Using Coal Combustion Residues for Abandoned Coal Mine Reclamation

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Abstract

Two full-scale demonstration projects using coal combustion residues (CCRs) to reclaim abandoned mines were carried out near the Conesville and Cardinal coal-fired power plants located in eastern Ohio. Water quality data collected over a ten-year period from 2010 to 2020 were analysed to assess the environmental impacts associated with this mine reclamation approach. Statistically significant water quality changes were observed at both sites after reclamations began. By using linear discriminant analysis on the hydrogeochemcial characteristics of the water samples, we identified if the backfilled CCRs have observable influences on the water quality of the underlying shallow aquifers.
CRs have observable influences on the water quality of the underlying shallow aquifers.

Keywords: Coal Mine Reclamation, Coal Combustion Residues, Flue Gas Desulfurization, Groundwater, Hydrochemical Property, Multivariate Statistical Analysis

Introduction

In the state of Ohio, there are over 800 km^2 of un-reclaimed strip-mined lands (AMLs) left behind after the mining operations were ceased, which pose risks to the public and the environment. These AMLs discharge highly acidic and mineralized mine drainages (AMD), disrupt the flows of surface water streams and lakes, create dangerous highwalls, and degrade the ecosystems and habitats of the impacted watersheds. Limited public funds and natural resources are available to reclaim these AMLs.

In a previous study (Wolfe *et al.* 2009), we identified hundreds of miles of potentially dangerous AML highwalls in close proximity of coal-fired power plants. Finding an environmentally benign and technically feasible approach using coal combustion residues (CCRs), including bottom ash, coal ash, flue gas desulfurization (FGD) gypsum, and stabilized FGD material (sFGD), to reclaim AMLs can reduce costs and consumptions of natural resources. sFGD is a mixture of lime, coal ash, and calcium sulphite FGD by-product. FGD is a wet scrubber used in a coal-fired power plant to remove sulfur dioxide from the flue gas. We carried out the first stage study investigating the chemical/leaching characteristics of CCRs, characterizing potential project sites, and gathering inputs from public and industrial stake holders. In the second stage, two full-scale demonstration projects were carried out at the highwall pit complexes near the Conesville and Cardinal coal-fired power plants located in eastern Ohio.

To demonstrate the potential of using high-volume CCRs in abandoned coal mine reclamation, the associated environmental impacts were evaluated by regularly characterizing the leaching properties of the backfilling CCRs and monitoring the water quality of the uppermost aquifers underlying the reclamation sites. The water quality monitoring started approximately 15 months prior to the beginning of the reclamation. In this study, we detected if there are any significant water quality changes as a result of the reclamation practice, differentiated the causes of occurring water quality changes, and discussed the environmental implications of this reclamation practice.

Reclamation Sites

Conesville Five Points

The Middle Kittanning No.6 coal seam underlying the Conesville Five Points site was extensively surface mined prior to the 1977 Surface Mining Control and Reclamation Act (SMCRA), resulting in exposed highwalls, open pits, and adjacent mine spoil deposits. This site comprises three phases. The reclamations at Phases 1 and 2 were completed in 2016. Approximately 1.5 million metric tons of bottom ash, fly ash, sFGD and FGD gypsum were placed. Over 7 km of highwall are eliminated and about 0.44 km^2 of abandoned mined lands were reclaimed (Figure 1(a)). Phase 3 is currently on going, which is expected to use ca. 2.0 million metric tons of sFGD and FGD gypsum to reclaim a total of approximately 1.7 km of highwalls.

Cardinal Star Ridge

The Cardinal site consists of a highwall complex created from previous pre-law mining and an active mining permit. The total length of the highwall was approximately 150 m. The reclamation involved placing a thick layer of calcareous mine spoil material at the bottom of the highwall pit to a height of five to eight feet above the high-water mark of the groundwater level. The highwall was reclaimed back to its original contour using approximately 410,000 metric tons of FGD gypsum produced from the nearby Cardinal power plant. The fill was encapsulated with alkaline mine overburden and revegetated. The reclamation was completed in 2015 (Figure 1(b)).

