9 (0.1)	9.69 (0.01)	9,120 (110)
	8	10.8 (0.8)	9.60 (0.02)	8,430 (20)
Bone meal	1	41.4 (0.2)	9.53 (0.04)	8,330 (0)
	2	25.3 (0.8)	9.44 (0.05)	8,180 (50)
	4	14.9 (0.1)	9.39 (0.01)	8,790 (20)
	8	6.2 (0.2)	8.92 (0.10)	8,770 (230)
Hydrotalcite	1	20.2 (1.7)	9.87 (0.03)	8,540 (20)
	2	17.5 (1.0)	9.77 (0.04)	8,560 (0)
	4	16.5 (0.5)	9.87 (0.00)	8,510 (20)
	8	16.6 (0.5)	9.74 (0.01)	8,090 (70)
MgO	1	80.4 (1.5)	9.93 (0.03)	8,630 (20)
	2	79.6 (0.5)	10.05 (0.01)	8,700 (10)
	4	76.4 (0.6)	10.31 (0.00)	9,030 (10)
	8	70.2 (0.6)	10.37 (0.01)	9,070 (10)
Activated alumina + MgO	1	54.5 (1.2)	9.82 (0.01)	9,470 (50)
	2	42.3 (0.3)	10.19 (0.02)	9,650 (10)
	4	30.3 (0.4)	10.68 (0.00)	9,900 (10)
	8	20.5 (0.4)	10.8 (0.01)	10,000 (0)
Bone char + MgO	1	41.8 (1.4)	9.92 (0.01)	8,510 (80)
	2	29.1 (0.1)	10.07 (0.02)	8,690 (40)
	4	22.2 (0.2)	10.54 (0.01)	9,050 (30)
	8	16.9 (0.2)	10.74 (0.01)	9,170 (10)
Bone meal + MgO	1	57.0 (0.4)	9.83 (0.01)	8,500 (30)
	2	37.8 (0.3)	9.93 (0.04)	8,490 (20)
	4	26.9 (0.2)	10.33 (0.01)	8,840 (40)
	8	18.0 (1.0)	10.44 (0.00)	8,880 (30)

Notes:
AAFS50 28×48 activated alumina obtained from Delta Adsorbents was tested.
Parentheses indicate standard deviation for duplicate tests.
µS/cm: microsiemens per centimeter
mg/L: milligrams per liter
MgO: magnesium oxide
SC: specific conductance

Table I1-3b
Kinetic Batch Test Results for Groundwater Collected from Well PZ-5

Reactive Media	Reaction Time (days)	Fluoride (mg/L)	pH	SC (µS/cm)
Initial	0	1,840	10.01	21,850
Activated alumina	1	544	9.85	24,330
	2	385	9.80	24,340
	4	169	9.70	23,280
	8	159	9.68	23,990
Bone char	1	755	10.20	18,060
	2	698	10.21	17,920
	4	559	10.23	17,790
	8	533	10.21	16,740
Bone meal	1	752	9.90	17,240
	2	696	9.93	17,080
	4	316	9.83	15,850
	8	271	9.80	15,680
Hydrotalcite	1	327	10.69	20,110
	2	336	10.56	21,210
	4	319	10.55	16,800
	8	299	10.52	16,380
MgO	1	1,510	10.73	21,110
	2	1,430	10.90	21,210
	4	1,310	11.51	21,380
	8	942	12.61	23,240
Activated alumina + MgO	1	1,050	10.31	22,760
	2	804	10.42	22,630
	4	523	11.28	20,480
	8	448	11.71	22,980
Bone char + MgO	1	1,110	10.58	19,560
	2	1,010	10.75	19,490
	4	884	11.35	19,630
	8	902	11.59	19,850
Bone meal + MgO	1	1,030	10.44	18,980
	2	906	10.62	18,540
	4	629	11.21	17,250
	8	596	11.38	17,960

Notes:
AAFS50 28×48 activated alumina obtained from Delta Adsorbents was tested.
µS/cm: microsiemens per centimeter
mg/L: milligrams per liter
MgO: magnesium oxide
SC: specific conductance

