CHAPTER 6. USE OF COAL ASH CEMENT GROUTS IN ABATEMENT OF ABANDONED MINE HAZARDS AND ACID MINE DRAINAGE

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6.1 INTRODUCTION

Coal ash has been used in a variety of abandoned mine reclamation projects in Pennsylvania for more than 30 years. This chapter will cover the range of those uses, but focus on three applications: mine subsidence control and abatement, mine fire control, and acid mine drainage (AMD) abatement. The historical use of coal ash in mine subsidence and mine fire control has been emphasized in the Anthracite Region, although examples of projects in the Bituminous Region are given. Conversely, most of the AMD abatement projects using coal ash are in the Bituminous Region because of the severe water quality degradation and the large number of abandoned mine discharges there.

The magnitude of the abandoned mine lands problem in Pennsylvania is enormous. Inventories of abandoned mine lands maintained by the DEP Bureau of Abandoned Mine Reclamation (BAMR) show that there were 175,000 acres of unreclaimed abandoned mines in Pennsylvania before the enactment of the Federal Surface Mining Control and Reclamation Act of 1977 (SMCRA). In the preamble to DEP remining regulations, it was stated, “In all likelihood, government funded reclamation of abandoned mine lands will not solve the estimated $15 billion in environmental problems caused by past mining in the Commonwealth.” (PA Bulletin, Vol. 15, No. 26, June 29, 1995, p. 2379).

Federal and state funding of abandoned mine reclamation and AMD abatement projects has been significant and highly successful to date, but the major portion of the work remains to be completed. For example, BAMR cost records and information described in Devlin (1994) and Scheetz et al. (1997) show that construction costs for just two categories of the 935 completed projects within the 1980 to 1996 time period exceeded $202 million. These projects included mine fires, mine subsidence control, AMD abatement and mine hazards. The estimated cost of sites not yet reclaimed exceeds $987 million for 2,455 sites in the same categories.

The AMLIS database maintained by the Office of Surface Mining Reclamation and Enforcement (OSM) shows a total of 3503 acres of high priority mine subsidence features in PA, and a total of 2635 acres of high priority mine fires. The database shows that through 2003, 2455 acres of mine subsidence were abated and 1038 acres of mine fire projects were completed in PA.

A large part of this chapter is devoted to an innovative mine subsidence abatement project using coal ash and other materials to create a cementitious grout mixture for filling the cropfall subsidence features in the city limits of Pottsville in the Southern Anthracite Field. That project was funded through a grant from the Commonwealth’s Growing Greener program to the City of Pottsville. The purpose of the project was to conduct a demonstration project (in cooperation with DEP and the Materials Research Laboratory (MRL)) to employ new technology to prevent recent mine subsidence features from resubsiding near homes and roads, as well as address the backfilling of extensive historical cropfalls on the flank of the Sharp Mountain. The beneficial use of fluidized bed combustor (FBC) coal ash as the major component in the grout mixture, and pulverized coal (PC) power plant ash as the bulk fill material for more extensive backfilling of the cropfalls is an excellent example of solving a significant public health and safety problem, as well as associated environmental problems.

6.2 HISTORICAL USE OF COAL ASH IN MINE SUBSIDENCE AND MINE FIRE CONTROL

6.2.1 Background

The use of coal ash for mine subsidence or mine fire control in Pennsylvania by federal and state agencies can be traced back to 1969 when the U.S. Bureau of Mines (USBM) and the PA DEP of Mines and Mineral Industries commenced a project to construct a non-combustible barrier to control the spread of the Centralia Mine Fire. According to Chaiken et al. (1983), "This was to be the first application of fly ash for controlling a mine fire in the Anthracite Region, although this technique had been used successfully in the bituminous area." (p. 29). Since then, coal ash has been used in numerous mine fire and mine subsidence projects by the USBM, OSM and DEP, some of which are described in this chapter.

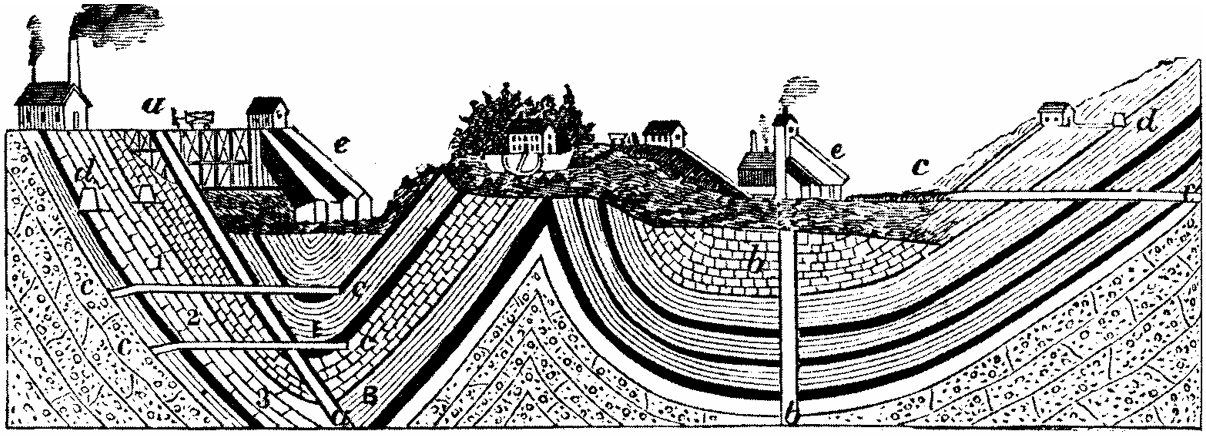
The use of coal ash in mine subsidence control and mine fire control is specifically provided for in the DEP residual waste management regulations, 25 PA Code Section 287.665, concerning the use of coal ash in the manufacture of concrete, stabilized products and other beneficial uses. That section of the regulation states that certain uses of coal ash are deemed to be beneficial and do not require a permit from the DEP as long as the uses are consistent with the requirements of this section, and Item (6) of the list of uses allows: "The use of coal ash for mine subsidence control, mine fire control and mine sealing, if the following requirements are met: ….(ii) The pH of the coal ash is in a range that will not cause or allow the ash to contribute to water pollution, and (iii) Use of the coal ash in projects funded by or through the DEP is consistent with applicable DEPal requirements and contracts."

There are three types of mine subsidence features in the Anthracite Region: 1) regional or area-wide subsidence, 2) local subsidence incidents where a collapse occurs at or near the location of a shaft, airway or other abandoned underground mine feature, and 3) cropfalls.

The regional or area wide type of subsidence is prevalent in the Lackawanna Basin of the Northern Field, where coal beds in the relatively flat bottom of the canoe-shaped geologic structure of that basin were extensively mined beneath the city of Scranton and other towns. The area wide type of subsidence is not restricted to the Lackawanna Basin. There are numerous areas in the Western Middle Field, such as, the villages of Gilberton and William Penn where there are groups of homes that are leaning and are obviously structurally affected by subsidence.

The local incident type of subsidence can occur almost anywhere in the four anthracite coal fields (or the Bituminous Region of PA) where abandoned underground mines exist, but the subsidence incidents are more serious where shafts are involved. Many shafts in anthracite collieries were more than 1,000 ft. deep; for example the Askam shaft and the Auchincloss shaft in the Wyoming Basin of the Northern Field were 2,117 feet and 1,697 feet deep respectively. There are numerous examples of the dangers of localized subsidence incidents involving shafts. One example in the Northern Field occurred in Scranton, in 1982, where a 35 ton crane was removing a concrete cap from a 288 foot deep shaft of the Pine Brook colliery when it disappeared as the ground suddenly gave way. Another example occurred in the Southern Field, in 1999, where a small pond adjacent to a recently completed home for the elderly subsided and exposed the underlying 84 foot deep shaft of the Coxe Colliery in the city of Pottsville

Cropfalls are subsidence features that are unique to the Anthracite Region of Pennsylvania, particularly the Southern and Western Middle Coal Field, because they occur in steeply dipping coal beds. Cropfalls occur where the outcrop of the coal bed "falls" into the subsurface underground mine, when adequate support is removed during mining or the support fails post-mining. To understand the concept of cropfalls it is important to understand the underground mining methods that were employed in the Anthracite Region. As explained in Chapter 2, the Anthracite Region consists of complexly folded geology. There are four alternative methods of access into underground anthracite mines that were used depending on the underground geology and the surface topography, as shown in Figure 6.1.



Methods of entry to veins of coal
Key: a–slope b–shaft c–tunnel d–drift e–breaker 1,2,3–lifts (i.e., levels)
E–Mammoth Vein B–Buck Mountain Vein

Figure 6.1. Methods of underground anthracite mining (from Wallace 1981).

