Short- and Long-Term Behavoir of Fixated FGD Material Grout at the Roberts-Dawson Mine

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Abstract

Here we examine both the short- (~ 1 year) and long-term (~ 4 years) behavior of fixated flue gas desulfurization (FGD) material grout following placement within an underground coalmine. Immediately after grout injection, significant increases in acidity, Fe, Al, S, and Ca were observed for most of the surface and groundwater monitoring locations near where grouting was carried out. However, after four years, the long-term fluxes of acidity, iron, sulfur and calcium were only slightly elevated compared to pre-grout conditions. We suspect that the initial increase in discharge of inorganic elements was due to dissolution of accumulated iron and aluminum sulfate salts and ferrihydrite within the mine voids following the increase in water level and/or rerouting of drainage flow. The long-term discharge of these constituents was likely controlled by the continued dissolution of these soluble salts as well as grout material (for Ca and S). Although the long term fluxes of some elements from the main seeps were slightly elevated, no measurable deleterious short- or long-term impact was observed for the underlying groundwater or adjacent surface water reservoir. Mineralogical analyses indicate that the fixated FGD material grout injected into the Roberts-Dawson mine was geochemically stable and groundwater sampling showed that the grout could locally neutralize mine drainage. However, a grouting strategy that minimizes the dissolution or transport of accumulated soluble salts within the mine voids upon changes in water flow paths is likely needed in order to bring about significant improvements in seep water quality.

Introduction

In a 1999 Report to Congress (USEPA 1999), the United States Environmental Protection Agency (USEPA) rule that coal combustion by-products (CCBs) not be regulated as a hazardous waste under Subtitle C of the Resource Conservation and Recovery Act, but excluded from this determination the placement of CCBs in deep mine environments. The report noted that the presence of acid mine drainage in deep mine environments may consume the acid neutralizing capacity of the CCBs and result in prolonged release of contaminants. Further, placement of CCBs in deep mines located beneath a regional water table could result in contamination of drinking water supplies. Prior to a final determination, the USEPA recommended more information be gathered related to the risks associated with the placement of CCBs in deep mine environments.

This paper represents a summary of the Roberts-Dawson project, a project focusing on the injection of a fixated FGD material grout in an abandoned underground coal mine in central-eastern Ohio. This paper presents a discussion of the characterization of the mine site, site geology and hydrogeology, FGD material placement design considerations, methods of FGD material placement and monitoring. Finally, a summary of the engineering lessons learned is presented. This paper is based on a number of previous documents which describe various aspects of the Roberts Dawson project (Bair and Hammer 1999; Damian and Mafi 1999; Laperche and Traina, 1999; Walker et al. 1999; Lamminen et al 1999; Whitlatch et al. 1999; Metheny and Bair; 2000; Lamminen et al. 2001; Whitlatch et al. 2002; Walker et al. 2002; Taerakul et al. 2003; Taerakul et al. 2004). The reader is referred to these documents for a more thorough description of the data and conclusions presented here.

Characterization of Mine Site

The mine drainage abatement project was carried out at the Roberts-Dawson coal mine which borders Coshocton and Muskingum counties in central-eastern Ohio. The mine was abandoned in the 1950s. Approximately 2 million cubic feet of coal were removed from the mine during the period of operation. The mine covers an area of approximately 14 acres. The mine is designated Mm-127 in the Ohio Department of Natural Resources (ODNR) registry.

There are four adits at the site which drain into a small un-named stream. The un-named stream enters a collection pond and eventually drains into Wills Creek Reservoir. Wills Creek drains to the Muskingum River.

Site Geology and Hydrogeology

This section contains a general description of the geology and hydrogeology of the Roberts-Dawson site. A more complete description is provided in Bair and Hammer (1999). The general topology of the site consists of steep hillsides ranging in elevation from 730 to 1100 feet above mean sea level. The geology consists primarily of interbedded, fine-grained sandstones, shales, claystones, limestones and coal. The geology can be conceptualized as consisting of three primary layers; an upper Clarion sandstone layer, a middle Kittanning #6 coal layer, and a lower Freeport sandstone layer. The coal seam is approximately 2-5 feet depending on location at the site.