Groundwater Monitoring

Conesville Five Points

Because Phase 3 is still on going, the discussion focuses only on Phases 1 and 2. In Phases 1 and 2, the water quality monitoring network comprises eight groundwater monitoring wells and four surface water locations. MW-0901 serves as a hydraulically up-gradient well. MW-0902, MW-1001, and MW-0904 are installed at the edge of the backfilling area to capture the water quality change in the down-gradient shallow aquifer. MW-0905, MW-0906, and MW-1101s are at further down-gradient locations representing

Figure 1 *Reclamations at (a) Conesville Five Points and (b) Cardinal Star Ridge sites. Pictures on the left are the landscapes before reclamation began. Pictures on the right are the conditions approximately five years after reclamations were completed.*

approximately 5-year groundwater travel time from the backfilling area.

Cardinal Star Ridge

A total six monitoring wells were installed. OAE-1001A and OAE-1002 are hydraulically down-gradient wells, located at the south and east sides, respectively, of the reclamation area. The screens of both wells were set in the mine spoil layer. OAE-1003 and OAE-1005 are located on the edge of the west and north highwalls, respectively, which were completed within the Pittsburg No. 8 coal seam. Two clustered wells, OAE-1504S and OAE-1504C, were installed in the reclaimed highwall/pit after the backfilling of FGD gypsum was completed. The shallow well (OAE-1504s) screens at the fractured bedrock at the base of the underlying mine spoil bench. The deeper monitoring well (OAE-1504C) screens within the limestone and sandstone stratigraphic layers.

At a given site, water quality monitoring started approximately 15 months before reclamation began to establish background levels. Monthly water samples were collected before and during reclamation. After the reclamation was completed, sampling frequency was reduced to quarterly and/or semi-annually. The water monitoring is still on going at the Conesville site. The last set of water samples from the Cardinal site was collected in July 2020.

Water Quality Change

For a given groundwater monitoring well, we compared the field observations recorded after the reclamation began to upper (UPL) and lower (LPL) prediction limits. These two-sided prediction intervals were established from the background data. Any observations that either exceed the UPLs or below the LPLs are considered statistically significant with 99% confidence. At both sites, after reclamations began, we observed statistically significant water quality changes. There is at least one monitored constituent in one or more of the sampling locations exceeds either a UPL or a LPL. The significance of the water quality changes has been discussed elsewhere (Cheng *et al*. 2016).

Impacts from Backfilled CCRs

To identify if the backfilled CCRs are the sources of the observed water quality changes, we used a linear discriminant analysis (LDA) method (Lambrakis et. al. 2004, Lautz *et al.* 2014) to differentiate two hydrogeochemical signatures of the water samples. "Sulfate signature", combining the equivalent ratios of major cations (i.e., Ca, Mg, and Sr) to sulfate, distinguishes the dominance of sulfate minerals, e.g., gypsum, in each water group. "Boron signature", a combination of the equivalent ratios of Ca, Mg, and Na to boron, is used to differentiate the background groundwater and leachates from CCRs. LDA detects the patterns of hydrogeochemical signatures implicit in different water groups, i.e., background data and leachates of CCRs, by generating discriminate functions using a set of "training" data (i.e., training dataset). In order to overcome the statistical constraints (Efron, 1979) associated with the limited numbers of available background and CCR leachate data, we used a multivariate bootstrapping method to increase the sample size of each water group to 1000.

Conesville Five Point Site

We compared the sulfate and boron hydrogeochemical signatures of the MW-0902 and MW-0904 groundwater samples collected after the reclamation began to that of the background samples and the leachates from laboratory leaching tests. With two linear discriminate functions (DFs), LDA is able to accurately identify the differences of the sulfate (99.97%) and boron (96.90%) signatures in the training dataset among different water groups. By using the LDA results, we created a sulfate-boron score biplot (Figure 2) to observe the changes of the hydrogeochemical characteristics at MW-0902 and MW-0904 after the reclamation began.