A *slope* mine enters the coal vein at the outcrop (a in Fig. 6.1) and was driven down the dip of the coal vein at whatever pitch the vein was on. A *shaft* mine(b in Fig. 6.1) is a vertical hole sunk straight down through solid rock intercepting multiple coal veins, and usually terminating in the lowest vein worked in the colliery. A *tunnel* mine(c in Fig. 6.1) is a nearly horizontal entry that is driven through solid rock, intercepting numerous coal veins, generally perpendicular to the strike of the coal veins. Once the coal vein is accessed, a similar long nearly horizontal tunnel is excavated in the coal vein parallel to the strike of the vein, which is referred to as a gangway. A drift mine is the fourth type of entry, which is a straight gangway driven directly into the outcrop of the coal bed in a water gap along a ridge. Tilted slightly upward as it proceeds, the *drift* mine drains itself of whatever groundwater that flows into the gangway from the rest of the mining complex. Gangways are tunnels usually 7 feet high and 10 feet wide (Wallace, 1981), driven along the strike of the coal. The drift mines enter above water level and are driven horizontally on a slight grade to allow positive water drainage from the mine. Once the main gangway is established the coal is mined up-dip creating a void or chamber called a breast or chute. Once the main gangway is established the coal is mined up dip creating a chamber called a breast. Breasts are usually up to 30 feet wide and are the thickness of the coal. Between the breasts, solid pillars of coal usually 15 to 40 feet are left in place for stability and support. The breasts are developed up the pitch of the coal approximately 300 feet and a chain pillar is left in place near the surface to prevent surface subsidence. This complex is known as a lift and is similar to room and pillar mining in the Bituminous Region, however it is tilted on the angle of the coal vein.

Figure 6.2 shows a mine plan for a typical anthracite underground mine. Depending on the 1) depth of coal, 2) economics of water pumping, 3) thickness of the coal vein, and 4) competence of adjacent rock, numerous lifts are often developed. Often times when the reserves are exhausted, the support pillars of coal are mined (robbing the pillars).

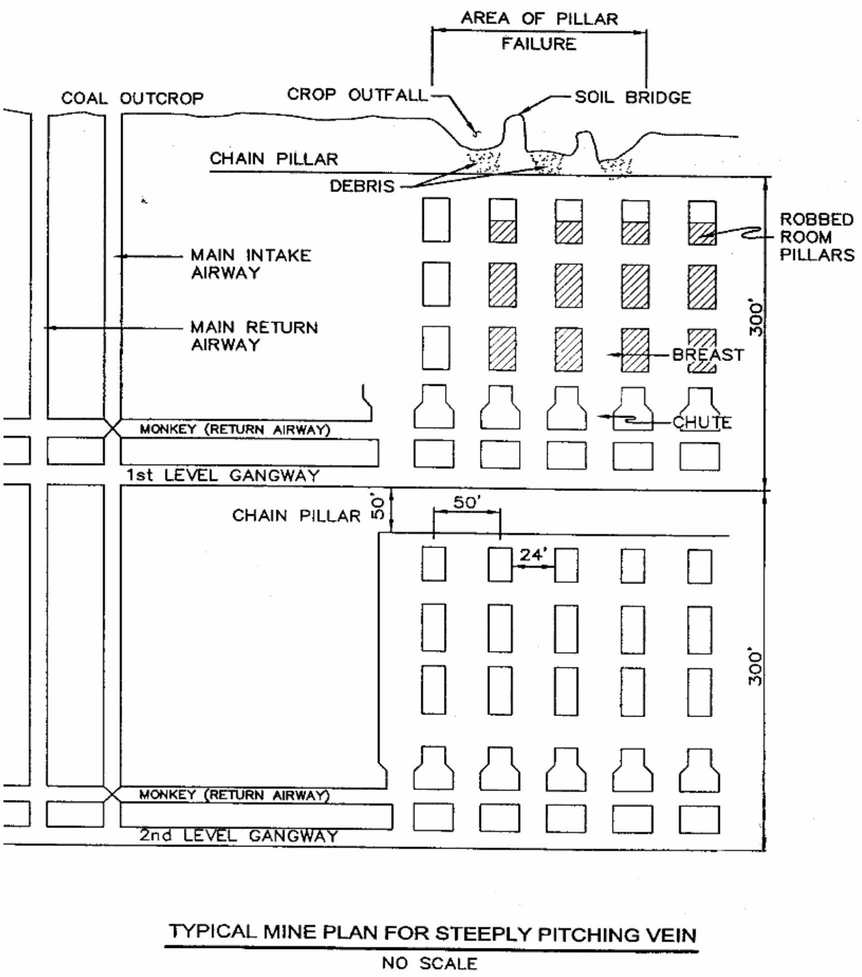


Figure 6.2. Typical mining plan of an anthracite underground mine (from Levitz, 2001).

These mining practices create the potential for large scale dangerous subsidence. If the support pillars or chain pillars fail or if they have been robbed out, the surface has the potential to fall 300 to 600 feet or further depending on how many lifts were developed. The result of the surface outcrop of coal falling into the abandoned voids below is known as a *cropfall*. In bituminous coal seams of western Pennsylvania, where the coal seams are generally flat lying, the vertical limit of subsidence is equal to the thickness of the coal seam. In the Anthracite Region, where the anthracite veins are steeply pitched, the subsidence is limited to the ultimate depth of the mining.

Cropfalls are dramatic features that often occur with little warning, resulting in deep narrow voids with near vertical walls as seen in Figure 6.3a. The tremendous underground exploitation of the coal during the industrial revolution and two world wars has created the potential for cropfalls that extend for several miles as seen in Figure 6.3b. The extensive cropfalls in Porter Township in western Schuylkill County shown in Figure 6.3b are in a relatively remote area unlike the cropfalls in the Pottsville area. When seen from the air, the cropfalls appear similar to a narrow surface mine. However, unlike most abandoned surface mines there is no overburden available to fill the hole.

Figure 6.3(a). Narrow cropfall.

Figure 6.3(b). View of extensive cropfalls on multiple veins.

The term “cropfall” is not recent, as it is clearly labeled on Figure 6.4, which is from a segment of the January 9, 1914 mine map of the Hickory Ridge and Hickory Swamp Collieries (see Section 4.2.4 in this book) in the Western Middle Field. The cropfalls delineated on Figure 6.4 are located at the updip end of the first lift workings of the Mammoth coal bed that is dipping at 80 degrees. This map and others like it document that some cropfalls occur during mining as well. Apparently some miners struggling to make their daily production quotas, did not adhere to the concept that the top of each breast on the first lift had to terminate 75 ft. from the land surface to prevent subsidence.

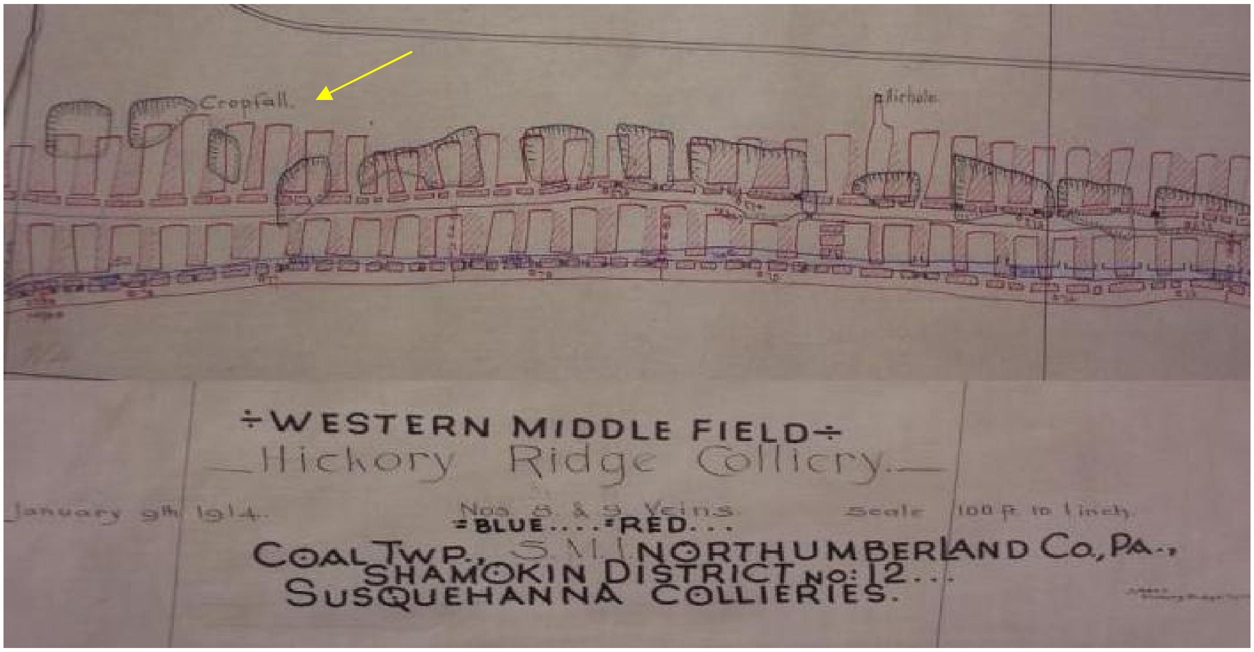


Figure 6.4. Map of Hickory Ridge Colliery showing cropfalls, January 9, 1914.