Table I1-4
Isotherm Batch Test Results

Reactive Media	Groundwater	Solution volume (mL)	Media mass (g)	L/S	C_0 (mg/L)	C_w (mg/L)	C_s (mg/kg)	pH	SC (µS/cm)
Delta AA	RL-2S	200	20	10	83.8	12.5	713	9.02	12,500
		200	10	20	84.8	11.9	1,460	9.14	10,350
		200	2	100	83.8	57.9	2,590	9.64	9,450
		200	20	10	83.6	10.8	728	8.97	12,490
		200	10	20	83.5	10.9	1,450	9.06	10,380
		200	2	100	83.6	58.7	2,490	9.66	9,470
	PZ-5	200	50	4	1,820	159	6,620	9.68	23,990
		200	20	10	1,820	807	10,100	10.22	22,020
		200	250	2	1,980	164	3,620	9.26	27,340
		500	100	2	1,820	229	3,030	9.85	26,130
Bone char	RL-2S	200	20	10	83.8	12.7	711	9.51	8,610
		200	10	20	84.8	11.9	1,460	9.62	8,400
		200	2	100	83.8	55.3	2,850	9.73	9,150
		200	20	10	83.6	10.1	735	9.54	8,640
		200	10	20	83.5	9.7	1,480	9.57	8,450
		200	2	100	83.6	53.9	2,970	9.74	9,150
	PZ-5	200	50	4	1,820	533	5,130	10.21	16,740
		200	20	10	1,820	1,220	5,980	10.34	19,900
		500	250	2	1,980	308	3,330	9.79	16,890
		200	100	2	1,820	376	2,880	9.93	15,550
Bone meal	RL-2S	200	20	10	83.8	18.4	654	8.20	11,400
		200	10	20	84.8	5.8	1,580	8.77	9,090
		200	2	100	83.8	60.8	2,300	9.54	9,180
		200	20	10	83.6	8.1	755	7.74	12,020
		200	10	20	83.5	8.1	1,510	9.06	8,450
		200	2	100	83.6	51.9	3,170	9.63	9,140
	PZ-5	200	100	2	1,820	321	2,990	8.92	17,710
		200	50	4	1,820	271	6,180	9.80	15,680
		200	20	10	1,820	979	8,360	10.09	19,030
Hydrotalcite	RL-2S	200	20	10	83.8	12.4	714	9.64	8,930
		200	10	20	84.8	17.3	1,350	9.72	8,190
		200	2	100	83.8	53.2	3,060	9.75	9,110
		200	20	10	83.6	7.7	759	9.69	8,820
		200	10	20	83.5	15.9	1,350	9.75	8,000
		200	2	100	83.6	47.8	3,580	9.80	9,120
	PZ-5	200	50	4	1,820	299	6,060	10.52	16,380
		200	20	10	1,820	803	10,120	10.69	20,460

Reactive Media	Groundwater	Solution volume (mL)	Media mass (g)	L/S	C_0 (mg/L)	C_w (mg/L)	C_s (mg/kg)	pH	SC (µS/cm)
Axens AA	RL-2S	100	20	5	81.8	2.1	398	8.43	12,790
		100	10	10	81.8	3.8	780	8.92	12,780
		100	5	20	81.8	12.8	1,380	9.38	12,800
		100	2	50	81.8	33.5	2,410	9.62	12,790
		100	1	100	81.8	49.1	3,270	9.69	12,810
	PZ-5 (x2 diluted with deionized water)	100	50	2	980	4.1	1,950	8.54	6,430
		100	10	10	980	195	7,850	9.9	6,420
		100	5	20	980	381	11,980	10.08	6,420
	PZ-5	100	50	2	1,930	37.3	3780	9.27	12,840
		100	10	10	1,930	672	12,560	10.16	12,850
		100	5	20	1,930	1,130	15,870	10.19	12,860
Quarry sand (PRB)	RL-2S (x2 diluted with deionized water)	100	50	2	39.2	31.8	15	9.45	5,160
		100	10	10	39.2	35.7	36	9.73	5,820
	RL-2S	100	50	2	81.8	63.2	37	9.56	12,820
		100	10	10	81.8	74.9	68	9.73	12,810
	Mixture of RL-2S and PZ-5	100	50	2	410	325	170	9.74	12840
		100	10	10	410	387	231	9.86	12870
	PZ-5 (x2 diluted with deionized water)	100	50	2	980	770	419	10.05	6,450
		100	10	10	980	936	437	10.15	6,470
	PZ-5	100	50	2	1,930	1,670	521	10.08	12,920
		100	10	10	1,930	1,880	474	10.12	12,900
Quarry fill (Reactive Backfill)	RL-2S (x2 diluted with deionized water)	100	50	2	39.2	32.7	13	9.43	5,200
		100	10	10	39.2	36.6	27	9.74	5,850
	RL-2S	100	50	2	81.8	65.1	33	9.54	12,900
		100	10	10	81.8	77.5	43	9.74	12,920
	Mixture of RL-2S and PZ-5	100	50	2	410	333	154	9.73	12,880
		100	10	10	410	394	167	9.86	12,880
	PZ-5 (x2 diluted with deionized water)	100	50	2	980	793	374	10.04	6,440
		100	10	10	980	952	280	10.16	6,470
	PZ-5	100	50	2	1,930	1,700	465	10.08	12,960
		100	10	10	1,930	1,900	317	10.12	12,980