As demonstrated in Figure 2 (a) and (b), the data points of water samples collected during site construction (black hollow circles) are close to (MW-0902) or within (MW-0904) the clusters of the background samples (grey hollow circles). It is also true

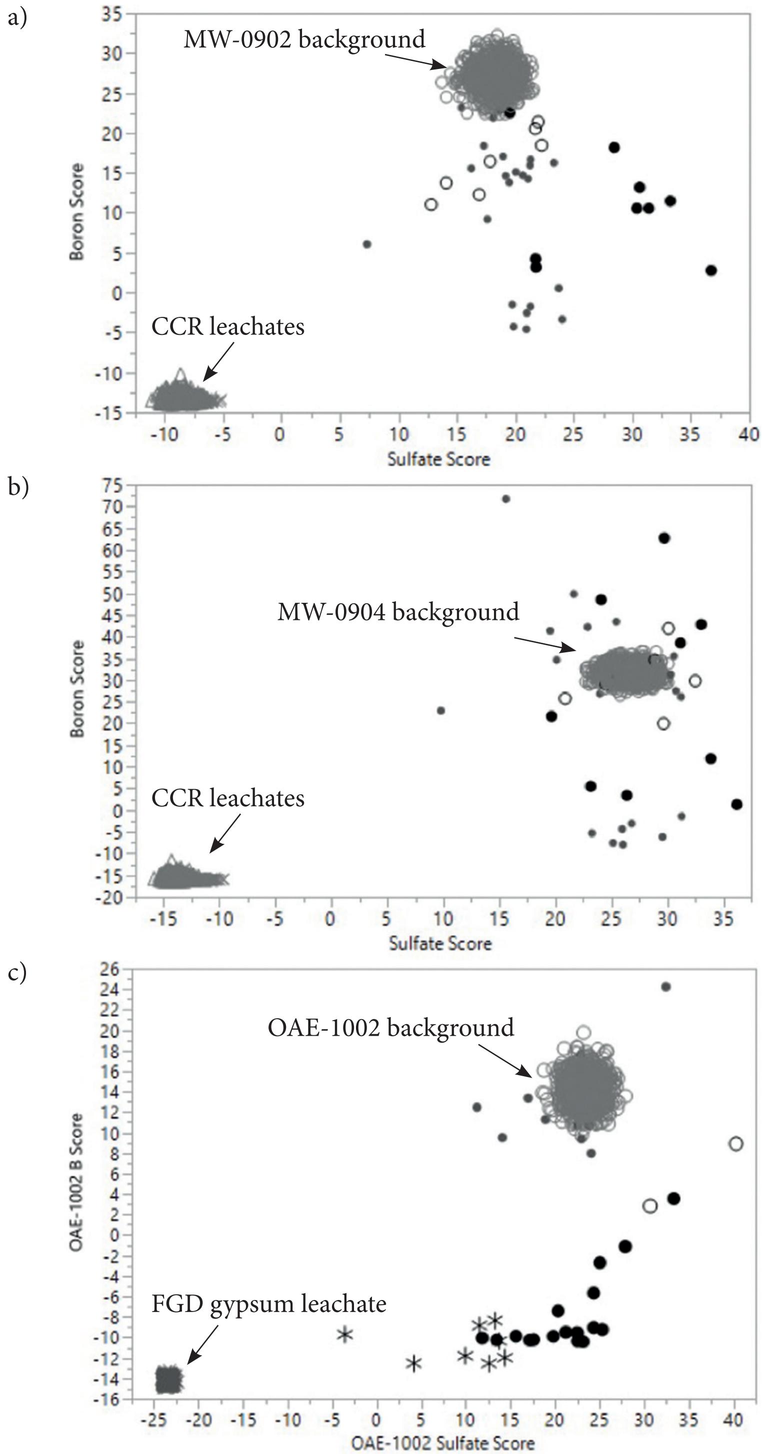

Figure 2 *Sulfate-Boron signature biplots of (a) MW-0902, (b) MW-0904, and (c) OAE-1002. Grey hollow circles, grey hollow triangle, and grey crosses progresses are the training data points of background, sFGD, and FGD gypsum leachates, respectively. Black hollow circles represent water samples collected during site construction. Grey dots are water samples collected during backfilling. Black dots are water samples collected after reclamation was completed.*

during the early stage of the backfilling period. As the backfilling of CCRs continued, boron scores (grey dots) started deviating from the background clusters. After the reclamation at Phases 1 and 2 was completed, both boron and sulfate scores of the water samples at both wells (black dots) were no longer within the ranges of the background samples. However, the changes do not move toward to the hydrogeochemical signatures of the CCR leachates.