Most cropfalls developed after the major collieries closed (and thus are not shown on the maps). Many of the cropfalls occur as result of the work of “bootleg miners” that operated above minepool levels, or by geological and climatological processes over a number of years that weakens the support until it fails abruptly. In this respect, cropfall formation can be very similar to “cover-collapse” sinkhole formation in carbonate rocks, where the incipient removal of subsurface support over the years is not seen on the land surface until it’s too late to prevent the subsidence. This type of cropfall feature frequently develops in the spring of the year, following freeze-thaw cycles, and can be very dramatic, considering that the gaping hole may extend downdip as much as 900 feet depth, or deeper, depending on how many lifts were mined and whether the chain pillars between the lifts were robbed during retreat mining. The magnitude of the extensive underground mine void system connected to the cropfall feature may make the abatement of the subsidence with coal ash or any other material problematic, as described in Section 6.3. In the years following the initial dramatic collapse of a cropfall, rock and soil materials gradually fall into the gaping hole and develop a weak or strong bridging system. This represents a mitigating factor in developing subsidence abatement plans (or may fool the unsuspecting hiker of lurking dangers beneath the rock and soil bridging material).

In addition to the safety hazard that cropfalls present, there are also hydrologic impacts. Since the cropfalls are linear features along the contour of the mountain, they essentially capture all runoff and surface water from the mountain ridge and direct it underground. As the captured surface water infiltrates into the abandoned underground mines, it chemically reacts with the pyritic material in the shale adjacent to the coal, producing acid mine drainage. The water collects in the mines and ultimately drains from the abandoned drift openings that were designed to provide a gravity flow discharge from the mines.

Subsidences occur in areas throughout the world and they present many challenges in their remediation and prevention. Whether they are naturally occurring from sinkholes in limestone areas or they are the result of coal mining activities, it is critical to understand why they have formed and what the potential extent of the subsidence is, in order to effectively remediate their effects. In both the Anthracite Region of eastern Pennsylvania and the Bituminous Region in the western part of the state, underground mining practices were prevalent for over a century and a half. Since that time, these areas have been subjected to mine subsidence, which has threatened local communities and recontoured the landscape. Mine subsidences are often a reflection of the underground mines below. They range from mild sagging of the surface to large open collapses into an old mine shaft.

6.2.2 Mine Subsidence Control in the Northern Anthracite Field

Numerous area wide mine subsidence problems have occurred in the Scranton area and other urbanized areas of the Lackawanna Basin in the Northern Field, especially where multiple seams of coal have been third mined (i.e. retreat mining) above the minepool and close to the land surface. In areas where subsidences are prevalent and they threaten the integrity of buildings and public health and safety, the state and federal government have conducted mine flushing projects in order to abate, ameliorate or prevent subsidence effects.

There are two types of mine flushing projects that were conducted in the Northern Field: *controlled flushing* and *remote hydraulic flushing*. In controlled flushing, which is essentially outdated, workers went into safe underground mines, built masonry bulkheads within the mines, and flushed in crushed coal refuse and coal ash materials through pipes. In remote hydraulic flushing projects, boreholes are drilled from the surface to intercept the target mine workings; then water is pumped from the minepool, mixed with the flushing material and injected down the boreholes into the appropriate point of entry in the abandoned underground mine. The intent of these remote flushing projects was to use enough pressure to distribute the flushed material several hundred feet or more from the borehole injection site in order to fill voids within the mine, while allowing continued groundwater/minepool flow at critical points, such as drainage tunnels. Numerous boreholes were drilled within the rights-of-ways of streets in urban areas or other accessible locations, in a grid-like array when possible, and coal refuse and coal ash were injected into the underlying mines through the borehole system.

6.2.3 Anthracite Mine Fire Control

The use of coal ash in mine fire control in the Anthracite Region commenced on May 5, 1969 at the Centralia mine fire site in Columbia County according to Chaiken et al. (1983). The historical account of the Centralia mine fire is described in the USBM report by Chaiken et al. (1983) and a book by DeKok (1986). The fire was initially discovered in May 1962 burning in refuse material in a borough waste disposal site located in an abandoned strip mine pit southeast of the Centralia borough. By July 1962, the fire had spread into an outcrop of the Buck Mountain coal bed and progressed about 200 ft. along the strike, despite efforts by borough workers to extinguish the refuse fire with water and a clay blanket. From August 1962 through October 1963 the PA Dept. of Mines and Mineral Industries attempted to extinguish or isolate the mine fire by injecting fine refuse material through boreholes and by trenching. Unfortunately, the isolation trench and borehole flushing efforts were unsuccessful in isolating the fire. The Appalachian Regional Commission was created in March 1965 (Public Law 89-4) and on June 8, 1965 it approved $2.5 million in funding for a cooperative project to extinguish the mine fire, involving the U.S. Bureau of Mines, the PA Dept. of Mines and Mineral Industries and Columbia County. This project was conducted in two phases as shown on Figure 6.5. In 1966 and 1967, additional boreholes were drilled in the area represented by horizontal hatching lines on Figure 6.5, and 81,000 cu. yds. of sand was flushed/injected into additional boreholes, but it did not form an effective barrier of noncombustible material.

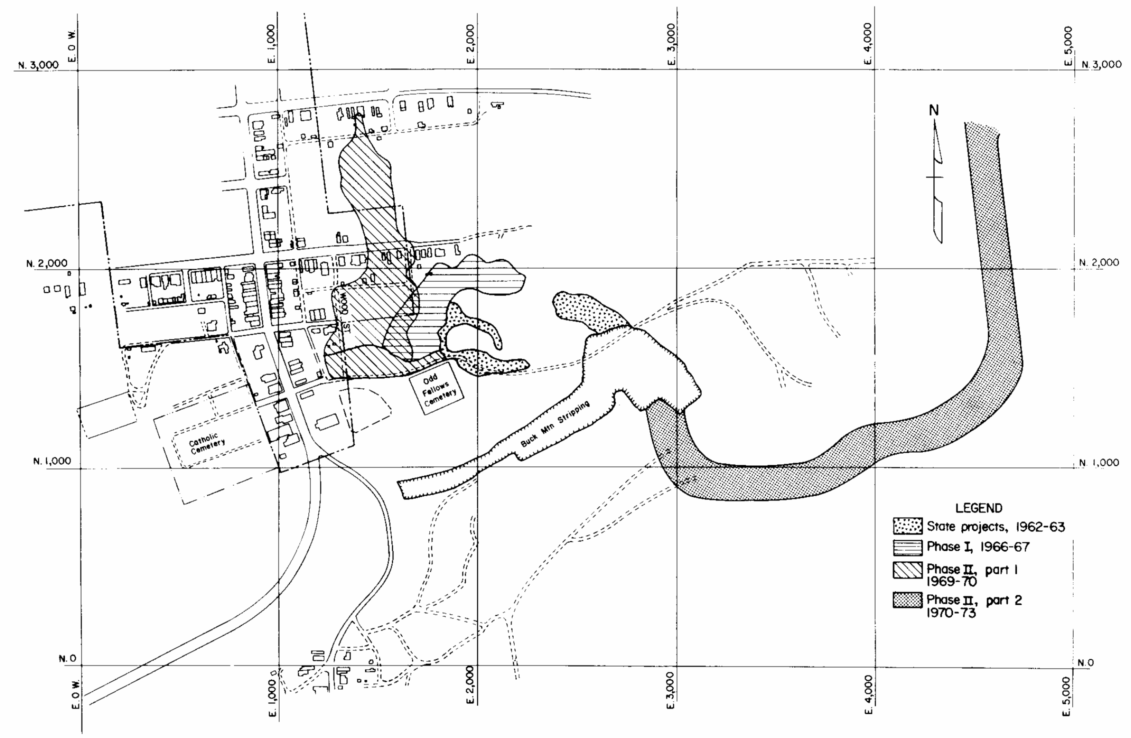


Figure 6.5. Composite of attempts to control the Centralia Mine Fire (Chaiken et al. 1983)).