Notes:
Reaction time is 8 days.
Delta AA, bone char, bone meal, and hydrotalcite were tested with groundwater samples collected on May 19th, 2019.
Axens AA, quarry sand (PRB), and quarry fill (Reactive backfill) were tested with groundwater samples collected on January 27th, 2022.
μS/cm: microsiemens per centimeter
Axens AA: ActiGuard F 14×28 activated alumina obtained from Axens Canada Specialty Aluminas Inc.
C_0: initial fluoride concentration in solution phase
C_s: calculated fluoride concentration on solid phase
C_w: final fluoride concentration in solution phase
Delta AA: AAFS50 28×48 activated alumina obtained from Delta Adsorbents
g: gram
mg/kg: milligrams per kilogram
mg/L: milligrams per liter
mL: milliliter
L/S: liquid to solid ratio
SC: specific conductance

Table I1-5
Cation Exchange Capacity of Quarry Sand and Quarry Fill

Sample	Exchangeable Cations (meq/kg)				Sum (meq/kg)
	Calcium	Potassium	Magnesium	Sodium	
Quarry Sand	24.4 (0.7)	1.8 (0.0)	10.0 (0.2)	0.8 (0.0)	37.1 (0.9)
Quarry Fill	23.3 (0.4)	2.6 (0.1)	10.6 (0.3)	1.3 (0.0)	37.8 (0.8)

Notes:
Parentheses indicate standard deviation for triplicate results.
meq/kg: milliequivalents per kilogram

Table I1-6
Extractable Aluminum and Iron Oxides of Quarry Sand and Quarry Fill

Sample	Aluminum (mg/kg)	Iron (mg/kg)
Quarry Sand	185 (8)	1,540 (30)
Quarry Fill	333 (24)	2,240 (280)

Notes:
Parentheses indicate standard deviation for triplicate results.
mg/kg: milligrams per kilogram

Table I1-7
Column Test Results

Sampling Point	Sample Date/Time	Elapsed time (days)	Flow rate (mL/min)	Pore volumes	pH	SC (µS/cm)	Fluoride (mg/L)	Phosphate-P (mg/L)
Influent reservoir	11/23/19 13:40	1.8	0.30	7.4	9.71	7,300	71.8	16.1
	11/25/19 20:00	4.1	0.30	16.5	9.71	7,490	71.6	--
	11/27/19 18:10	6.0	0.30	24.2	9.71	7,380	71.5	16.8
	11/30/19 18:00	9.0	0.30	36.3	9.73	7,390	71.4	--
	12/3/19 14:30	11.9	0.30	47.8	9.79	7,280	71.0	16.3
	12/6/19 17:20	15.0	0.30	60.3	9.75	7,450	71.3	--
	12/9/19 16:50	18.0	0.30	72.3	9.83	7,080	71.5	16.3
	12/12/19 12:40	20.8	0.30	83.7	9.66	7,470	77.8	--
	12/16/19 14:00	24.8	0.30	100	9.72	7,460	80.4	17.4
	12/20/19 14:30	28.9	0.30	116	9.66	7,500	79.4	--
Column effluent (50% Delta AA + 50% quartz sand)	11/23/19 13:30	1.8	0.30	7.3	7.00	9,010	<0.1	0.1
	11/25/19 18:25	4.0	0.30	16.2	6.73	6,830	<0.1	--
	11/27/19 13:40	5.8	0.30	23.5	7.31	6,620	<0.1	0.1
	11/30/19 12:20	8.8	0.30	35.3	9.66	7,020	<0.1	--
	12/3/19 9:40	11.7	0.30	46.9	9.86	7,340	0.9	0.2
	12/6/19 10:00	14.7	0.30	59.1	9.83	7,320	11.2	--
	12/9/19 9:15	17.6	0.30	71.0	9.87	7,420	28.0	0.2
	12/12/19 7:40	20.6	0.30	82.8	9.74	7,480	47.3	--
	12/16/19 8:30	24.6	0.30	99.1	9.76	7,530	56.6	0.4
	12/20/19 11:00	28.7	0.30	116	9.71	7,510	61.7	--