The regional water table is present in the lower Clarion sandstone layer, while the coal and Freeport sandstone layers contain perched aquifers. The general direction of groundwater flow at the site is downward, except for preferential flow paths within the mine voids.

FGD Material Placement and Design Considerations

The goal of the design at the Roberts-Dawson site was to seal the major mine entrances and coat exposed iron sulfide surfaces utilizing two different mixtures of FGD material. The hypothesis underlying this design was that the sealing of the major seeps would reduce the drainage flow and raise the water table within the mine voids, thereby reducing the levels of dissolved oxygen. Coating iron sulfide surfaces within the mine voids would further reduce the exposure of these surfaces to oxygen. Reducing the exposure to oxygen would then limit the oxidation of iron sulfides, and therefore, reduce the dissolution of these materials and the formation of acid mine drainage.

To accomplish this goal, two types of FGD material grout were used; a high strength grout and a lower strength grout. The FGD material grout used at the site consisted of a 1.25:1 mixture of fly ash and dewatered scrubber sludge (filter cake) with an additional 5% CaO. Different amounts of water were mixed with the grout to alter the strength and flow characteristics of the material. The high strength grout was used to create a "plug" at the known mine entrances. The high strength grout was designed to have a strength of 145 lb/in.^{2} and the actual strength as tested in the laboratory was 284 lb/in.^{2}. The goal in using the high strength grout was to completely fill the mine voids near the entrances of the mine. Bore-hole cameras were used during the time of grout placement, and showed that the high-strength grout effectively filled the mine voids near the injection wells. The lower strength grout, on the other hand, was used to coat exposed pyritic surfaces within the upper reaches of the mine voids, rather than completely filling the mine voids. The design strength of the lower strength grout was 75 lb/in.^{2} and the strength of the grout used was determined to be 171 lb/in.^{2}.

The design of the high strength FGD material plug was based on a "blow-out" force analysis as well as consideration of the required friction necessary to keep the plug in place. The force analysis was used to determine the design strength of the high strength FGD material with a safety factor of 4-6. Forces considered included the water pressure due to the maximum expected increase in groundwater elevation and the weight of the soil.

Methods of Placement

The placement of the high- and lower strength grouts took place between August 27, 1997 and January 26, 1998. The grout mixing and injection was carried out by an outside contractor (Gunite Construction Company). Fixated FGD material from the Conesville Power Plant was mixed with water on site. Injection holes were grouted by pumping the grout from the mixer site and allowing the grout to move via gravity flow into the drilled holes.

A total of 318 vertical grout holes were drilled and grouted at the site. In addition, 5 horizontal drain pipes at the old mine entries were also grouted. A total of 41,859 linear feet were drilled and 23,778 cubic yards of grout placed. The majority of drilled holes were filled to refusal with the high strength grout. Lower strength grout was injected in the upper portions of the mine void until refusal or a predetermined volume. A significant fraction of the drilled holes (~200 out of 218) took 10 cubic yards or less of grout.

The grouting process was complicated by the presence of an area of unmapped mine voids (~7 acres). After the initial grouting described above was completed, water continued to flow from some of the adits of the unmapped area (site 3 on Figure 1). To reduce or eliminate this flow, pressure grouting of 20 holes was conducted directly above the mine openings. Water flow continued after this initial pressure grouting, so pressure grouting in the drain pipes was then carried out. This final pressure grouting stopped flow and resulted in an increase in water elevation within the voids of the coal layer. However, due to effective sealing of the adit and the