Phase I, as originally planned, would have backfilled and sealed abandoned stripping pits at the southern edge of the mine fire, completed exploratory drilling in the northern, eastern and western edges to delineate the boundaries of the fire, and flushed sand down boreholes to form a temporary noncombustible barrier around the fire area to constrain its expansion until the second phase was completed. Phase II would have excavated a permanent isolation trench on the "cold" side of the temporary flushed barrier (2500 ft. long), and backfilled that trench with a lower layer of noncombustible material and an upper layer of mine spoil and refuse. Thus, at the completion of the project, the Centralia mine fire would be confined and eventually burn itself out within a confined area where it would not threaten structures, public health and safety, or to the remaining coal reserves. Unfortunately, Chaiken et al. (1983) reported that exploratory drilling conducted for Phase I showed that the fire had progressed further north and east than anticipated. In addition, the flushing operation encountered unusually large voids that swallowed more sand than anticipated and the flushed sand did not form an effective barrier or airtight seal. Also, the revised estimate to complete the Phase II trench significantly increased in time and would have almost doubled the total project costs (i.e. $4.5 million for the trench), due to the great depth of the trench and the hardness of the rock to be excavated. Therefore, it was determined that the Phase II plan would be revised to attempt to control the mine fire by constructing underground barriers by pneumatically injecting coal ash into the underground mine voids through boreholes.

The initial use of coal ash for mine fire control in the Anthracite Region at Centralia was considered a demonstration project, according to Chaiken et al. (1983), although the installation of fly ash barriers had been successfully used to control a mine fire in the Bituminous Region of Pennsylvania. The coal ash demonstration project would allow the second phase of the cooperative project to be completed with the remainder of the available funds. The coal ash used in this demonstration project was supplied from pulverized coal powerplants to Columbia County, at no cost to the state or federal government.

The western coal ash barrier, represented by diagonal hatch lines on Figure 6.5, was constructed from May 1969 through August 8, 1970 by drilling a total of 362 boreholes (i.e. exploratory holes, fly ash holes, flushing holes) and pneumatically injecting 39,272 tons of coal ash into voids in the Buck Mountain, Seven Foot and Skidmore coal beds, according to Chaiken et al. (1983). In addition to the coal ash material used in the western barrier, approximately 12,000 cu. yds of screened coarse rock materials were hydraulically injected into the abandoned underground mine workings to form a buttress between the fly ash and the minepool. The total cost for the western noncombustible barrier was $582,693.

The eastern coal ash barrier, shown as the dark stippled pattern on Figure 6.5, was constructed from August 25, 1970 to December 14, 1973, using 83,084 tons of pneumatically injected coal ash, plus 36,220 cu. yds. of hydraulically injected sandy clay, through a total of 1,049 boreholes (1,017 ash boreholes, 32 flushing boreholes). The cost of this phase of the project was $1,858,391, according to Chaiken et al. (1983), and a total of 122,356 tons of coal ash were used in the Centralia mine fire project.

Coal ash has been used in at least 3 other mine fire projects in the Northern Field of the Anthracite Region since the historic Centralia Mine Fire project, as shown in Table 6.1. These more recent mine fire projects have been completed by the Wilkes Barre OSM Field Office using several coal ash grout specifications. A typical “fly ash-cement grout” mixture would consist of a ratio of 3 parts fly ash: 1 part Portland cement: 2 parts water, to achieve a water: solid ratio by volume of 0.5 for grouting mine voids. Several specific grout mixtures have been used in site specific mine fire applications, and there are several alternatives included in the generic specifications for these projects. A common mixture in these specifications consists of 282 lbs. dry cement, 1,903 lbs. (oven dry weight) flyash, and 800 lbs. (95 gallons) of water. Two alternative mixtures for large voids and “excessive take” holes include sand, or sand plus gravel, in addition to the fly ash, cement and water. One of these mixtures consists of 340 lbs. dry cement, 1,375 lbs. fly ash, 1,323 lbs. sand, and 458 lbs. (55 gallons) of water. The coal ash used in these grout mixtures is usually obtained from PC power plants. If FBC coal ash sources were used, the specifications could be revised to account for the differences in bulk chemistry, mineralogy and cementitious behavior of these different ash sources.

Table 6.1. Coal Ash use in Anthracite Mine Fire Projects.

Project Name	Location	Agency	Year	Tons of Ash Used
Centralia – West Barrier	Columbia County	USBM/PA-MMI	1969-1970	39,272 tons
Centralia – East Barrier	Columbia County	USBM/PA-MMI	1970-1973	83,084 Tons
Powderly		OSM		3,617 yds^3
Washington West		OSM		9,046 yds^3
Maffett Red Ash		OSM		10,413 yds^3

6.2.4 Bituminous Region Mine Subsidence and Mine Fire Control Project

Coal ash has been used for more than 35 years in the bituminous coal region of Pennsylvania in mine subsidence and mine fire control projects, in a manner that is very similar to the Centralia project described in the previous section. The results of five mine subsidence control projects at public school sites in the Bituminous Region are described by Jones and Kasi (1990), in which four of the sites used coal ash from PC power plants, and three of the five were done in cooperation with OSM. Several other large subsidence control projects involving the use of coal ash cement grout mixtures are located in the town of Belle Vernon in Fayette County, Plum Borough in Allegheny County and Chartiers Township in Allegheny County. There were three subsidence control projects in which coal ash was used in the area of Belle Vernon from 1987 to 1992. The Regency Park project in the area of Plum Borough was recently completed using PC power plant coal ash. These projects involved the pneumatic injection of the coal ash into the abandoned underground mine through boreholes, using ash cement grout mixtures and methods similar to those used in the Anthracite Region. The Chartiers Township project is a large proposed coal ash injection project involving about 300 homes, and an estimated cost of approximately $7 million.

Coal ash has also been used in mine fire control projects in the Bituminous Region. Two of these projects involved the Percy Mine Fire in North Union Township, Fayette County, near Uniontown, and were completed as a cooperative effort of OSM and DEP. The first Percy project was completed in 1997 and used 5,879 tons of coal ash, and the second was completed in 1998 and used 14,456 tons of ash. The beneficial use of coal in mine subsidence contracts has been more widespread and successful than mine fire projects in the Bituminous Region of Pennsylvania. A concern in the use of coal ash/cement grout injection techniques in abandoned mine voids in relatively flat-lying bituminous coal beds, is that the ash cement mixture shrinks or develops gaps near the roof of the mine which do not fully prevent the mine fire from spreading. The use of coal ash in bituminous mine subsidence control projects is presently occurring on a scale larger than the Anthracite Region.

6.3 USE OF COAL ASH IN CROPFALL REMEDIATION - SHARP MOUNTAIN, POTTSVILLE, PA

Coal ash has been used to fill mine subsidences and to create barriers to limit mine fire propagation for several decades. The particle size of the ash allows it to be used as a flowable fill material and its pozzolanic properties have made it a choice material in grout mixtures as a cement-like material on numerous projects. Typically, in subsidence remediation, the ash is injected into the subsidence and the goal is to fill the void entirely. In the Anthracite Coal Region however, the unique cropfall phenomenon presents several difficulties that are quite a bit different than other subsidence features. The cropfalls are extensive subsidence features that can occur suddenly and often leave tremendous voids requiring large volumes of fill material. The potential for further subsidence is subject to the extent of the mining, which is often unmapped and unknown.

The City of Pottsville, in east-central Pennsylvania, has been plagued by cropfalls for decades. However, the accelerated occurrence of cropfalls in recent years, near residential areas, has prompted the need for immediate action. Attempts to backfill a few of the cropfalls under an OSM emergency project in 1999 on Sharp Mountain experienced failure after just a few months, when settlement occurred and the need for a more permanent solution became evident.

The City embarked on an effort to reclaim the mountain in a manner that would not only eliminate the safety hazard of the cropfalls, it would minimize or prevent future subsidence and reduce the amount of acid mine drainage that discharges to the Schuylkill River. In 1999, the City of Pottsville received a PA Growing Greener Grant to develop a demonstration project for backfilling the cropfalls in a manner that is both economically feasible and permanent. The project study area shown in Figure 6.6 is confined to the city limits and is bound by the crest of Sharp Mountain to the south, the Schuylkill River watergap to the east, the West Branch of the Schuylkill River watergap to the west, and the residential development to the north. The streets of Pottsville are numbered from east to west beginning with Center Street as number one and 30th street at the west end. Cropfalls exist from 3rd Street to 25th Street and the most recent subsidences have occurred between 20th and 25th street. The project study area encompasses a total of 340 acres and addresses 15,000 linear feet of cropfalls, which are occurring on several coal veins.

To understand the nature of the cropfalls and the potential dangers in their reclamation it is necessary to explore the local geology, historical mining in the area, the extent of the underground mining, and the mining methods employed which created the voids.

6.3.1 Historic Mining and Local Geology

The City of Pottsville lies on the northern exposure of Sharp Mountain along the southern boundary of the Southern Anthracite Coal Field. The mountain rises 400 feet above much of the city to a maximum of approximately 1,300 feet msl and elevations of the rivers at each water gap are approximately 600 feet msl at the east and 675 feet msl at the west. As the gateway to the Anthracite Region, Pottsville played an important role in the early shipment and mining of anthracite coal. Extensive coal mining in the 19th century under the City of Pottsville and along the Sharp Mountain not only provided millions of tons of anthracite coal, but also left significant voids. Since much of the mining was conducted prior to the 1930’s, nearly all of the coal mining was underground mining. By the time heavy machinery was available for surface mining, the city was already well established and only shallow surface mines on the order of 20 to 30 feet were dug along the contour of the mountain slopes. The local geologic structure and the extent of the mining under Sharp Mountain left a hidden potential danger, which was dormant for decades until recently.