Notes:
-- not measured
µS/cm: microsiemens per centimeter
Delta AA: AAFS50 28×48 activated alumina obtained from Delta Adsorbents
mg/L: milligrams per liter
mL/min: milliliters per minute
SC: specific conductance

Table I1-8

Supplemental Column Test Results

Column	Date	Time	Elapsed Time (days)	Pore Volumes	Fluoride (mg/L)	Phosphate-P (mg/L)	pH	SC (µS/cm)
Influent Reservoir for Column S1 and S2 (RL-2S)	3/17/2022	10:36	0.00	0.0	78.4	18.7	9.83	12827
	3/17/2022	14:30	0.17	0.8	76.8	--	9.79	13072
	3/18/2022	8:01	0.90	4.2	76.5	18.7	9.73	12793
	3/19/2022	10:30	2.00	9.4	76.5	--	9.75	12903
	3/20/2022	8:30	2.92	13.7	76.2	--	9.77	12827
	3/21/2022	9:02	3.94	18.5	76.5	17.9	9.80	12782
	3/22/2022	9:30	4.96	23.3	77.8	--	9.80	12829
	3/23/2022	8:45	5.93	27.8	76.8	--	9.83	12882
	3/24/2022	11:10	7.03	33.0	76.6	17.6	9.81	12880
	3/25/2022	10:45	8.01	37.6	76.4	--	9.81	12754
	3/26/2022	9:10	8.94	42.0	76.6	--	9.92	12811
	3/27/2022	9:50	9.97	46.8	76.3	18.0	9.92	8566
	3/29/2022	8:22	11.9	55.9	76.4	--	9.85	7317
	3/30/2022	8:30	12.9	60.7	77.4	--	9.84	7434
	3/31/2022	8:45	13.9	65.4	76.9	17.8	9.86	7315
	4/1/2022	8:00	14.9	70.0	76.2	--	9.85	7333
	4/5/2022	10:35	19.0	89.3	74.1	--	9.86	7368
	4/8/2022	8:39	21.9	103	74.0	17.7	9.86	7550
	4/11/2022	11:15	25.0	118	74.7	--	9.91	7508
Column S1 Effluent (15% Axens AA + 85% quarry sand)	3/17/2022	10:36	0.00	0.0	0.53	0.0	8.35	2784
	3/17/2022	14:30	0.17	0.8	0.20	--	8.34	2249
	3/18/2022	8:01	0.90	4.2	0.17	0.0	9.33	12711
	3/19/2022	10:30	2.00	9.4	0.39	--	9.51	12835
	3/20/2022	8:30	2.92	13.7	0.60	--	9.54	12823
	3/21/2022	9:02	3.94	18.5	2.39	0.2	9.54	12715
	3/22/2022	9:30	4.96	23.3	19.53	--	9.55	12765
	3/23/2022	8:45	5.93	27.8	40.52	--	9.51	12838
	3/24/2022	11:10	7.03	33.0	60.30	0.2	9.51	12884
	3/25/2022	10:45	8.01	37.6	62.66	--	9.54	12746
	3/26/2022	9:10	8.94	42.0	65.6	--	9.56	12826
	3/27/2022	9:50	9.97	46.8	67.8	0.3	9.54	8512
	3/29/2022	8:22	11.9	55.9	67.8	--	9.59	7317
	3/30/2022	8:30	12.9	60.7	70.1	--	9.55	7403
	3/31/2022	8:45	13.9	65.4	70.0	0.3	9.52	7323
	4/1/2022	8:00	14.9	70.0	70.1	--	9.54	7425
	4/5/2022	10:35	19.0	89.3	70.9	--	9.52	7430
	4/8/2022	8:39	21.9	103	71.7	0.3	9.52	7474
	4/11/2022	11:15	25.0	118	69.5	--	9.50	7545

