

EFFECTIVENESS OF LIME KILN FLUE DUST IN PREVENTING ACID MINE DRAINAGE AT THE KAUFFMAN SURFACE COAL MINE, CLEARFIELD COUNTY, PENNSYLVANIA¹

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Abstract: A careful test of alkaline addition combined with special handling has been performed during mining of 27 acres of coal overlain by slightly to moderately pyritic overburden at the Kauffman Mine. Overburden holes indicate alkaline deficiencies of up to 1090 tons CaCO₃/acre. Sulfur contents for 1- to 3- foot intervals average 0.26%S and range up to 4.4%. An adjacent mine produces severe AMD. Lime kiln flue dust, a waste product, was added in amounts adequate to neutralize maximum potential acidity. High-S zones were special-handled into compacted pods up to 2 ft. thick and covered by about 30% of the total lime requirement. About half the lime was spread on the surface prior to blasting and mixed during subsequent handling; the remaining lime was spread on the pit floor and beneath the topsoil.

Over the period up to 1.5 years after mining, water in backfill and monitoring wells has pH of 6 to 7, alkalinity exceeding acidity, and generally low Fe, Al and Mn, indicating that that procedure is a success. However, concurrent experiments with 400-ton test cells indicate that prompt addition of lime, and compaction of the material may be crucial for successful results.

Additional key words: Alkaline addition, acid mine drainage, surface coal mining.

Introduction

Large tonnages of coal in eastern U.S. and elsewhere have appreciable pyritic sulfur in the overburden and are usually not permitted for surface mining under current regulations, because of predicted formation of acid mine drainage (AMD). Overburden with a moderate content of natural carbonate minerals (calcite and dolomite) generally does not produce AMD despite presence of appreciable pyrite, suggesting that alkaline amendments to pyritic surface mine spoil that lacks natural carbonate minerals may prevent acid generation. However, past addition of limestone and lime to spoil during mining has produced mixed results, though most such attempts were not well documented as to the amount and distribution of pyrite, the nature and amount of added alkalinity, and the result of the experiment. The intent of this paper is to describe a carefully planned and conducted experiment on alkaline addition.

Review of Past Attempts to Use Alkaline Addition

An experimental addition of lime kiln flue dust by Waddell et al. (1980) was successful in markedly decreasing AMD from pyritic sandstone excavated for a road cut. Brady et al. (1990) described eight strip mines at which alkaline material was added, usually in amounts only about one-third of the deficiency in neutralization potential (NP) calculated from conventional acid-base accounting (Sobek et al, 1978; Smith and Brady, 1990). Six of the eight sites produced acid after completion of mining, though most showed some decrease in acid production. Two sites, both with positive net neutralization potential prior to mining, produced net alkaline water after alkaline addition.

Geidel and Caruccio (1984) tested a combination of lime addition (39 tons/acre), bactericide, clay capping, and placement of spoil on a limestone pad at a site in central West Virginia. Although tracers indicated

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that the capping inhibited flow of water through the pyritic spoil, seeps from the area remained strongly acid. At another site in West Virginia, several field tests using 400-ton lots of pyritic material treated with various alkaline materials were only partly successful in preventing AMD, based on sampling over an 11-year period (Ziemkiewicz and Meek, 1994). At the Upshur Complex in Upshur County, WV, special handling and alkaline addition (limestone at 30 to 45 tons/acre, quicklime at 250 tons/acre) decreased acid flux by about 50%, but effluent remained very acid (Meek, 1994).

At a 20-year-old strip mine, the addition of 327 tons/acre of limestone to the surface did not lead to any improvement in the acid drainage based on 1 year of monitoring (Lusardi and Erickson, 1985). Burt and Caruccio (1986) suggested on the basis of lab experiments that an alkaline environment initially accelerates the oxidation of ferrous iron and speeds oxidation, but that development of an Feoxide coating in the alkaline environment later slows the reaction.

The above reports indicate that although alkaline addition usually improves water quality, it has been not been consistently successful in stopping AMD production, and that addition of amounts of alkaline material at least adequate to neutralize the maximum potential acidity (MPA, calculated using 31.25 tons CaCO₃/1000 tons per 1%S) is necessary to produce alkaline discharges. Brady et al. (1990) suggest that a factor of 62.5 is more appropriate.