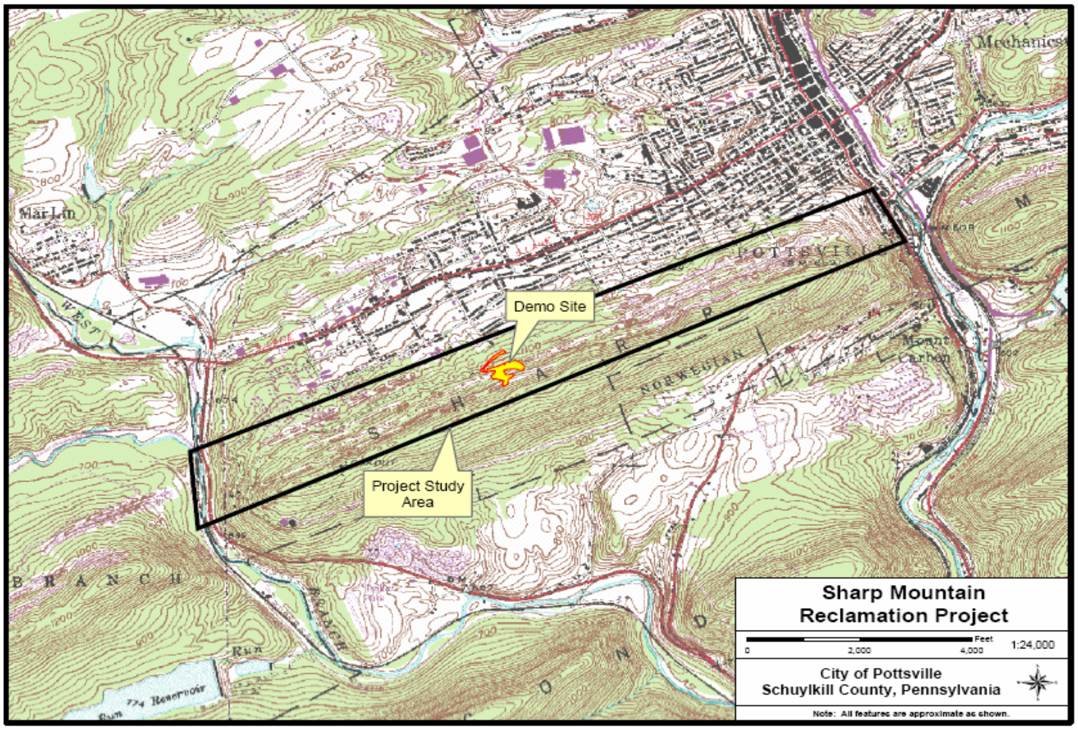


Figure 6.6. Site map of Sharp Mountain Reclamation Project.

In the mid-1800's, Pottsville was a significant metropolitan hub and the mines in the area were pioneers in both anthracite mining techniques and mining equipment. The York Farm Colliery (Lehigh Valley Coal Co.) mined significantly under the city of Pottsville and was the most extensive colliery in the United States from 1837-1845 (Wallace, 1987). Much of the York Farm workings were further north in the city, however, tunnels were extended to the veins under Sharp Mountain. Sharp Mountain was extensively mined from the mid-1800's to the 1950's in the Pottsville area primarily by underground mining methods. The earliest legible date on available mapping of the underground mine workings on Sharp Mountain was 1887, and there are indications of earlier and more significant mining activity (Levitz, 2001). The mountain was accessed primarily at the watergaps, by the Sherman Colliery at the Main Branch of the Schuylkill River to the east and by at least 14 different drift mines including the York Farm Colliery (Lehigh Valley Coal Co.) at the West Branch Schuylkill River from the west.

The coal veins mined on Sharp Mountain were all within the Pottsville Formation. As described in Chapter 2.3.6, there are 14 coal beds in the Pottsville Formation, however only 8 of the coal veins were mined significantly within the project study area shown in Figure 6.6. The southernmost mineable coal vein is the Buck Mountain vein (further north, and at correspondingly lower elevations, Skidmore, two splits of the Mammoth, Holmes, Primrose, Orchard and Diamond Veins. The cross-sectional map shown in Figure 6.7 demonstrates the steep pitch of the various coal veins and the relative distance of the cropfalls to the residential areas along Howard Avenue (Norris and Sons, 1927).

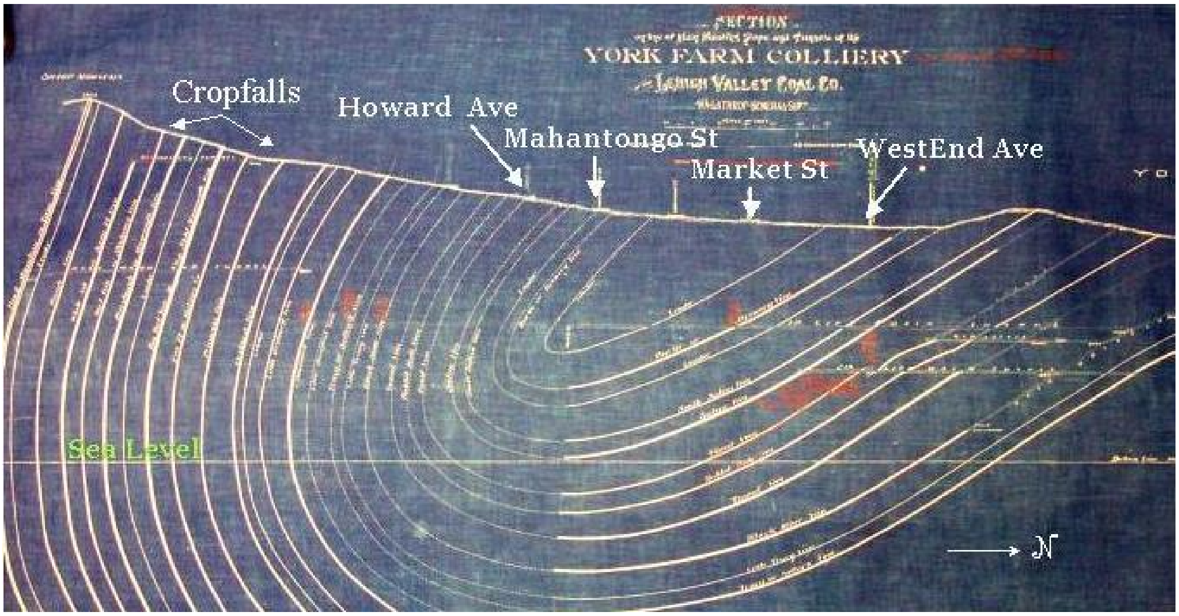


Figure 6.7. Cross-section of York Farm Colliery Pottsville, 1892.

The workable coal veins are of varying thickness as shown in Table 6.2 and the beds are overturned more than 30 degrees from vertical. The coal veins in Figure 6.7 are estimated to extend well over 1000 feet deep, far below sea level. The map also shows a tunnel at an elevation of 485 feet msl that extended over to the mountain from the York Farm workings to the north. The fact that the tunnel is over 800 feet below the surface indicates that there may be several lifts that were mined under the mountain. The mining on several of the coal veins is extensive. Due to the steep pitch of the coal, the mining was very efficient on the mountain with an 80% extraction ratio according to a Report on Property of the Sherman Coal Corporation, 1927. The report was an evaluation of the feasibility of mining multiple veins, on several lifts down to sea level, for the entire length of the mountain in Pottsville. The report concluded that it was not feasible at that time to invest the resources for mining to that extent.

The coal veins outcrop at the surface along the contour of the mountain. The steep nature of the rock units is demonstrated at the eastern water gap of the Schuylkill River along Route 61, as seen in Figure 6.8. It is in the vicinity of this photo that the type section of the Pottsville Formation was described by C. D. White (1900) and more recently by Wood et al. (1956) and Levine and Slingerland (1987).

Table 6.2. Thickness coal veins (from Norris and Sons, 1927).

Coal Beds	Estimated thickness of workable coal (feet).
Buck Mountain	3.50
Skidmore	5.75
Mammoth	9.00
Holmes	4.50
Primrose	7.00
Orchard	4.5
Little Orchard	7.00
Diamond	5.50
Tracy	5.25

Figure 6.8. Exposure of the Pottsville Formation, along Rt. 61, Pottsville.
Note the vertical stop sign at the bottom of the photo.