It suggests the impacts from the backfilled CCRs on the water quality of the shallow aquifer underlying the Phases 1 and 2 area is currently not apparent. Instead, the water quality changes are likely associated with the Appalachian Regional Reforestation Initiative (ARRI) approach used to reclaim the area. This approach is characterized by the use of local end dumped spoil piles placed in an interlocking manner to encourage saturation and limit offsite erosion to promote tree survival and growth. With higher infiltration of rainfalls and runoffs, increasing concentrations of sodium and chloride are observed in the underlying aquifer (data not shown).

Cardinal Star Ridge Site

The resulting DFs accurately (100%) identified the differences between OAE-1002 and FGD gypsum leachate in both sulfate and boron signatures. The Sulfate-Boron signature biplot is shown in Figure 2 (c). Also included in the figure are the data points representing the OAE-1002 water samples collected during and post reclamation.

As shown in Figure 2 (c), the sulfate and boron signatures of OAE-1002 all deviated from the background (grey circles) after the backfilling began (grey and black dots). For the samples collected after the reclamation was completed (black dots), the signatures became similar to the signatures of the porewater in the FGD gypsum fill (OAE-1504S). The observation indicates the water quality of the underlying shallow aquifer has been affected by the leachate from the backfilled FGD gypsum.

Among all monitoring wells, OAE-1504S has the highest concentrations of Ca, sulfate, and B, which is attributable to the weathering of the backfilled FGD gypsum. After reclamation was completed, not only the concentrations of these constituents at OAE-1002 started increasing, the equivalent ratios of Ca to sulfate (Ca/SO_4^{-2}) also increased and became similar to the ratio observed in the fill (MW-1504S) (data not shown).

Environmental Implication

The water quality data were compared to the primary drinking water standards, i.e., maximum contaminant levels (MCLs) or action levels. A statistical summary of the data is shown in **Table 1**. As shown in the table, at both Conesville and Cardinal sites, As and Sb in at least one of the water samples collected after the reclamation was completed exceeded the respective drinking water standards. Five out of the total 95 water samples showed F exceeding the MCL at the Cardinal site. None of the water samples exceeded the drinking water standards for Ba, Be, Cd, Cr, Cu, Hg, Pb, and Se.

Both As and Sb are within the naturally occurring background levels. After the reclamation was completed, the water samples collected from the porewater of the FGD gypsum fill (OAE-1504s) contained the highest fluoride concentration among the ones collected from other wells, ranging from 1 to 6 mg/L. The concentration range is slightly higher or similar to the ones observed in the background levels (Figure 3). No fluoride exceedance was observed in the downgradient underlying aquifer (OAE-1001 and OAE-1002) after reclamation was completed.

Conclusion

At both demonstration sites, the change of local hydrogeological condition from reclamation activities, such as logging, grading, dewatering, and backfilling, likely caused temporary and some permanent water quality changes. However, at the Cardinal site, the effect of CCR leachate from the reclaimed highwall pit on the water quality of a hydraulically downgradient well was later detected. Higher concentrations of B, sulfate, and calcium were observed. Currently, no constitutes have exceeded the regulatory leaching limits set by the state agency for utilizing CCRs in mined land reclamation. In addition, the concentrations