Table I1-8
Supplemental Column Test Results

Column	Date	Time	Elapsed Time (days)	Pore Volumes	Fluoride (mg/L)	Phosphate-P (mg/L)	pH	SC (µS/cm)
Column S2 Effluent (30% Axens AA + 70% quarry sand)	3/17/2022	10:36	0.89	3.6	0.12	0.0	6.56	4935
	3/17/2022	14:30	1.90	7.6	0.07	--	6.64	4217
	3/18/2022	8:01	2.98	12.0	0.07	0.0	7.10	12697
	3/19/2022	10:30	3.98	16.0	0.20	--	7.65	12840
	3/20/2022	8:30	4.83	19.5	0.2	--	7.65	12804
	3/21/2022	9:02	5.98	24.1	0.2	0.2	8.32	12677
	3/22/2022	9:30	6.95	28.0	0.4	--	9.73	12736
	3/23/2022	8:45	8.06	32.5	0.5	--	9.85	12819
	3/24/2022	11:10	8.85	35.6	1.9	0.2	9.87	12881
	3/25/2022	10:45	9.82	39.5	5.9	--	9.88	12740
	3/26/2022	9:10	10.8	43.6	15.4	--	9.82	12800
	3/27/2022	9:50	11.8	47.4	28.5	0.2	9.82	8512
	3/29/2022	8:22	12.9	51.8	40.5	--	9.83	7249
	3/30/2022	8:30	13.9	56.0	47.9	--	9.82	7331
	3/31/2022	8:45	14.9	59.8	54.5	0.2	9.82	7269
	4/1/2022	8:00	15.9	63.8	59.1	--	9.83	7339
	4/5/2022	10:35	16.8	67.6	66.4	--	9.84	7426
	4/8/2022	8:39	17.9	72.0	66.3	0.2	9.85	7440
	4/11/2022	11:15	18.9	75.9	67.6	--	9.87	7552
Influent Reservoir for Column S3 and S4 (PZ-5)	3/17/2022	10:36	0.00	0.0	1710	25.1	10.2	12802
	3/17/2022	13:50	0.14	0.7	1699	23.3	10.1	13155
	3/18/2022	8:00	0.90	4.2	1678	24.5	10.1	--
	3/19/2022	10:30	2.00	9.4	1686	--	10.0	--
	3/20/2022	8:30	2.92	13.7	1746	23.5	10.1	12890
	3/21/2022	9:01	3.94	18.5	1710	--	10.2	12825
	3/22/2022	9:30	4.96	23.3	1767	23.4	10.1	--
	3/23/2022	8:45	5.93	27.8	1783	--	10.2	--
	3/24/2022	11:10	7.03	33.0	1705	--	10.2	--
	3/25/2022	10:45	8.01	37.6	1727	--	10.2	12980
	3/26/2022	9:10	8.94	42.0	1722	24.0	10.2	--
	3/27/2022	9:50	9.97	46.8	1710	--	10.3	12878
	3/28/2022	8:55	10.9	51.4	1690	24.0	10.1	--

Table I1-8
Supplemental Column Test Results

Column	Date	Time	Elapsed Time (days)	Pore Volumes	Fluoride (mg/L)	Phosphate-P (mg/L)	pH	SC (µS/cm)
Column S3 Effluent (5% Axens AA + 95% quarry soil)	3/17/2022	10:36	0.00	0.0	0.3	0.0	6.55	12981
	3/17/2022	13:50	0.14	0.7	0.3	--	6.80	2603
	3/17/2022	17:01	0.27	1.3	0.1	--	6.53	9347
	3/17/2022	20:10	0.40	1.9	0.1	0.1	7.74	12900
	3/17/2022	22:00	0.48	2.3	0.2	--	8.31	12860
	3/18/2022	8:00	0.90	4.2	150	--	9.93	12839
	3/18/2022	10:00	0.98	4.6	210	--	10.0	12833
	3/18/2022	14:00	1.15	5.4	386	0.2	10.1	12836
	3/18/2022	16:35	1.25	5.9	489	--	10.1	12850
	3/19/2022	10:30	2.00	9.4	1021	--	10.2	12952
	3/19/2022	21:00	2.44	11.4	1201.1	--	10.2	12905
	3/20/2022	8:30	2.92	13.7	1293.2	0.1	10.3	12886
	3/20/2022	14:30	3.17	14.9	1343.7	--	10.3	12887
	3/21/2022	9:01	3.94	18.5	1393.2	--	10.3	12804
	3/21/2022	13:22	4.12	19.3	1431.5	--	10.3	12696
	3/22/2022	9:30	4.96	23.3	1480.5	0.3	10.2	12818
	3/23/2022	8:45	5.93	27.8	1471.3	--	10.3	12820
	3/24/2022	11:10	7.03	33.0	1382.8	--	10.3	12953
	3/25/2022	10:45	8.01	37.6	1400.6	--	10.2	12831
	3/26/2022	9:10	8.94	42.0	1404.5	0.8	10.3	12844
	3/27/2022	9:50	9.97	46.8	1389.6	--	10.3	22455
	3/28/2022	8:55	10.9	51.4	1400.5	1.2	10.2	18877