6.3.2 Extent of the Cropfalls

Although cropfalls occur throughout the Southern & Western Middle Coal fields, the cropfalls in Pottsville area are unique in that they are very close to residential areas. Cropfall features have existed on Sharp Mountain in the Pottsville and are shown on maps of the Sherman Coal Company as early as 1925. The cropfalls shown on those maps are located between 4th and

15th street in Pottsville and they currently appear stable with overgrown vegetation. In the 1990's however, the areas between 20th and 25th street began to collapse significantly. The subsidences have continually occurred and expanded causing an imminent danger to the safety of the public. From 20th street, westward there are 4 distinct continuous lines of subsidence that are dramatic and unstable, as seen in Figure 6.9. The active subsidences are within 300 feet of residential lots in the 20th street area.

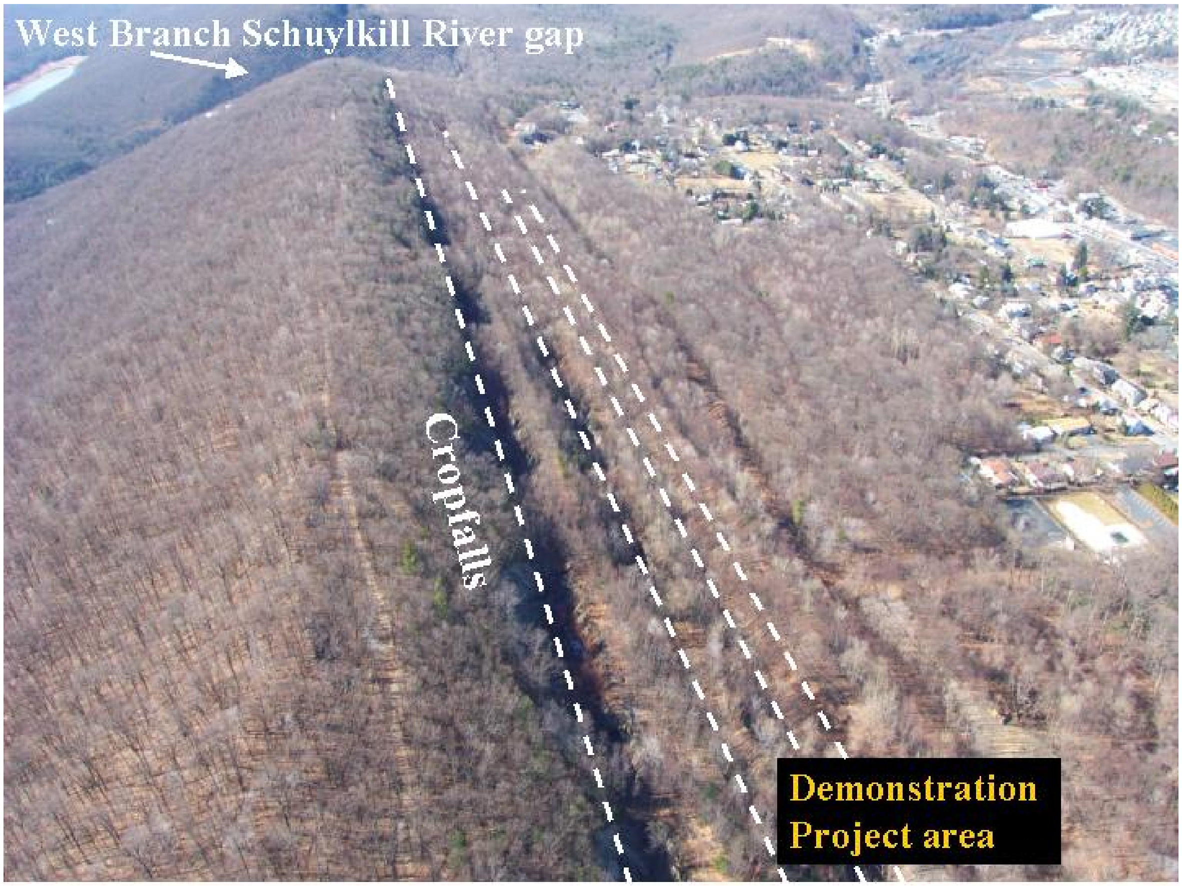


Figure 6.9. An aerial view of Sharp Mountain and the City of Pottsville from above 20th street looking west. Four lines of subsidence are evident. The demonstration project reclaimed 2.0 acres of in cropfalls in the black highlighted area.

East of 20th street these features are not as continuous, but there are 4 distinct lines of subsidence apparent. The extent of the cropfalls and shallow surface mines can be seen far beyond the project area. Research of existing mine maps and mine tonnage records of mines in the project study area conservatively estimate the volume of abandoned mine workings at 4,000,000 cubic yards. The length of the combined open voids is estimated at 15,000 linear feet. The affected zone is a maximum width of 400 feet and traverses 100 to 130 feet of elevation change. Generally, the width of the individual subsidences range from 40 to 100 feet and exceed depths of 50 feet. The total open void volume on the various coal veins is estimated at 500,000 cubic yards (Levitz, 2001).

Each year the normal weathering processes act on the existing voids and they continually expand. As the voids occur, they exhibit a funnel shape that is wider at the surface and narrows with depth. As the void tapers, it becomes blocked with rock, topsoil, trees and plant debris. The opening then remains camouflaged until there is further failure of the coal pillar and the debris clogging the void falls deeper. When the pillars fail underground, the surface failure can be catastrophic and it often causes instability of other pillars. As the cropfall matures, the hole widens and becomes more shallow as the debris from the walls accumulate in the void. It is difficult to determine the true depth of the void, as the debris may be only temporarily bridging the void.

The aerial view of the cropfalls in Figure 6.10(a) show very recent subsidences where the breasts collapsed, leaving the pillars intact (soil bridges). The upper "more developed" cropfalls expanded as the pillars failed and the cropfalls matured. In 1993, when a significant collapse occurred, a chainlink fence was installed around a portion of the hole to prevent access and warn the public of the dangerous condition. In a few years the hole expanded and the fence fell into the void as seen in Figure 6.10b. Note the dip and the thickness of the coal outcrop at the far end of the pit.

Figure 6.10(a). Recent and more mature subsidences.

Figure 6.10(b). Expanding subsidence, notice the hanging chainlink fence on the left. Wall at the far end represents a stable pillar.

6.3.3 Previous Backfilling Attempts

In 1999, a group of cropfalls began to subside, resulting in several significant holes that swallowed a well-traveled unimproved road that traverses the mountain (Fig. 6.11a). As an emergency project, the Office of Surface Mining imported durable rock and a high strength concrete mixture to backfill five subsidences. This was an attempt to create a concrete plug formed solely of cement. The purpose of the rock was to increase the frictional forces between the backfilled cement and the adjacent rock, and thus, slow the movement of the cement until it could set up and cure. During the project, the backfill material had subsided, requiring more fill than was originally anticipated. Within a few months of project completion, the fill material subsided once again to varying degrees in each of the five subsidences. Some of the failures resulted in minor sagging of only a few feet as in Figure 6.11b, while others were severe collapses where nearly all of the fill material was lost, Figure 6.11 c. Figure 6.11d shows the area that became the main site of the demonstration project described in Section 6.3.4.


3/25/1999

Figure 6.11(a). Emergency cropfalls.


08 30 2001

Figure 6.11(b). Sagging of filled area


8/25/1999

Figure 6.11(c). Severe collapse and loss of fill.


07 19 2001

Figure 6.11(d). Subsidences. Site of Demonstration Pit A.

6.3.4 Demonstration Project

In order to address the problem of chronic failure of backfilling materials, the City of Pottsville employed a unique approach. The City evaluated two basic reclamation methods typically used in mine subsidence restoration projects. The first method considered, which is typical method, was to completely backfill or inject a non-structural bulk fill material to replace the coal that had previously been extracted. Since most of the mining on the Sharp Mountain was underground, there is very little onsite material available on the surface to use as a fill material. The efforts required to import and place enormous volume of material needed to fill the all the voids, an estimated 300,000 truckloads, would generate unrealistic demands upon funding sources, city infrastructure and ultimately the community's tolerance. For these reasons, the first option was impractical.

The second method was to partially backfill all open voids with fill materials that exhibited desireable structural characteristics (i.e. slurries, flowable fills and low grade cements), which may prevent further subsidence into the uncollapsed voids below. As part of the Growing Greener project, the city conducted a full-scale demonstration project to apply a concept similar to the OSM emergency project. However, the cement plug would include structural reinforcement components and measures to prevent material loss during the project.

The three main objectives of the project were to 1) prevent continued vertical displacement of the surface, 2) provide a stable platform upon which to proceed with future restoration efforts and to establish an acceptable final grade for revegetation and positive drainage, and to 3) minimize the total amount of required backfill material. The materials utilized were selected for their structural properties, availability, and cost effectiveness. The general concept was to use a cementitous grout mixture in conjunction with reinforcing material to form a structural plug at the current bottom of the void. A bulk fill material was to be placed upon the plug to fill the remainder of the void up to the surface grade, and then the area was to be planted. It was intend that the combination of these materials would form an adequate plug if the void would subside further.