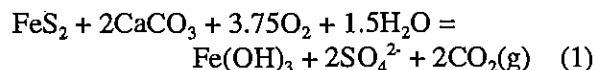
Selective Handling

Selective handling has been well studied and documented. The guidelines of the West Virginia Mine Drainage Task Force (1978) suggest that in contour strip mines the toxic material should be placed as a unit above a non-toxic free-draining layer which has a minimum thickness of 4 feet. Also, where there is a highwall, non-toxic free-draining material with a thickness of at least 10 feet should be placed against it. The toxic material should be placed away from this free-draining zone. The purpose of the free-draining zones is to keep the toxic material out of the groundwater flow region. These toxic zones should be maintained alkaline with the addition of alkaline material. Phelps et al. (1981) suggest additional shaping and compacting, plus capping with low permeability material.

The Pennsylvania Department of Environmental Resources (PA DER) requires that acid-forming material, other than coal refuse, be buried above the groundwater table and a minimum of 5 feet above the base of coal seam elevation. The selectively handled zone should consist of alternate layers of clean spoil with toxic spoil. Each layer of acid-forming material is not to exceed 2 feet in thickness, and each layer of non-toxic spoil is not to exceed 30 inches in thickness. The top layer of non-toxic spoil must be a minimum of 4 feet thick. To meet special local conditions, thicker amounts of non-toxic spoil, compaction and isolation from groundwater contact may be specified (PA DER, 1993).

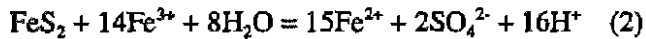
Chemical Theory

The stoichiometry of pyrite reaction with carbonate depends on whether the product is CO₂(g) or HCO₃⁻. If it is the former, the reaction is



In this reaction, 31.25 tons of CaCO₃ neutralize the acid from 1000 tons of rock containing 1% pyritic S. If the reaction product is HCO₃⁻, twice as much CaCO₃ is required (Cravotta et al., 1990), or a factor of 62.5. Lime requires only the 31.25 factor (Rose and Daub, 1994).

Although O₂ is shown as the oxidant in the above reaction, ferric iron (Fe³⁺) is probably the main direct oxidant in forming severe AMD, by the following reaction:



Under acid conditions, Fe^{3+} is formed by bacterial oxidation of Fe^{2+} , using O_2 as the ultimate oxidant. Thus, the rate of pyrite oxidation to make severe AMD is considered to depend most importantly on the rate of bacterial oxidation to produce ferric iron (Fe^{3+}) (Singer and Stumm, 1970; Kleinman et al., 1981). The maintenance of a near-neutral pH limits the solubility of Fe^{3+} to extremely low levels so that pyrite oxidation is slow, and conversely, under acid conditions Fe^{3+} solubility is high so a high AMD generation rate is possible. Therefore, near-neutral pH values are generally considered to inhibit AMD formation.

If an Fe^{3+} -bearing solution contacts calcite or other alkaline materials (dolomite, lime, etc.), the iron will rapidly precipitate:



This $\text{Fe}(\text{OH})_3$ usually precipitates as a coating on the calcite and greatly slows further neutralization by the calcite. Also, if the water has high SO_4 from the acid-generating reaction, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) may be precipitated, also coating the reactant. Thus, influx of alkaline water (derived by dissolution of alkaline material) into a pyritic zone is expected to be more effective in preventing AMD than is neutralization of an Fe-bearing acid solution by encountering alkaline material. This feature indicates that at least some of the alkaline material should be placed above or upflow from the pyritic material.

Geology and Hydrology of the Kauffman Mine

The Kauffman Mine is located in Boggs Township, Clearfield County, 6.4 miles southeast of Clearfield on Highway PA 153 (Fig. 1). Annual precipitation is about 100 cm, approximately equally spaced throughout the year. Mean monthly temperatures range from about 19.4°C in July to -5.5°C in January. The thin sandy soil supports a growth of small hardwoods and brush.