Table I1-8
Supplemental Column Test Results

Column	Date	Time	Elapsed Time (days)	Pore Volumes	Fluoride (mg/L)	Phosphate-P (mg/L)	pH	SC (µS/cm)
Column S4 Effluent (15% Axens AA + 85% quarry soil)	3/17/2022	10:36	0.00	0.0	0.4	0.1	6.71	4875
	3/17/2022	13:50	0.14	0.7	0.1	--	7.05	4313
	3/17/2022	17:01	0.27	1.3	0.1	--	7.13	9179
	3/17/2022	20:10	0.40	1.9	0.1	0.0	7.70	12880
	3/17/2022	22:00	0.48	2.3	0.1	--	8.37	--
	3/18/2022	8:00	0.90	4.2	3.2	--	9.53	12813
	3/18/2022	10:00	0.98	4.6	9.9	--	9.69	12838
	3/18/2022	14:00	1.15	5.4	48.7	0.2	9.92	12827
	3/18/2022	16:35	1.25	5.9	89.9	--	10.0	12860
	3/19/2022	10:30	2.00	9.4	504	--	10.2	12950
	3/19/2022	21:00	2.44	11.4	706	--	10.3	12917
	3/20/2022	8:30	2.92	13.7	876	0.1	10.4	12881
	3/20/2022	14:30	3.17	14.9	940	--	10.4	12887
	3/21/2022	9:01	3.94	18.5	1100	--	10.4	12787
	3/21/2022	13:22	4.12	19.3	1129	--	10.3	12740
	3/22/2022	9:30	4.96	23.3	1226	0.1	10.3	12798
	3/23/2022	8:45	5.93	27.8	1279	--	10.3	12807
	3/24/2022	11:10	7.03	33.0	1136	--	10.3	12960
	3/25/2022	10:45	8.01	37.6	1217	--	10.3	12822
	3/26/2022	9:10	8.94	42.0	1249	0.3	10.3	12865
	3/27/2022	9:50	9.97	46.8	1253	--	10.4	22441
	3/28/2022	8:55	10.9	51.4	1256	0.4	10.3	18749
Influent Reservoir for Column S5 and S6 (PZ-5)	3/28/2022	12:50	0.00	0.0	1726	--	9.83	12826
	3/29/2022	8:21	0.81	1.9	1755	--	10.2	--
	3/30/2022	8:30	1.82	4.3	1749	23.8	10.2	12827
	3/31/2022	8:45	2.83	6.6	1753	22.7	10.2	12803
	4/1/2022	8:00	3.80	8.9	1734	23.9	10.2	12921
	4/4/2022	8:31	6.82	16.0	1728	--	10.2	12782
	4/5/2022	10:35	7.91	18.6	1703	25.2	10.2	12813
	4/8/2022	8:39	10.8	25.4	1706	--	10.3	22499
	4/11/2022	11:15	13.9	32.7	1715	--	10.3	19350