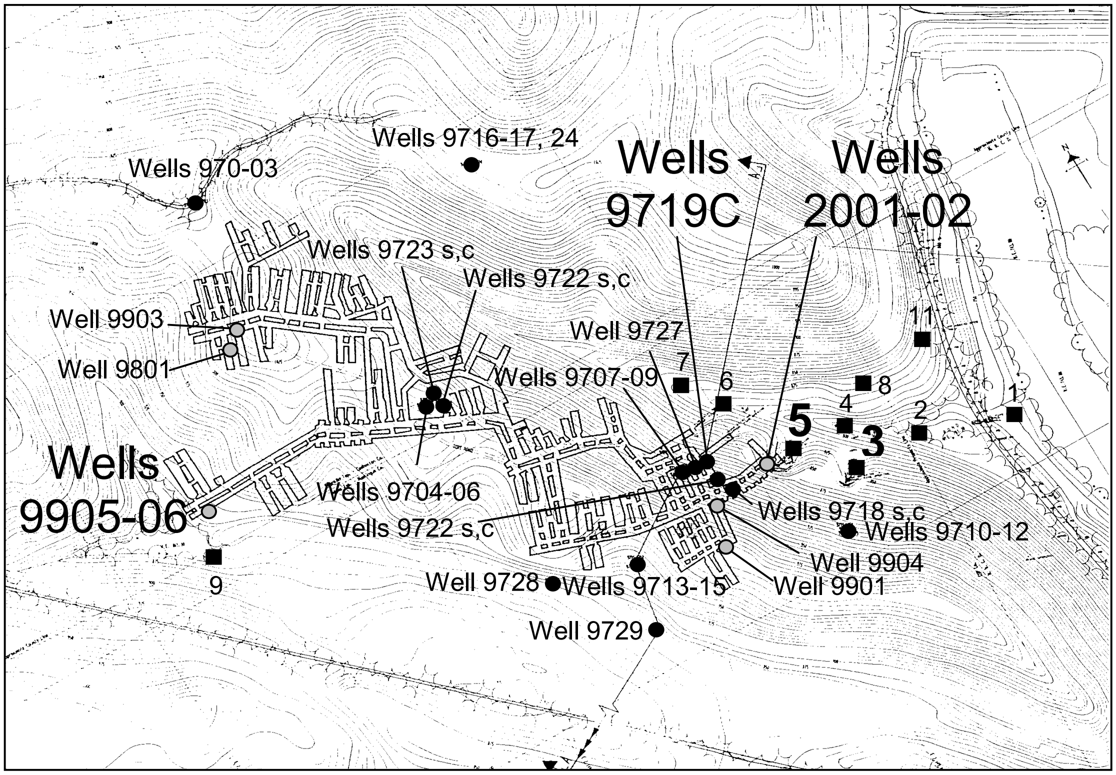

Figure 1 Groundwater and surface water sampling locations at the Roberts-Dawson mine.

buildup of water, a leak in the plug developed as water escaped through a sandstone layer approximately 8 feet above the mine roof. This created a 4 ft. x 3 ft. deep channel due to the erosion of the top edge of the clay bulkhead at the mine entry. Engineering calculations and observations at the site suggested that the mine seal was functional and not the cause of the leak.

Monitoring

Sampling and Analysis Methods

Water quality samples were collected from seeps and groundwater wells for over 4 years, from January 1997 through September 2001. Figure 1 shows the monitoring locations at the site. Groundwater samples were collected from the upper Freeport sandstone layer, the middle Kittanning coal layer as well as the lower Clarion sandstone layer. Monitoring results from the main seeps (sites 3 and 5) and select groundwater wells within the coal layer will be presented here.

Both filtered and un-filtered (0.45 micron cellulose acetate filters) samples were collected on-site and then analyzed for a host of inorganic compounds including Al, Ba, Be, B, Cd, Cr, Ca, Co, Cu, Fe (total and dissolved), Pb, Li, Mg, Mn (total and dissolved), Mo, Ni, P, K, Si, Na, Sr, S, and Zn. Trace metal analysis was conducted by using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) system. Arsenic was analyzed by using a Zeeman Graphite Furnace Atomic Absorption (GFAA) Spectrometer. Sulfate and chloride were determined by using a Dionex Ion Chromatography (IC) model DX-500 with AS-11 anion column. Alkalinity