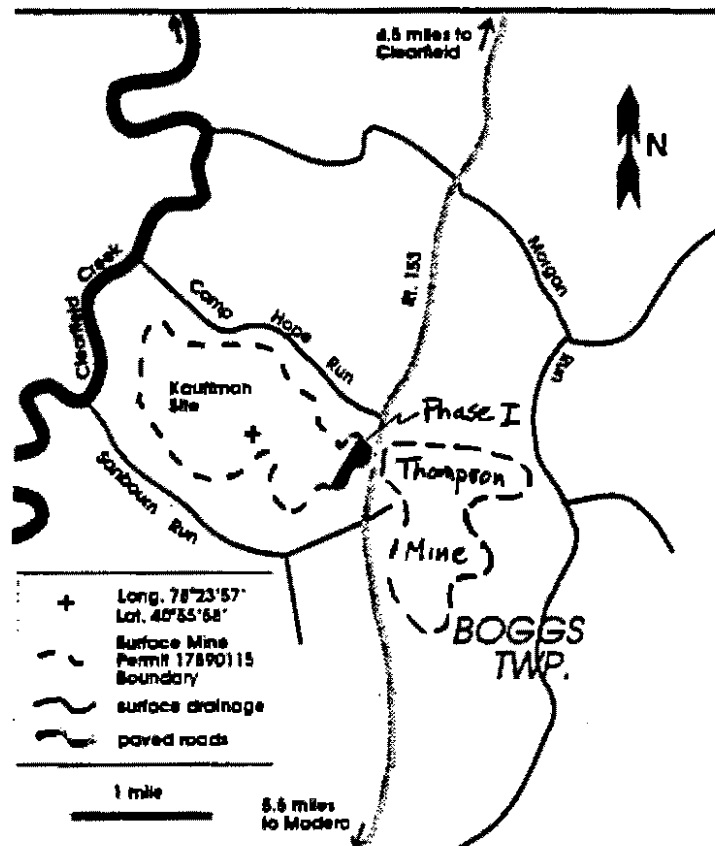


Figure 1. Location map of the Kauffman Demonstration site, Clearfield Co., PA.

The main coal seam mined on the property is the Lower Kittanning coal (LK coal), occurring as two seams about 20 and 10 inches thick separated by a carbonaceous shale about 8 inches thick (Fig. 2). A thin L. Kittanning Rider coal locally overlies the main seam. The LK coal is commonly overlain by 10 to 25 ft. of shale, and then by up to 50 ft. of Worthington Sandstone which underlies most of the hilltop at the site. Beneath the coal is up to several feet of underclay, in turn underlain by shale and the Kittanning Sandstone. Clarion and Mercer coals lie at depths of 60 to 120 ft. beneath the Kittanning sandstone. The sedimentary units dip at a few degrees WNW toward Clearfield Creek. The previously mined John A. Thompson Mine lies east of the Kauffman Mine across Highway 153 and up-dip from it. The LK coal was mined extensively from the Thompson site, which produces severe AMD that contaminates Camp Hope and Sanbourn Runs (Table 1).

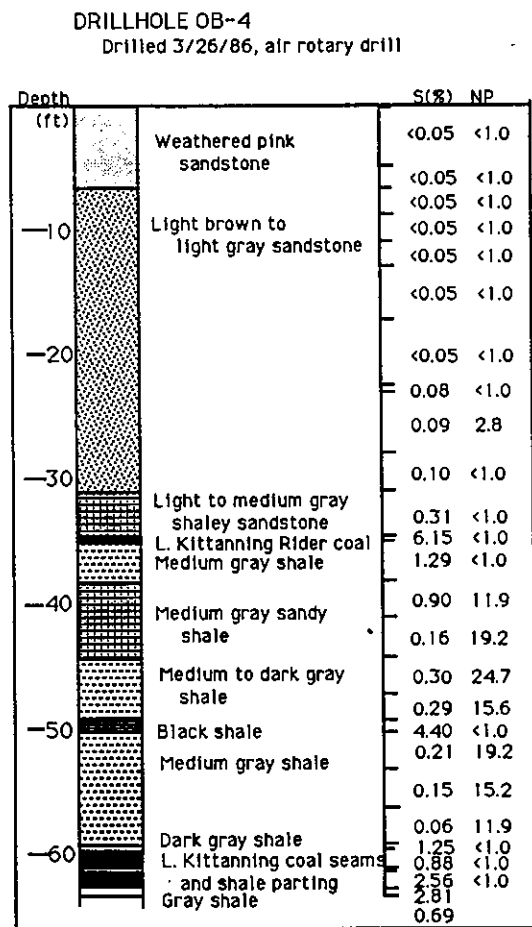


Figure 2. Drill log and overburden analyses of S and neutralization potential (NP) for air rotary hole OB-4.

Table 1. Typical Analyses of Acid Mine Drainage from the Thompson Mine

Constituent	Units	GR441 ¹	N-1 Seep ²	W10A ³
Date		2/12/91	2/90	1/9/91
pH		3.37	3.1	3.8
Cond.	uS	1980	2910	
Acidity	mg/L CaCO ₃	266	320	428
Fe	mg/L	98.8	44.8	
Mn	mg/L	37.9	64.9	
Al	mg/L	28.6		
SO ₄	mg/L	1461	2371	2333

¹ Camp Hope Run at PA Highway 153

² Seep along PA Highway 153 roadcut

³ Water from drillhole W10A at LK horizon in spoil of Thompson Mine

Mining at the Kauffman Mine is planned for several phases, of which only Phase I has been mined to date and is discussed in this report. Phase I lies nearest the highway, and is bounded on the west by a gas pipeline (Fig. 3). Phase I was selected for this demonstration project on alkaline addition because the overburden in this section is essentially lacking in alkalinity but contains appreciable pyrite in some horizons. Thus it would not be permitted for mining under normal policy of PA DER. Also, the area just across the highway at the Thompson Mine is producing severe AMD.