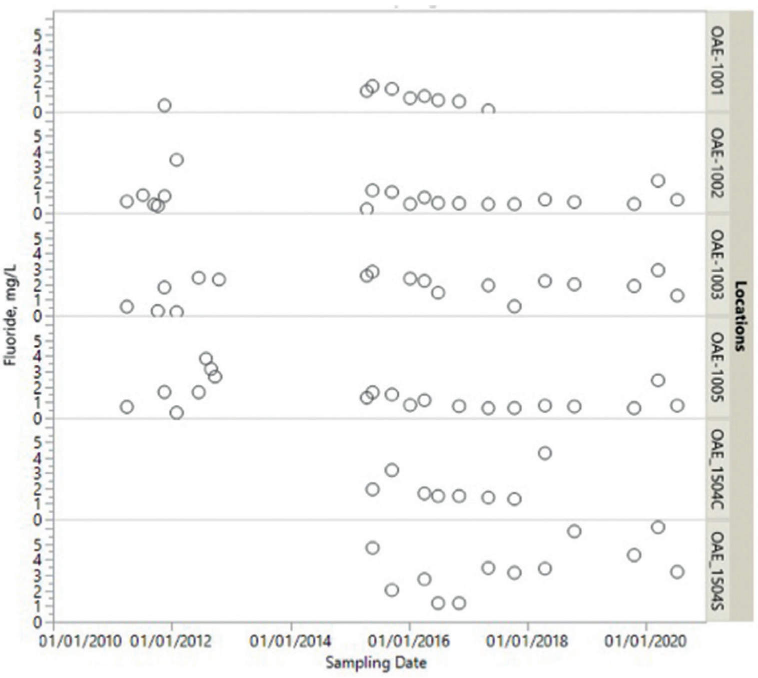

***Figure 3** Temporal trends of fluoride at Cardinal Star Ridge site.*

***Table 1** Statistical summary of constituents of concern in water Samples collected after reclamation was completed.*

		As	Ba	Be	Cr	Cd	Cu	Hg	Pb	Se	F	Sb
		µg/L	mg/L	µg/L	µg/L	µg/L	µg/L	ng/L	µg/L	µg/L	mg/L	µg/L
100.0%	maximum	19.6	1.630	0.390	9.70	4.50	1.10	17.6	4.70	15.60	0.93	80.0
75.0%	quartile	4.3	0.117	0.200	0.63	1.40	0.20	3.4	0.06	2.40	0.40	23.1
50.0%	median	2.0	0.043	0.106	0.10	0.08	0.10	2.3	0.03	0.09	0.22	16.9
25.0%	quartile	1.3	0.019	0.010	0.08	0.02	0.06	1.6	0.02	0.05	0.10	0.05
0.0%	minimum	0.4	0.007	0.004	0.03	0.01	0.03	0.7	0.01	0.03	0.04	0.02
Total N of Samples		94	94	94	94	94	94	94	94	94	94	94
N of detectable		62	94	26	74	70	44	17	31	28	77	48
MCL		10	2.00	4	100	5	1300*	2000	15*	50	4	6
% higher than MCL		8.5	0	0	0	0	0	0	0	0	0	83.0
Cardinal Star Ridge												
100.0%	maximum	14.0	0.400	0.058	7.00	1.00	3.20	28.2	4.60	11.00	6.07	38.0
75.0%	quartile	2.7	0.066	0.045	2.00	0.60	1.51	4.3	0.56	8.60	2.22	25.0
50.0%	median	1.9	0.047	0.030	2.00	0.50	0.62	1.7	0.06	1.00	1.41	19.0
25.0%	quartile	0.9	0.022	0.010	1.00	0.02	0.14	0.9	0.02	0.20	0.76	17.0
0.0%	minimum	0.6	0.011	0.010	0.11	0.01	0.03	0.2	0.01	0.07	0.10	8.0
Total N of Samples		95	95	95	95	95	95	95	95	95	95	74
N of detectable		20	95	6	42	19	23	46	20	15	67	62
% higher than MCL		1.1	0	0	0	0	0	0	0	0	5.3	83.8

Unit: mg/L except for Hg (ng/L); * Action Level of eleven selected constituents of concerned in all of the water samples remained at comparable levels with the local aquifers. The water quality monitoring is still ongoing at both sites to evaluate long-term effect. This study helps validate and improve current safeguards in permits authorizing CCRs placement in coal mines. The placement of virgin CCR materials under the permitting and performance standard requirements at mine sites, can result in a positive impact to human health and the environment when it is used to mitigate pre-existing mining hazards. With the passage of the CCR regulations, greater emphasis has been placed upon utilizing CCRs within mine reclamation practices to ensure that water quality is not impaired.

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