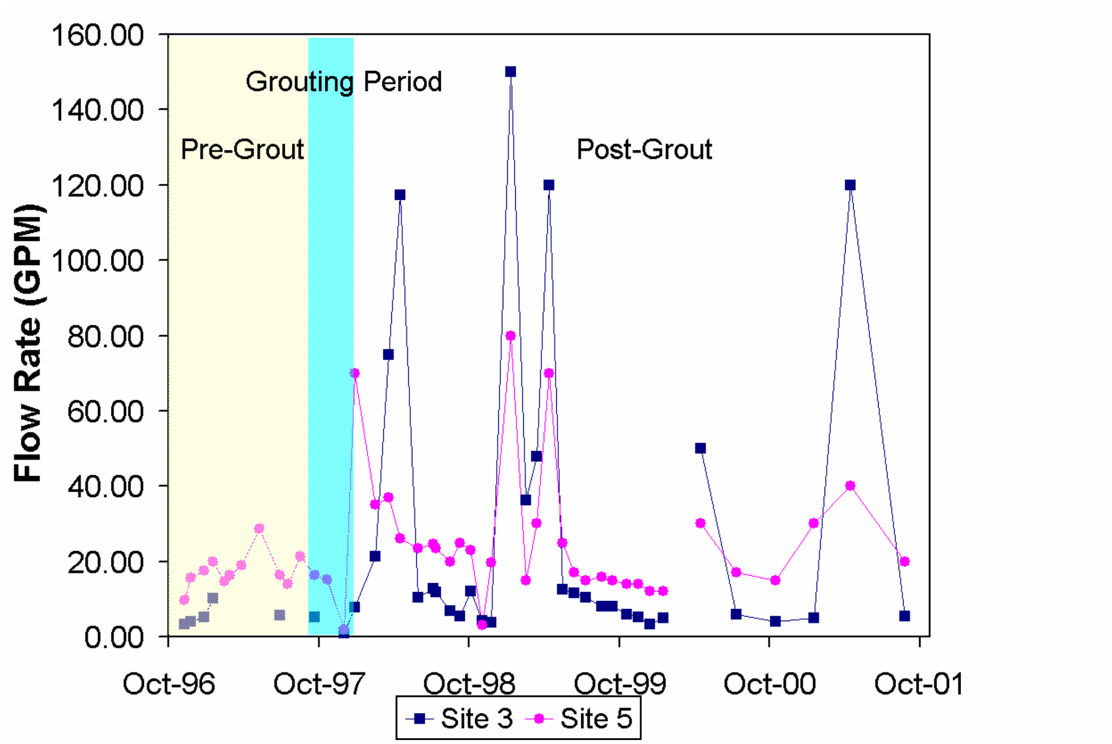

Figure 2. Surface water flow rates at the main seeps of the Roberts-Dawson mine.

analysis was conducted by a titration method using hydrochloric acid and bromocresol green as an indicator. pH measurements were carried out using an ATI Orion pH meter. Conductivity and total dissolved solid measurements were performed using a Fisherbrand conductivity meter. The measurements of pH and conductivity were conducted either at the site or in the laboratory immediately upon returning from field sampling.

Water levels in groundwater wells were measured with a Heron Water Level Probe (Hamilton, OH). Prior to sample collection, wells were purged using either dedicated submersible Redi-Flow™ pumps (Ben Medows Company, Canton, GA) or by using a Reel E-Z portable well pump (Redmond, WA). Some wells were purged manually using disposable one-liter, high-density polyethylene bailers (Timco Manufacturing, Prairie Du Sac, WI). Stream flow rates were measured using the "bucket and stopwatch" technique for low flow rates and weirs installed at the site for high flow rates.

Core samples were also collected at the site 2-3 years following injection of fixated FGD material grout. Core samples were analyzed using a Philips Analytical x-ray diffractomer (Natick, Mass.). Prior to analysis, grout core samples were air dried and ground to less than 250 microns. After collection of core samples, monitoring wells were installed.