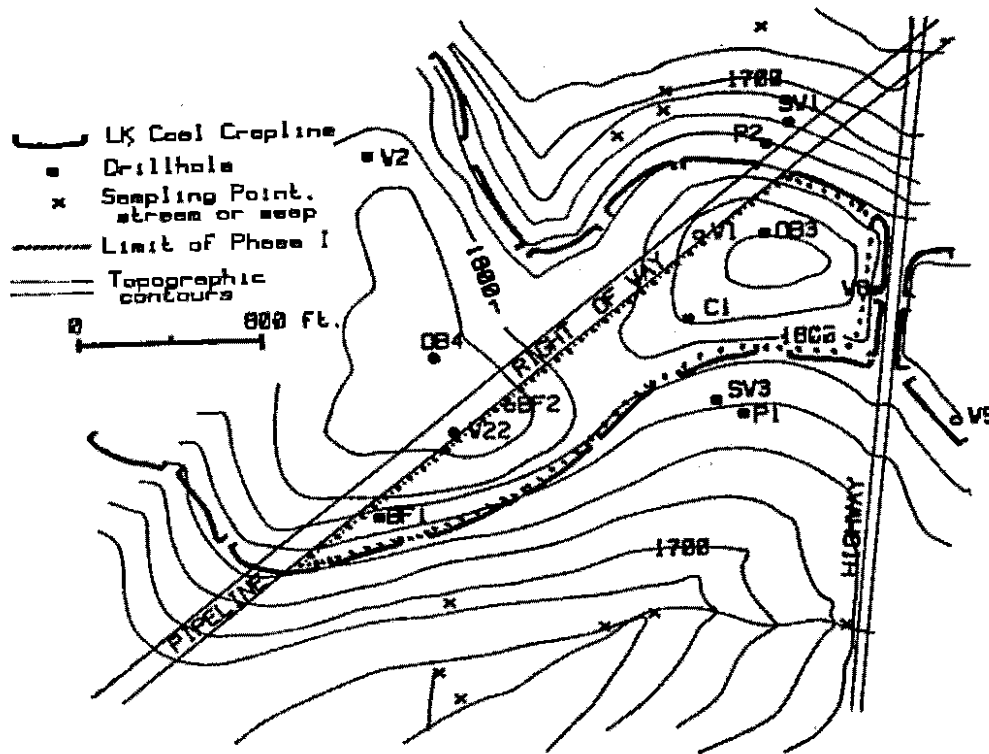


Figure 3. Map of Phase I at the Kauffman Mine, showing coal outcrop, drillholes, seeps, and other features.

Nineteen holes were drilled and analyzed for overburden character on the approximately 1500 acres of the permit. Of these, three overburden holes (OB-3, OB-4, C1) were used to estimate the sulfur and neutralization potential (NP) of the Phase I area (Fig. 2). In general, holes of the OB series (air-rotary drilling) sampled sandstones at 5-foot maximum intervals, and other strata at 3-foot intervals. A- and C- holes (air rotary and core, respectively) utilized a 3-foot interval for all rock types. In addition, samples were cut off at all changes in lithology. The samples were analyzed for total S and NP at Hess and Fisher Engineers, Clearfield, PA for the OB holes, at Geochemical Testing, Somerset, PA, for the A holes, and at Materials Research Lab, Penn State University, University Park, PA for the C holes. The analyses were conducted according to the procedures of Sobek et al. (1978). Additional samples of exposed rock faces were collected in the southern part of Phase I, and analyzed for total S, and one blast hole was sampled during mining, with results similar to those of Figure 2.

Based on tests of 13 nests of wells (W series), coals are the best aquifers, with hydraulic conductivities of 10^{-5} to 10^{-2} ft/day (geometric mean about 10^{-1} ft/d, Abate, 1993). Sandstones are approximately as permeable. Shales and underclays in the region generally are aquitards, with hydraulic conductivities of underclays in nearby areas of 10^{-3} to 10^{-5} ft/d (Booth, 1984). Flow of groundwater is expected to be down the dip to the WNW along the coal beds, on top of the underclays and shales.