Table I1-8
Supplemental Column Test Results

Column	Date	Time	Elapsed Time (days)	Pore Volumes	Fluoride (mg/L)	Phosphate-P (mg/L)	pH	SC (µS/cm)
Column S5 Effluent (15% Axens AA + 85% quarry soil)	3/28/2022	12:50	0.00	0.0	2.4	0.0	7.08	736
	3/28/2022	15:12	0.10	0.2	0.1	--	6.25	599
	3/29/2022	8:21	0.81	1.9	11.7	0.1	8.01	9189
	3/29/2022	11:45	0.95	2.2	54.6	--	8.60	11166
	3/29/2022	14:15	1.06	2.5	114	--	9.20	12286
	3/30/2022	8:30	1.82	4.3	952	0.3	10.2	17486
	3/30/2022	11:15	1.93	4.5	971	--	10.2	17839
	3/30/2022	14:24	2.07	4.9	1036	--	10.2	18304
	3/31/2022	8:45	2.83	6.6	1363	0.2	10.3	18671
	3/31/2022	11:50	2.96	6.9	1384	--	10.3	18726
	3/31/2022	14:10	3.06	7.2	1394	--	10.3	18856
	4/1/2022	8:00	3.80	8.9	1457	0.3	10.2	19179
	4/4/2022	8:31	6.82	16.0	1501	--	10.2	19165
	4/5/2022	10:35	7.91	18.6	1524	0.6	10.3	18930
	4/8/2022	8:39	10.8	25.4	1581	--	10.3	19226
	4/11/2022	11:15	13.9	32.7	1530	--	10.3	19167
Column S6 Effluent (30% Axens AA + 70% quarry soil)	3/28/2022	12:50	0.00	0.0	0.8	0.0	7.22	855
	3/28/2022	15:12	0.10	0.2	0.3	--	6.71	812
	3/29/2022	8:21	0.81	1.9	0.3	0.0	8.01	8169
	3/29/2022	11:45	0.95	2.2	0.4	--	8.78	10131
	3/29/2022	14:15	1.06	2.5	2.5	--	9.48	11333
	3/30/2022	8:30	1.82	4.3	227	0.2	10.1	15474
	3/30/2022	11:15	1.93	4.5	285	--	10.1	16071
	3/30/2022	14:24	2.07	4.9	364	--	10.2	16465
	3/31/2022	8:45	2.83	6.6	568	0.2	10.3	17258
	3/31/2022	11:50	2.96	6.9	624	--	10.3	17422
	3/31/2022	14:10	3.06	7.2	633	--	10.3	17473
	4/1/2022	8:00	3.80	8.9	793	0.2	10.2	18063
	4/4/2022	8:31	6.82	16.0	1127	--	10.3	18813
	4/5/2022	10:35	7.91	18.6	1219	0.2	10.4	18680
	4/8/2022	8:39	10.8	25.4	1259	--	10.4	18943
	4/11/2022	11:15	13.9	32.7	1330	--	10.4	18902

Notes:
--: not measured
µS/cm: microsiemens per centimeter
Axens AA: ActiGuard F 14×28 activated alumina obtained from Axens Canada Specialty Aluminas Inc.
mg/L: milligrams per liter

Table I1-9
Fluoride Accumulation and Extraction Test Results

Column No.	Total Accumulated Fluoride[1]	Fluoride Extracted by 0.01 M HCl		Fluoride Extracted by 0.01 M NaCl		Fluoride Extracted by 0.01 M NaOH	
	mg/kg	mg/L[2]	mg/kg[3]	mg/L[2]	mg/kg[3]	mg/L[2]	mg/kg[3]
S1	465	0.17	8.57	3.26	163	1.00	49.9
S2	845	0.13	6.30	5.64	282	0.52	26.0
S3	1,950	6.63	331	25.6	1,280	26.0	1,300
S4	4,170	1.35	67.7	35.9	1,800	24.1	1,210
S4 (Dup)	4,170	1.38	68.9	40.1	2,000	25.7	1,290
S5	3,910	1.26	62.9	42.2	2,110	29.1	1,450
S6	6,230	1.08	54.3	60.9	3,050	33.8	1,700

Notes:

1. Calculated from the difference between influent and effluent fluoride mass divided by dry weight of solid media in the column.
2. Dissolved fluoride concentration measured in 100 mL of solution following extraction of 2 grams (dry weight) of column media sample.
3. Concentration recalculated on a dry weight solids basis.

Axens AA: ActiGuard F 14×28 activated alumina obtained from Axens Canada Specialty Aluminas Inc.
HCl: hydrochloric acid
M: moles per liter
mg/kg: milligrams per kilogram
mg/L: milligrams per liter
mL: milliliter
NaCl: sodium chloride
NaOH: sodium hydroxide