Short- and Long-Term Water Quality Trends

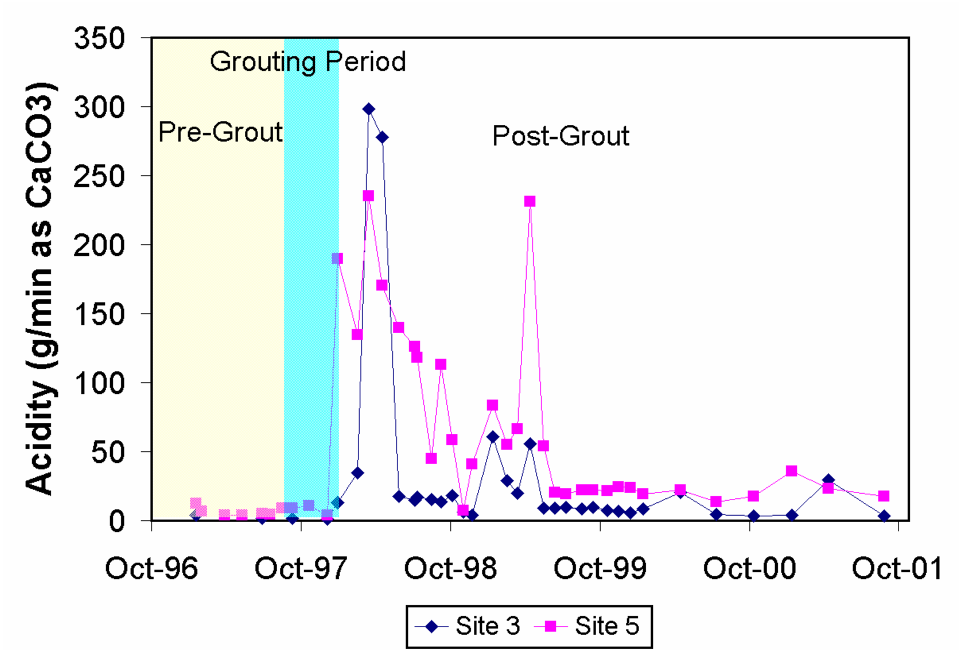

Figure 3. Acidity as a function of time at the two major seeps

The flow rates of water exiting the two major seeps at the Roberts-Dawson site, before and after grouting, are shown in Figure 2. As can be seen, significant flow occurred after grouting. The cause of the flow for site 3 was described above and was due to erosion of the sandstone layer above the mine roof. Subsequently, a drainage pipe was installed at this location to prevent further erosion around the FGD material plug. The flow at site 5 also increased after grouting. The increase in flow at this site was due to the emergence of a new drainage seep, approximately half way between the original mine entrance and the receiving stream.

Figure 3 shows the levels of acidity in the two major seeps before and after grouting operations. As can be seen, significant increases in acidity occurred at both seeps immediately after grouting operations. These high acidity concentrations then decayed to levels similar to before grouting operations began. Similar trends in both the concentrations and fluxes of Al, B, Ca, Co, K, Li, Fe, Mg, Mn, Ni, Pb, S, Si, Sr, and Zn were also observed in surface water samples collected from the main seeps exiting the mine voids as well as in groundwater wells installed within the coal layer.

Field data and geochemical speciation calculations suggested that the increase in concentration of a number of these elements immediately after grouting was at least partially due to re-routing of mine drainage waters and the dissolution of accumulated metal salts previously present within the mine voids (Lamminen et al. 2001). For example, iron containing solids including Jarosite-K and a number of iron hydroxides had saturation indices orders of magnitude above saturation, suggesting these were important solids controlling the solubility of iron in the mine drainage waters. This is consistent with previous studies by Nordstrom (Nordstrom 1982; Nordstrom and Ball 1986) who found that the levels of iron and aluminum in mine drainage waters below pH 4.5 are controlled by the dissolution of evaporated metal salts such as aluminite, jurbanite, siderotil, coquimbite, and basaluminite. Also, groundwater flow into previously inaccessible areas could provide new exposed surfaces for pyrite oxidation.