Special Handling and Alkaline Addition Plan

The special handling plan for the permit provides as follows:

1. Any strata with a total sulfur percentage of 1.0% or greater and a 3-foot thickness or greater and not located adjacent to the LK coal seam will receive special handling.
2. Strata with a total sulfur percentage of 0.5% or greater and located adjacent to the LK coal seam will receive special handling.
3. Binders and LK pit cleanings not removed with the coal will receive special handling.

The 3-foot thickness requirement for the 1.0% or greater sulfur strata was chosen because lesser thicknesses are difficult to identify and segregate. From an operational standpoint, a decision was made to selectively handle the 10-foot zone at and below the LK Rider seam everywhere it was present.

The alkaline addition was applied as follows:

1. On the pit floor in relatively small amounts not to exceed 100 tons/acre.
2. Around special-handled material pods including between the 2-foot layers in large pods.
3. Around the shot area immediately following a blast to that mixing with overburden occurred during overburden removal. It also served to intercept rainwater and keep the water alkaline.
4. On the backfill prior to topsoil placement. In this instance the alkaline material area was backdragged with a bulldozer following its placement, in order to mix the lime into the spoil and minimize the problem of excess alkalinity in the root zone.

The special placement zones had specific placement requirements (Fig. 4). Special-handled acidic material was placed in 2-foot lifts and compacted with the haulage trucks. Where necessary, additional 2-foot lifts were constructed over the initial lift following compaction and placement of alkaline material. The zones were positioned so as to be at least 10 feet above the pit floor, 10 feet from the highwall and 15 feet below the regraded spoil surface.

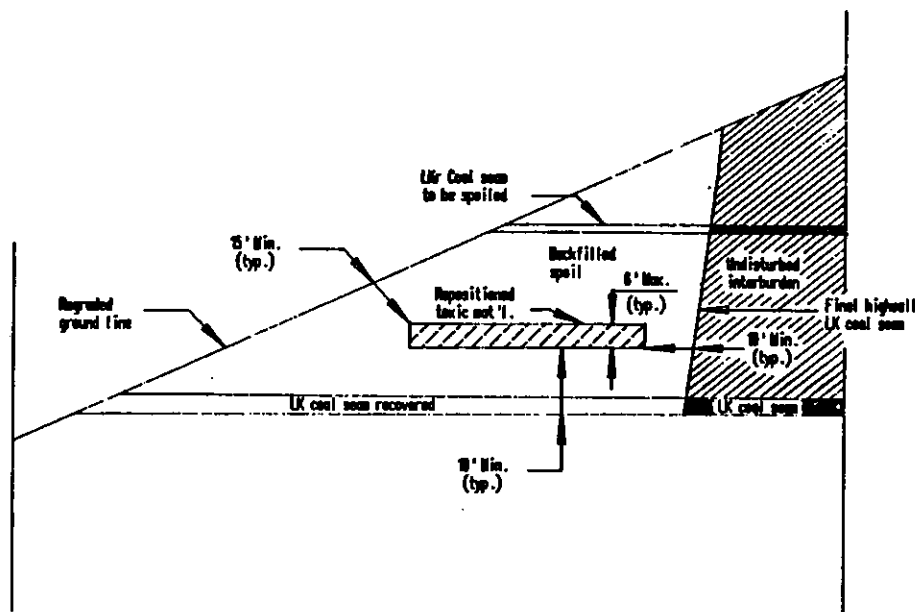


Figure 4. Typical cross-section showing placement of potentially toxic material.

The requirement for alkaline additional was calculated using current PA DER practices, using the spreadsheet program of Smith and Brady (1990). The thresholds used for this calculation are:

1. Only sulfur values > 0.5% are used to calculate MPA.
2. Only samples that fizz with 25% HCl are used to calculate NP.

Areas of influence were calculated for each of the three drillholes, with boundaries midway between the holes. Allowance was made for weathering by not counting any NP within 60 ft. of the surface, based on several holes that showed a lack of NP to this depth, even where nearby holes at the crest of the hill under deeper cover showed appreciable NP. Based on this analysis, the alkaline deficiency for Phase I was calculated to be:

Hole	Area of Influence	Alkaline Deficiency	Req. Alk. Addition
OB4	9.20 acres	1094 tons/acre	10,065 tons CaCO ₃
C1	8.80	43	378
OB3	8.80	169	1,487

Total: 11,930 tons

The drillholes also showed that the S contents requiring treatment occur in the few feet of shale just above the LK Coal, in the binder between the LK seams, and in the LK Rider coal and the first few feet of gray shale below this seam (Fig. 2). These zones were specified for special handling in the area of influence of the OB4 drillhole (the southwestern end of the mined area). In this OB4 area, the alkaline materials was distributed as follows:

Special Handling Zones	145 T/acre-ft.	3257 T CaCO ₃ -equiv.
Pit Floor	100 T/acre	920
Mining Area after Blast	540 T/acre	4968
Prior to Topsoil Placement	100 T/A	920

Total: 10065 T

In the combined OB3 and C1 area, the distribution of alkaline material was: 809 T with special handled material, 352 T on pit floor, 352 T on the mining area after blasting, and 352 T at the surface prior to topsoil emplacement. The special-handled material in this part of Phase I consisted mainly of the binder between the LK seams.

The alkaline material used at the project was baghouse lime, a waste product from lime production at Centre Lime and Stone, Inc., Pleasant Gap, PA. An analysis of this material is shown in Table 2. X-ray diffraction and chemical analysis indicate that this material is composed of about 42% CaCO₃, 28% Ca(OH)₂, 8% quartz, 7% other minerals and 15% moisture (Evans, 1994). The neutralization potential of one lot was 798 tons CaCO₃-equiv./1000 tons of field moist lime; other lots contain somewhat higher values. The lime is gray colored, generally fine grained with some coherence, but sometimes lumpy. A total of 14,250 tons of lime was actually added to the area of Phase I, based on weights of truckloads received at the site.

Table 2. Analysis of lime kiln flue dust added at Kauffman Mine

Constituent	Wt%
SiO ₂	6.57
Al ₂ O ₃	2.32
TiO ₂	0.12
Fe ₂ O ₃	1.58
MnO	0.01
CaO	55.6
MgO	0.79
BaO	0.01
SrO	0.05
Na ₂ O	0.03
K ₂ O	0.28
P ₂ O ₅	0.05
SO ₃	0.9
Loss on ign.	31.8
Total	100.1
Total C	5.95
Neut. Pot.	798 Tons CaCO ₃ /1000 Tons

Analysis by Materials Characterization Lab, Penn State University, and Derek Evans. Sampled in Oct. 1993.

Mining started in June 1993 at the south end of Phase I. A NW-trending box cut was excavated up to the pipeline, and a NW-trending crop cut was taken out for about 1000 ft. along the southern end of the phase. Mining then proceeded as NW-trending box cuts successively to the NE. Total overburden depth ranged from 38 to 61 ft. Site preparation and topsoil removal was completed with a dozer. Overburden blasting was accomplished with a 6-3/4 in. drill. Each blast was 40 holes with an 18-foot burden and 20-foot spacing. In areas where special handling was necessary, drilling and blasting were performed in lifts to get the proper selectivity. A 12 cu. yd. front end loader was used along with 50-ton off-highway rear-dump trucks to move the overburden. Most of the southern 1000 ft. of Phase I, including the area surrounding monitoring well BE-1, was reclaimed with topsoil and planted in fall 1993. The central section was mined during winter and spring 1993-1994, and the north end was mined in summer and fall 1994. At the time of writing (February 1995), the mine is regraded, but only part of the topsoil has been replaced.

Monitoring

The major source of monitoring data has been two air-rotary drillholes in the regarded and reclaimed backfill. These holes were drilled in locations where surveys of the pit floor showed local depressions at the base of the coal that left closed "ponds" on the pit floor, so that drainage through the spoil or flowing down-dip at the base of the spoil would collect against the buried highwall. Hole BE-1 was drilled to a depth of 62 ft. in December 1993 and hole BE-2 drilled to 53 ft. in July 1994 (Table 3). A third such hole is planned in the northern part of phase I. In addition, a suction lysimeter was placed at a depth of 27 ft. in a drillhole adjacent to BE-2. Additional monitoring is provided by holes W-1A and W-22A along the pipeline right of way. These holes are completed in the LK coal and sample any flow down-dip from Phase I. Two shallow wells (SW series) in the weathered zone below the cropline were also drilled, and numerous springs and seeps existing prior to mining have been sampled, starting in 1986. Many of those near Phase I are contaminated by the AMD plume in the Clarion and deeper horizons from the Thompson Mine. No seeps related to Phase I mining have developed, since drainage is flowing down-dip into the highwall.