Since funding was limited and fill material nonexistent on-site, discarded or recycled materials were used wherever possible to minimize costs. The concept of using a “discarded” material was a significant factor in the economic viability of the project. Various materials were explored for their physical characteristics, availability, cost and any potential permitting requirements that would be necessary to utilize the material. The list of potential materials included coal fire boiler ash, cement kiln dust (CKD), foundry sand, river and harbor dredge, coal refuse and various reinforcing material, including steel beams and specialty concrete products.

Various materials were tested to form the cementitious grout necessary for the plug. Coal ash, particularly that produced in a fluidized bed combustion unit with limestone injection, has long been noted for its cementitious behavior. Coal ash from five anthracite fired fluidized bed combustion (FBC) co-generation plants were tested at the Pennsylvania State University, Material Research Institute (MRI) for cementitious properties and potential strengths. The FBC ash from the Northampton Generating Company, L.P. in Northampton, PA ranked highest in potential strength tests. FBC ash is preferred since limestone is added in the combustion process to control sulfur emissions. The combustion of the coal and coal refuse in a fluidized bed combustor results in an ash that is chemically reactive when placed into contact with agricultural lime. The presence of chemically reactive thermally altered clays and excess lime in the ash from sulfur removal result in materials that exhibit chemical reactions similar to those seen in commercially available Portland cement.

Experience from the Knickerbocker Demonstration project discussed in Chapter 8 have shown that CKD enhances the strength of the coal ash. Data obtained from preliminary mechanical properties testing on grouts made from mixtures of FBC ash and CKD show a synergistic strength gain of approximately 30% from the mixture of the two components. Penn State conducted strength tests of FBC ash from Northampton Generating with CKD from Keystone Cement, Bath, PA at various ratios to provide an optimal formula for a grout mixture.

The mixtures were blended and placed in 2 inch cubes for laboratory testing. In addition, experiments including foundry sand in the mixture were also conducted to determine if the sand would provide improved cementitous strength. Results of the tests are shown in Table 6.3.

Table 6.3. Laboratory tests of various grout mixtures.

Mix #	formulation	7 day strength (psi)	28 day strength (psi)
1	60%FBC - 40%CKD	246	329
2	67%FBC - 33%CKD	347	466
3	67%Mixture 1 - 33%sand	94	92
4	67%Mixture 2 - 33%sand	97	105
	FBC Ash Alone	252	287

It was determined that a mixture of 2 parts FBC coal ash to 1 part CKD would be used to produce the grout mixture. Based on the achievable strengths in the laboratory tests a target of 275 psi in a 7-day period was the specification for the grout mixture.

As the project began, there were difficulties in achieving a mixing procedure that was practical for the size of the demonstration project. The scale of the demonstration project did not warrant the expense of setting up a pug mill to blend the grout mix. The initial mixtures of conditioned FBC coal ash and CKD were trucked to the site in one vehicle. The truck would load 2/3 full of ash from Northampton Generating and then fill the remaining 1/3 with CKD from nearby Keystone Cement. It was important that the ash was conditioned with approximately 20% water at Northampton to provide some dust suppression.

A hopper device was fabricated at James Quandel & Sons Concrete, Inc. to blend the grout components and additional water was added to the mixture. Quandel continually tested the strength of the blended mixture, but obtaining a consistent grout mixture that would meet the 275 psi in 7 days became very problematic. The mixture of ash/CKD showed very low strength of 70 psi in 7 days as seen in Table 6.4. It appeared that the grout mixture retained water and did not cure like the laboratory tests. It was preferred that the Northampton FBC ash would be used with the Keystone Cement CKD since both companies agreed to donate the material for the demonstration project and Northampton donated the trucking costs. Several truckloads of FBC ash/CKD were tested, however, obtaining a consistent mix was difficult.

Additional tests were conducted with various other materials and mixtures to achieve the target strength, as tabulated in Table 6.4. Portland cement was added in Mix 2 and 3 and the desired strength was achieved. Several tests were done to minimize the amounts of Portland. In Mix 4 and 5, the Northampton ash was replaced with a quartz rich bottom ash from another co-generation facility. Both mixtures were treated with equal amounts of a performance additive developed by Grace Construction Products specifically for controlled low strength materials. They yielded significantly different results, but neither met the target strength in a 7 day period. Due to time constraints and the fact that a consistent ash/CKD mixture that met the specification could not be attained, the CKD was eliminated from the project and was replaced with a relatively small amount of Portland cement. Ultimately, a blend of Northampton FBC ash with 9% Portland cement by weight was the mixture used. Varying amounts of water were added depending upon the actual moisture content of the delivered ash. The total moisture content was adjusted by the operator to maintain a suitable slump of 6-7 inches.

Table 6.4. Summary of project-scale grout mixture strength tests (from Levitz, 2003).

Product	FBC Ash	CKD	Portland Cement	Water	7day (psi)	14 day (psi)	28 day (psi)	Observation
Mix 1	67%	33%			70	73		Grout did not dry
Mix 2	1100 lb		310 lb (18%)	290	700 (96 hr)			Significantly more than target 275psi
Mix 3	1100 lb		150 lb (9.4%)	333	320		1200	Displayed shrinkage Bulk density was 102 lb/CF instead of desired 60 lb/CF
Mix 4	5400		600 lb (8.5%)	1095	92			Quartz rich bottom ash + additive
Mix 5	5400		660 lb (9.1%)	1162	169			Quartz rich bottom ash + additive

Obtaining the proper grout mixture and establishing a handling procedure was a critical component of the project. Dust suppression and consistency of the materials are additional factors to be considered. The calcium content of the FBC ash from Northampton varied with changes in the fuel blend at the plant. The amount of limestone used at the plant varied directly with the amount of petroleum coke in the fuel blend. The CKD should be investigated further since it did show strength enhancing properties in the laboratory. A procedure for importing consistent CKD would be necessary. The CKD may possess different properties if it comes directly from the cement kiln or if it is weathered CKD from the stockpile. The handling of the materials, transportation costs, and placement of the material can significantly inflate the cost of the project.

The scope of the entire cropfall remediation project is enormous. The cropfalls selected for the demonstration project were at the location where the previous efforts under the emergency projects were experiencing failure. Since the previous measures taken were very short lived, it was obvious that a more permanent solution was needed. The sequence of the subsidences, their restoration, their failure, and the demonstration project are shown in Figure 6.12 a-c. The field conditions provided an ideal opportunity to test three slightly different methods of constructing a structural plug to seal the voids. The project area shown in Figure 6.12d consists of three distinctly separate areas, Pit A East, Pit A West and Pit B. The area referred to as Pit A was previously backfilled and failed. Pit B subsided in 2000 and had not been backfilled.

Pit A consisted of 2 subsidences within the previously backfilled area (Fig. 6.12c). The voids, one roughly rectangular, the second circular, were initially 41 feet apart and 64 feet long by 38 feet wide and 30 feet deep and 17 feet in diameter by 6 feet deep, respectively. The presence of tension cracks between the voids suggested that the voids would continue expanding, ultimately forming one cropfall. In order to install the structural plug, the subsidences were further excavated and prepared. Approximately 2,250 cubic yards of material was removed from Pit A to locate solid competent rock adjacent to the subsided coal vein. The excavation resulted in one hole separated into 2 fairly equal sections by a solid coal pillar that was exposed and intact as displayed in Figure 6.13a.

Figure 6.12(a). Subsidence in 1999.

6.12(b). Restoration effort, 2000.

6.12(c). Area resubsides, 2001.

6.12(d). Demonstration Area, 2002. An orange safety fence surrounds the construction area.

The method of backfilling in Pit A was to develop a wedge that if the potentially false bottom of the pit would fail, the wedge would become lodged and would not undergo catastrophic failure. Concrete panels were placed on the floor of the excavated pit in both the eastern and western portion of Pit A. The purpose of the concrete panels was not to create an additional structural member of the plug, but to provide a means to retard the flow of the grout until it had time to cure. The concrete panels were originally manufactured to be used as sound barriers along major highways. The panels were flawed or damaged and they were donated by Schuylkill Products, Inc. a nearby concrete fabrication operation. In the eastern portion of Pit A an inverted steel truss was fabricated to act as a structural support member that spanned the void and was wedged into the competent solid rock on the north and south end of the pit (Fig. 6.13b). The self leveling cementitious grout mixture, not unlike controlled low strength flowable fills, was then placed in the eastern portion of Pit A covering the steel member. The grout mixture of FBC ash, approximately 9% Portland cement, and water was blended at Quandel Concrete, Minersville and imported to the site in cement mixers (Fig. 6.13c). The consistency of the grout mixture allowed it to flow throughout the east pit and it hardened relatively quickly allowing the vehicles to travel on the grout mixture (Fig. 6.13d).