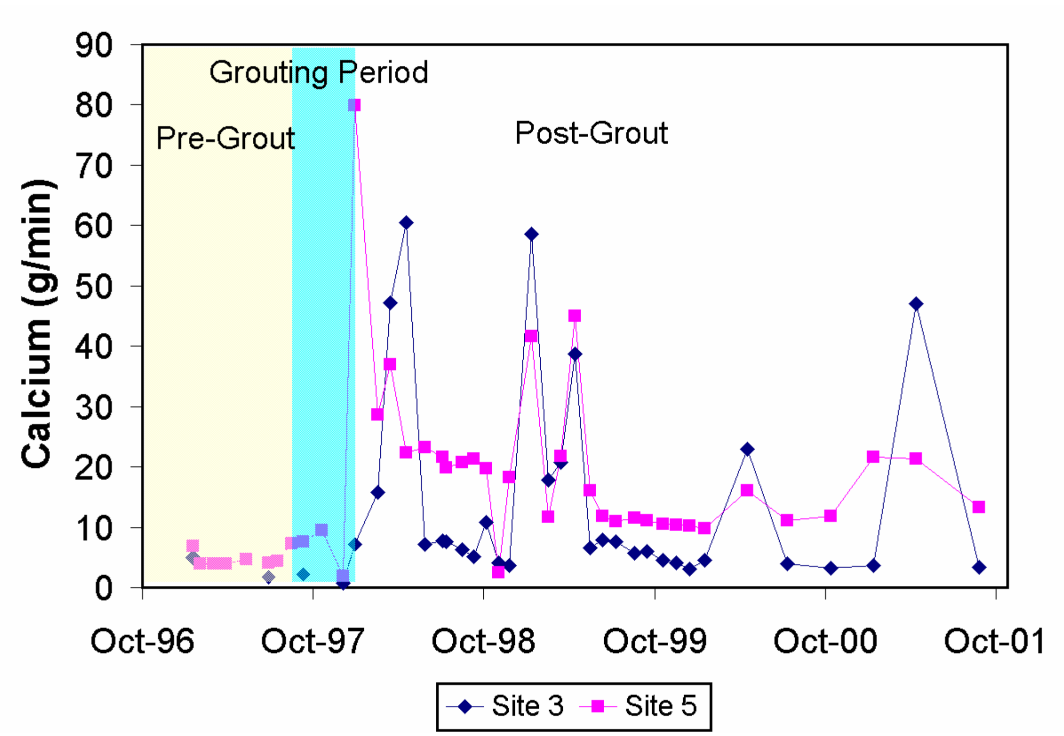

Figure 4. Flux of calcium at sites 3 and 5 at the Roberts Dawson site.

As indicated above, high concentrations and fluxes of calcium and sulfur were also observed immediately after grouting, followed by a decrease to near pre-grouting levels. Figure 4 shows the flux of calcium at sites 3 and 5 before and after grouting. Previous laboratory studies have shown that AMD may accelerate the dissolution of FGD material grout. Thus, the high levels of calcium and sulfur immediately after grout may be partially attributable to dissolution of the FGD material grout. However, the re-routing of mine drainage waters within the voids also may have resulted in the exchange of calcium or the dissolution of calcium from the bulk soil. Also it is evident from Figure 4 that the flux was dependent on seasonal factors. In particular, strong precipitation events typically in January and April resulted in the highest flux values.

Two monitoring sites were selected to assess the impact of the Roberts-Dawson project on the regional groundwater table (Site 9727) and Wills Creek Reservoir (Site 12). Except for Mn, all parameters throughout the duration of the project generally met all relevant primary and secondary drinking water standards, including pH, TDS, sulfate, As, Al, Ba, Be, Cd, Cr, Cl, Cu, Fe, Ni, Pb and Zn. Although Mn concentrations were generally above the established MCL, the concentrations were not significantly greater after grouting than compared to before grouting. It should also be noted that the MCL values were not established as regulatory limits for the project. This analysis simply demonstrates that the project had no detectable deleterious impact on the water quality of the surrounding surface and groundwater.

Table 1. Water quality in wells in the downdip area of the mine, installed either before (9719) or after (2002) grouting operations. Water quality data for one well (9906) installed in the upper mine works after grouting are also shown. Concentrations are in mg/L, unless noted. All concentrations correspond to average values over the period April 2000 to September 2001. The number of sampling dates (n) recorded for each well during this period is shown in parentheses.