Table 3. Sulfur and Neutralization Potential for Backfill Drillholes

Hole BF-1				Hole BF-2			
Depth Ft.	S wt. %	Fizz ¹	NP ² T/1000T	Depth Ft.	S wt. %	NP ² T/1000T	
0-2 ft	0.10	1	24.7	0-2	0.05	27.4	
2-4	0.13	0	5.4	2-4	0.22	5.8	
4-6	0.45	0	4.0	4-6	0.23	4.3	
6-8	0.52	0	6.7	6-8	0.14	12.7	
8-10	0.39	0	7.4	8-10	0.28	4.5	
10-12	0.31	0	5.0	10-12	0.28	8.2	
12-14	0.38	0	9.2	12-14	0.18	<1.0	
14-16	0.25	0	10.4	14-16	0.25	<1.0	
16-18	0.34	1	13.1	16-18	0.29	<1.0	
18-20	0.16	1	26.9	18-20	0.22	<1.0	
20-22	0.15	2	57.7	20-22	0.13	<1.0	
22-24	0.05	2	50.4	22-24	0.08	<1.0	
24-26	0.09	2	38.1	24-26	0.09	<1.0	
26-28	0.05	2	18.4	26-28	0.08	<1.0	
28-30	0.04	1	6.7				
30-32	0.04	1	9.9	30-32	0.09	1.5	
32-34	0.05	1	6.4	32-34	0.28	1.3	
34-36	0.09	1	14.3	34-36	0.60	6.7	
36-38	0.84	1	6.9	36-38	0.36	4.7	
38-40	0.04	2	64.5	38-40	0.36	4.7	
40-42	1.51	0	4.2	40-42	0.26	1.7	
42-44	0.28	1	9.6	44-50	0.42	11.3	
44-46	0.12	1	3.5	50-52	0.46	3.7	
46-48	0.07	1	5.9	52-53	0.22	2.0	
48-50	0.03	2	63.9				

¹ Fizz with 25% HCl: 0=none, 1=slight, 2=moderate

² Neutralization potential (Sobek et al., 1978), tons CaCO₃/1000 tons of rock

Note: Poor recovery for most intervals below 40 ft., so results are of lower reliability. Also, some fines may have been blown away during air rotary drilling.

Wells BE-1 and BE-2 have been sampled monthly since drilling, and other wells are being sampled quarterly as long as no contamination is recognized in the backfill wells.

Results

In general, pH in the backfill wells and lysimeter has been between 6 and 7, with alkalinity exceeding acidity. Alkalinity values are up to 350 mg/l CaCO_3 exceptions that appear to result from inadequate filtration. The water quality is generally very acceptable. Sulfate values are up to 590 mg/l, indicating that some pyrite oxidation is probably occurring, but the water is being neutralized by the time it reaches the static groundwater sampled by the drillholes. Relatively high Ca in the water indicates dissolution of lime or reaction with it. The lysimeter in the middle of the spoil at BE-2 indicates strongly alkaline but high-sulfate conditions for water in the unsaturated spoil. Holes W-22A and W-1A have been dry most of the time, presumably because water is drained into the adjacent spoil at these sites. Temperatures at depth in BE-1 and BE-2 are slightly elevated in the unsaturated zone compared to the saturated zone below and the shallow spoil above, also suggesting that some oxidation is occurring (Wilson, 1994).

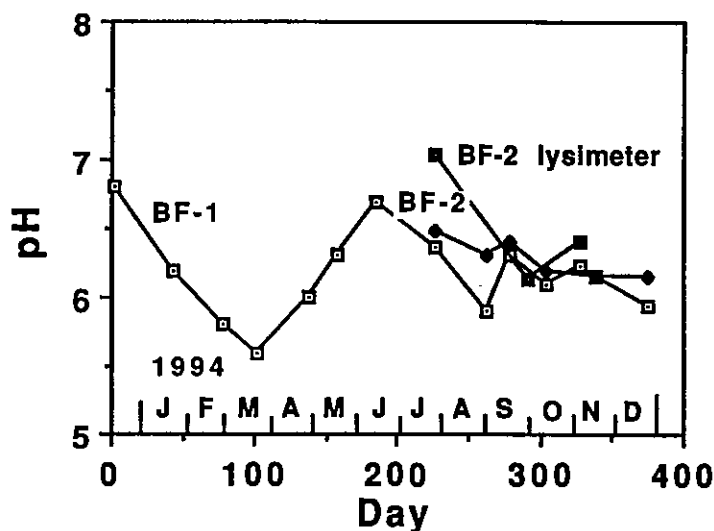


Figure 5. Values of pH for water from backfill wells BF-1 and BF-2 and from a lysimeter at a depth of 27 ft. adjacent to BF-2.

Table 4. Analyses of Backfill Wells

Hole BF-1

Date	Fld pH	Lab pH	Sp Cond uS	T °C	Alk. mg/L	Acid. CaCO ₃ mg/L	Fe mg/L	Mn mg/L	Al mg/L	SO ₄ mg/L	Ca mg/L	Water Depth ft	Splr.
12/10/93		6.81	300	11	37	2	0.81	0.1	1.98	79			H
1/25/94	6.2	6.07	300	9	21	13	0.65	0.65	0.49	91		49.9	H
2/28/94	5.8	6.03	244	8	16	21	0.34	1.33	0.59	57	18	48.9	H
3/23/94	5.62	6.02	146	10	15	12	0.31	0.93	0.61	41	12	47.8	H
4/28/94	6.00	6.78	700	12	103	2	0.19	0.80	1.24	340	149	48.8	H
5/19/94	6.30	6.73	700	12	106	6	0.41	1.03	0.96	309		49.3	H
6/16/94	6.70	6.94	900	13	87	13	0.18	1.72	1.23	268		48.1	H
7/27/94	6.36	6.76	670	13	160	6	0.11	0.51		322	336	48.2	H
8/31/94	5.90	6.19	400	15	58	25	0.06	1.10	0.1	97		48.2	H
9/16/94	6.30	7.97	1400	15	195	18	0.18	0.37		460		49.1	H
10/12/94	6.10	6.80	1300	14	238	21	0.45	0.37		512		49.3	H
11/4/94	6.23		1400	6	220								P

Hole BF-2

7/27/94	6.49	6.39	700	13	132	24	5.03	2.28	0	422		50.8	H
8/31/94	6.30	6.39	1400	15	276	46	1.2	3.7	0	383	167	52.0	H
9/16/94	6.40	6.53	1900	17	195	24	0.14	0.40		458		47.7	H
10/13/94												dry	

BF-2 Lysimeter (27' depth)

7/27/94	7.04		1770	16	140		<1	2.9	<1	1014	434		P
9/29/94	6.14		2200	25	300					888	520		P
10/29/94	6.41		1550	14	360								P

Water depth is depth below collar elevation of 1797.95 for BF-1 and 1812.1 for BF-2.

Sampler: H, Hamilton; P, Penn State

Most analyses by Hess and Fisher, Clearfield, PA

Ca values and some field pH by Penn State

In contrast to these results, a set of experiments (test cells) in which varying amounts of lime were added to 400-ton lots of Kauffman spoil containing 2.0% S produced acid drainage, though much lower acidity than untreated spoil (Evans, 1994; Evans and Rose, 1995). For example, spoil with 170% of the lime requirement (31.25 factor) produced effluent with pH of 2.5 and acidity 4000 mg/l, compared to pH 1.9, and acidity 50,000 mg/l for effluent from untreated spoil.

Several factors are inferred to cause the acidity of effluent from the lime-amended test cells. The pyritic material sat in a pile for about a month before it was mixed with lime and placed in the cells, and it clearly had started to produce acid in this period. The lime could be only partly mixed with the spoil when the 400-ton lots were prepared with a front-end loader, undoubtedly leaving micro-environments that generated acid. The reaction of the AMD with the lime produced gypsum, which appears to have cemented high-lime zones and inhibited water flow through them, as indicated by negligible effluent production from the most highly limed cells starting about

8 months after construction. Also, estimates of the maximum possible rate of Fe²⁺ oxidation by *Thiobacillus ferrooxidans* in comparison to the rate of alkalinity influx from downward-flowing water indicate that bacterial oxidation may easily outpace influx of neutralizing water in micro-environments, once they are started, indicating that such micro-environments may produce significant acid.

The success of the mine-scale experiment indicates that the alkaline addition and special handling approach used in this study can prevent AMD, but the results of the 400-ton test cells and the reports of previous experiments in the literature show that the method requires careful implementation. In particular, it appears that prompt mixing with the alkaline material, and thorough mixing as obtained by adding lime after blasting but prior to handling of overburden may be crucial. The placement of the toxic material in compacted pods overlain by lime may be crucial, both because of compaction and because of cementation of the lime layer by gypsum, as observed in the test cells. The overall effect may be to cause downward percolating water to flow laterally around the pods, thus minimizing generation and transport of acid. The cases of unsuccessful alkaline addition described in the literature probably reflect deficiencies from these requirements.

Conclusions

Based on over a year of monitoring the water in the backfill, the alkaline addition and special handling procedure has been successful in preventing acid mine drainage. Although the data suggests that a small amount of acid either is or has been formed, this acid is being neutralized by the lime added to the spoil. However, literature data and 400-ton experiments indicate that the alkaline addition must be done carefully for satisfactory results.

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