Parameter	9719 (n=5)	9906 (n=6)	2002 (n=4)
Acidity (mg/L as $CaCO_3$)	284 ± 34	9.1 ± 4.6	21.1 ± 36.7
Alkalinity (mg/L as $CaCO_3$)	nd	262 ± 98	8.7 ± 3.1
pH (pH units)	4.1	10.2	5.9
Conductivity (μS/cm)	1431 ± 135	1786 ± 186	330 ± 109
TDS	956 ± 91	1194 ± 124	217 ± 77
As (ppb)	5.1 ± 2.1	61.2 ± 17.5	nd
Al	3.75 ± 1.11	1.501 ± 0.864	0.216 ± 0.419
B	0.297 ± 0.030	0.398 ± 0.057	0.073 ± 0.049
Ba	0.004 ± 0.001	0.020 ± 0.010	0.021 ± 0.012
Be	0.001 ± 0.001	nd	nd
Cd	0.021 ± 0.028	nd	nd
Ca	184 ± 14	78 ± 48	36 ± 12
Cl	27.6 ± 9.1	409.4 ± 64.6	10.2 ± 5.3
Cr	0.001 ± 0.002	0.002 ± 0.003	nd
Cu	0.093 ± 0.089	nd	0.007 ± 0.010
Fe (dissolved)	94.2 ± 10.7	0.246 ± 0.525	6.9 ± 12.4
Mg	40 ± 5	7.6 ± 16.5	10.2 ± 4.6
Mn (dissolved)	2.74 ± 0.44	0.077 ± 0.148	0.59 ± 0.61
Na	25 ± 3	93 ± 40	4.1 ± 1.7
Ni	0.045 ± 0.015	0.003 ± 0.006	0.008 ± 0.011
Pb	0.010 ± 0.022	0.010 ± 0.013	nd
S	284 ± 24	71 ± 17	44 ± 24
Si	17.15 ± 1.82	2.86 ± 0.83	6.84 ± 2.07
Zn	0.101 ± 0.009	nd	0.020 ± 0.017

Long-Term Geochemical Stability of FGD Material Grout

Previous laboratory studies and the field data suggested the potential for FGD material grout dissolution. To examine the stability of the grout, core samples were collected in both the upper portions and down-dip portions of the mine void areas. The core sample collected at the site of well 9906 had a fluid, paste-like consistency. The x-ray diffraction pattern for this sample indicated the presence of hannebachite, ettringite, quartz, ferrihydrite and gismondine. The presence of ferrihydrite clearly indicates the reaction of the FGD material grout with mine drainage waters either during or after grout placement. The core sample collected in the downdip area of the mine voids at site 2002 was much harder than the core collected from site 9906. The core was dominated by hannebachite and ettringite with lesser quantities of quartz. The lack of any iron hydroxide phases indicates little or no penetration of mine drainage waters into the FGD material grout at this location. The long-term persistence of hannebachite in these core samples is noteworthy as it suggests minimal altering of the fixated material grout.

Water in Vicinity of FGD Material Grout

Monitoring wells were installed following collection of core samples to better understand the chemical interactions occurring within the grout material. Data for two of these monitoring wells (9906 and 2002), along with data from a well installed prior to grouting (well 9719) are shown in Table 1. In general, monitoring wells installed following core sample collection (i.e., well 2002) had higher pH, higher alkalinity and lower trace element concentrations than water collected from wells installed within coal pillars prior to grouting operations (i.e., well 9719). Exceptions to this were the concentrations of Ca and B which were higher in wells installed following grout core collection, which likely reflects the greater contribution of the FGD material to the solution properties. These data indicate that the mine drainage waters were partially neutralized within the immediately vicinity of the grout.

Lessons Learned

From the results observed from this project, a number of lessons were learned which may prove useful in future projects involving the injection of fixated FGD material grout into underground coal mines.

- Core samples of fixated FGD material grout injected into the downdip portions of the Roberts-Dawson mine had strengths exceeding the design strength, and therefore, the hardening of these samples was not significantly affected by the presence of AMD.
- Injection of grout, such as fixated FGD material, into underground mines can result in significant re-routing of mine drainage flow which may release previously accumulated metal salts deposited on the mine floor and walls.
- Since the water flow rate at both major seeps was not reduced, complete filling of mine voids with fixated FGD material may be a better solution to eliminate the formation of AMD water. Bypassing of AMD water under a grout seal could potentially be prevented by adding a high strength fixated FGD material grout trench, starting at the mine openings and extending vertically downward.
- Bore hole cameras indicated that the grout had good flowability, however, it was likely that portions of mine voids were inaccessible to the grout. A multistage grouting approach could help to provide more extensive coverage of the grout and eliminate the water flow paths in the coal layer. Borehole tomography surveys could also be useful to determine the extent of inaccessible regions.
- After the seeps were sealed, accumulated salts in previously inaccessible regions were flushed out. This flushing process could be reduced by starting grouting at the upper mine works instead of near the mine entry points.

Acknowledgement

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References Cited

Bair, E. S., and Hammer, M. J. (1999). ”Injection of FGD grout to mitigate acid mine drainage at the Roberts-Dawson underground coal mine, Coshocton and Muskingum Counties, Ohio, Volume 2: Site geology and hydrogeology.” The Ohio State University, Final Technical Report submitted to Ohio Coal Development Office, State of Ohio, Columbus, Ohio, May 3, 1999.

Damian M. T. and S. Mafi (1999) “Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 5: Grouting Operations”, Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, May 3, 1999.

Lamminen, M., Wood, J., Walker, H. W., Y.-P. Chin, Y. He, and S. Traina (2001) “Effect of Flue Gas Desulfurization (FGD) By-Product on Water Quality at an Underground Coal Mine”, J. Env. Quality, 30, 1371-1381.

Lamminen, M., Walker, H. W., Wood, J. and Y.-P. Chin, “Acid Mine Drainage Abatement Using Flue Gas Desulfurization By Product: Water Quality Aspects,” Proceedings of the International Ash Utilization Symposium, Lexington, Kentucky, October 18-21, 1999.

Laperche, V. and S. J. Traina (1999) “Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 7: Grout Weathering and Chemical Characterization”, Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, May 3, 1999.

Metheny, M. A. and E. S. Bair (2000) “Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 8: Contaminant Transport Model”, Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, July 26, 2000.

Nordstrom, D. K. (1982) The Effect of Sulfate and Aluminum Concentrations in Natural Waters; Some Stability Relations in the System Al_2O_3-SO_3-H_2O at 298 K. *Geochem. Cosmochem Acta*, 46, 681-692.

Nordstrom, D. K. and J. W. Ball 1986) The Geochemical Behavior of Aluminum in Acidified Surface Waters. *Science*, 232, 54-56.

Taerakul, P., Lamminen, M., Walker, H. W., Traina, S. J., and E. Whitlatch (2004) “Long-Term Behavior of Fixated FGD Material Grout in Mine Drainage Environments,” Journal of Environmental Engineering ASCE, 130(7), 816-823.

Taerakul, P., Walker, H. W. and E. Whitlatch, “Injection of Fixated FGD Material Grout at the Roberts-Dawson Underground Coal Mine: Lessons Learned,” Proceedings American Coal Ash Association Symposium 2003, St. Petersburg, FL, January 27-30, 2003.

United States Environmental Protection Agency (1999) “Report to Congress: Wastes from the combustion of fossil fuel. Volume 2. Methods, findings and recommendations.” United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, EPA 530-R-99-010.

Walker, H. W., Taerakul, P., Lamminen, M., Y. He, Traina, S., and E. E. Whitlatch, "Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 9: Groundwater and Surface Water Quality, Years 1-5, and Mineralogical Analysis of Grout Core Samples", Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, February 15, 2002.

Walker, H. W., Wood, J. T., Lamminen, M., Chin, Y.-P., and E. E. Whitlatch, "Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 5: Groundwater and Surface Water Quality", Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, May 3, 1999.

Whitlatch, E. E., Bair, E. S., Chin, Y.-P., Traina, S. J., Walker, H. W., and W. E. Wolfe, "Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 10: Public Abstract and Executive Summary, Phase II", Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, February 15, 2002.

Whitlatch, E. E., Bair, E. S., Chin, Y.-P., Traina, S. J., Walker, H. W., and W. E. Wolfe, "Injection of FGD Grout to Mitigate Acid Mine Drainage at the Roberts-Dawson Underground Coal Mine, Coshocton and Muskingum Counties, Ohio: Volume 1: Public Abstract and Executive Summary", Final Technical Report submitted to the Ohio Coal Development Office, State of Ohio, May 3, 1999.