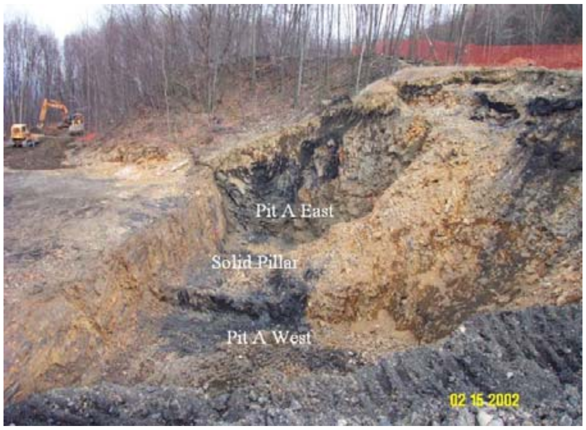


Figure 6.13(a). Pit A prepared.

6.13(b). Steel trusses installed in Pit A east.

6.13(c). Grout mixture placement, Pit A east.

6.13(d). Pit A east grout complete.

The west side of Pit A was prepared similarly in that reject concrete panels were placed in the floor of the pit. Instead of the fabricated steel trusses, recycled reinforcement bar (rebar) was imported from Glasgow, Inc. to form a wire mat similar to a large expanded Brillo pad in the grout mixture for structural support (Fig. 6.14a). The rebar was loosely packed and it allowed the grout to flow through it. The grout was placed and leveled with the eastern portion of Pit A. Grout depth in all of Pit A was approximately 10 feet. The remainder of the pit was then filled with coal ash from PPL Montour Station to serve as a bulk fill material that will also be beneficial due to its cemetitious properties (Fig. 6.14b). As with the Northampton ash, PPL donated the ash and delivered it to the site. Once the area was backfilled and graded to the adjacent contours, topsoil was added and the area was vegetated, Figure 6.14c-d.

Figure 6.14(a). Scrap rebar in replaces trusses, Pit A west.

6.14(b). Grout added. Notice the mixer is driving on previously poured grout.

6.14(c). Ash bulk fill placed.

6.14(d). Prepared for topsoil. Pit A complete.

Pit B is a subsidence feature on the upper, southern line of cropfalls as seen in Figure 6.12d. This cropfall was not previously addressed in any backfilling attempt. Unlike Pit A, this cropfall appeared somewhat stable. The bottom seemed well choked with large boulders. Therefore, the temporary floor of concrete panels was not used. Both the north and south walls of Pit B were well exposed and required little excavation. Only 180 cubic yards of material were removed from the hole to prepare it for grout placement. There were no reject concrete panels, steel trusses or rebar used in this void. The void was filled solely with 8-10 feet of the ash-based grout mixture. Coal ash was used as a bulk fill material and the area was revegetated. As the grout mixture was added, one load of grout material (8 yards) was lost as it flowed into cracks in the pit floor.

The demonstration project, Pit A was completed in September 2002, Pit B was completed June 2003 and the areas appear to be stable as seen in Figure 6.15. The project withstood one of the wettest years on record with no adverse effects. Already the area is visited by the unsuspecting public with little respect for the potential dangers that exist on the mountain, as evidenced by a dirt bike trail across the area. The 2.5 acre project set the stage for future phases of reclamation within the 340 acre overall project area. The success of the stability of the demonstration project will be tested in time; however the methods and material employed in the project have provided very valuable information and direction for approaching the large amount of cropfalls that lie ahead.

Figure 6.15. Completed Sharp Mountain demonstration project.

6.4 USE OF COAL ASH IN MINE DRAINAGE REMEDIATION

Production of AMD requires the presence of pyrite, oxygen, and water. If a barrier can be configured that will isolate the pyrite from the oxygen and water, then AMD can be prevented or abated. FBC ash was used in two different applications on reclaimed mine sites in an attempt to isolate pyrite in the backfill from coming into contact with water and oxygen. One of the applications involved spreading a 3 ft. thick layer of FBC ash beneath the topsoil of a 100-acre mine site in Clearfield County to serve as an infiltration barrier. In the second application, buried piles of pyrite rich materials were identified using geophysics, and FBC ash was mixed with water and injected as a grout to encapsulate the buried pyrite piles of pyrite.

Acid mine drainage is formed by the oxidation of metal sulfides, primarily the oxidation of pyrite by the familiar mechanism (Stumm and Morgan, 1996):

$$\mathbf{2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4\ H^+} \quad \mathbf{(1)}$$

$$\mathbf{4\ Fe^{2+} + O_2 + 4\ H^+ \rightarrow 4\ Fe^{3+} + 2\ H_2O} \quad \mathbf{(2)}$$

$$\mathbf{Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3(s) + 3\ H^+} \quad \mathbf{(3)}$$

$$\mathbf{FeS_2(s) + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+} \quad \mathbf{(4)}$$

As shown in equations 1 and 2, oxygen must be present to initiate pyrite oxidation. At a low pH level (on the order of $pH \leq 3$) the ferrous iron oxidation given in equation 2 is accomplished primarily by iron oxidizing bacteria, such as *Thiobacillus ferrooxidans*. This low pH level is promoted by hydrolysis, as shown in equation 3. The overall oxidation reaction in solution is accelerated as shown in equation 4, wherein Fe^{3+}, instead of O_2, is the oxidizing agent.

Guo and Cravotta (1996) point out that pyrite oxidation occurs mainly in the unsaturated zone of mine spoil. Although infiltrating H_2O carries dissolved O_2 at an equilibrium solubility of between 9.2 mg/L at 20° C to 14.6 mg/L at 0° C (Greenberg et al. 1992), oxidation by atmospheric O_2 (normal atmospheric volume = 21%, Perry, 1976) is more effective than oxidation in solution, considering the low solubility and the low replacement of dissolved O_2 by molecular diffusion (Diffusivity = 2.5×10^{-6} cm^2/sec: at 25° C, Perry, 1976). Guo and Cravotta observed at a mine where the spoil was a compacted, friable shale that the atmospheric oxygen diminished to less than 2% at a depth of about 33 ft. This suggests that initial AMD formation (equations 1 and 2) occurs in the upper layer of backfilled spoil, approximately 20 ft in depth. The remaining pyrite oxidation depends on molecular diffusion of O_2 from aqueous solution to the pyrite surfaces as well as dissolution of the reaction products (equations 1-4).

6.4.1 Use of FBC Ash to Form and Impermeable Cap – McCloskey Surface Mine

6.4.1.1 Site description

A watershed in north central Pennsylvania was being polluted by an acidic mine drainage discharge from a 100 acre surface coal mining operation. In an effort to abate the pollution, an application of a 3 ft. thick cap based on FBC ash/LKD cementitious grant was placed on the reclaimed surface prior to spreading the topsoil and revegetating the mined area. The FBC ash layer serves a dual purpose, first as an aquitard that prevents the infiltration due to precipitation from reaching acid forming materials in the backfilled mine. Secondly, the formation of acid from the oxidation of pyrite, FeS_2, is inhibited, and the concentrations in the groundwater and in the surface discharges of Fe, Mn, and Al are diminished substantially below levels present before the application of the FBC layer.

Original mining on this site began as a Lower Kittanning underground mine, which closed in the early 1950s. Surface mining began in the late 1940s. In 1976, John Teeter Coal Company received a permit to daylight the Lower Kittanning deep mine and to mine the Middle Kittanning coal seam as well. It was repermitted in 1985, renewed as River Hill Coal Company in 1991 and became known as the McCloskey operation.

The McCloskey surface mining operation is located in Karthaus Township, Clearfield County, Pennsylvania. Runoff from the mine drains to Saltlick Run; Marks Run (tributary of Upper Three Runs), an unnamed tributary of Upper Three Runs, and directly to Upper Three Runs, all tributaries to the West Branch Susquehanna River (Fig. 6.16). During active mining, it was necessary to pump and treat the pit water before it was discharged to Upper Three Runs.

The operator was left with the problem of treating or abating the acid mine drainage that formed within the backfilled McCloskey mine. The operator attempted to passively treat the resulting average 60 gpm polluted discharge with a horizontal flow aerobic constructed wetland having an area of 10,650 yd^2 and incorporating aeration at the inlet. This system had the disadvantage that the mine drainage must be pumped to the wetland inlet due to space and elevation constraints. Although the 1991 average sample results given in Table 6.5 shows substantial improvement in water quality by the constructed wetland, the wetland was not successful in meeting effluent limits.

Table 6.5. Influent and effluent water quality from aerobic constructed wetland.

Location	pH	Alkalinity mg/L	Acidity mg/L	Iron mg/L	Manganese mg/L	Sulfate mg/L
Influent	4.8	33	657.0	230.7	146.3	4766
Effluent	3.3	12	31.7	31.7	107.9	4752

With treatment costs approaching $100,000 a year and with mining completed, the mine operator was facing potential bankruptcy. In 1991, the operator attempted to abate the AMD discharge through the use of an impermeable FBC as cap on the backfilled surface mine.

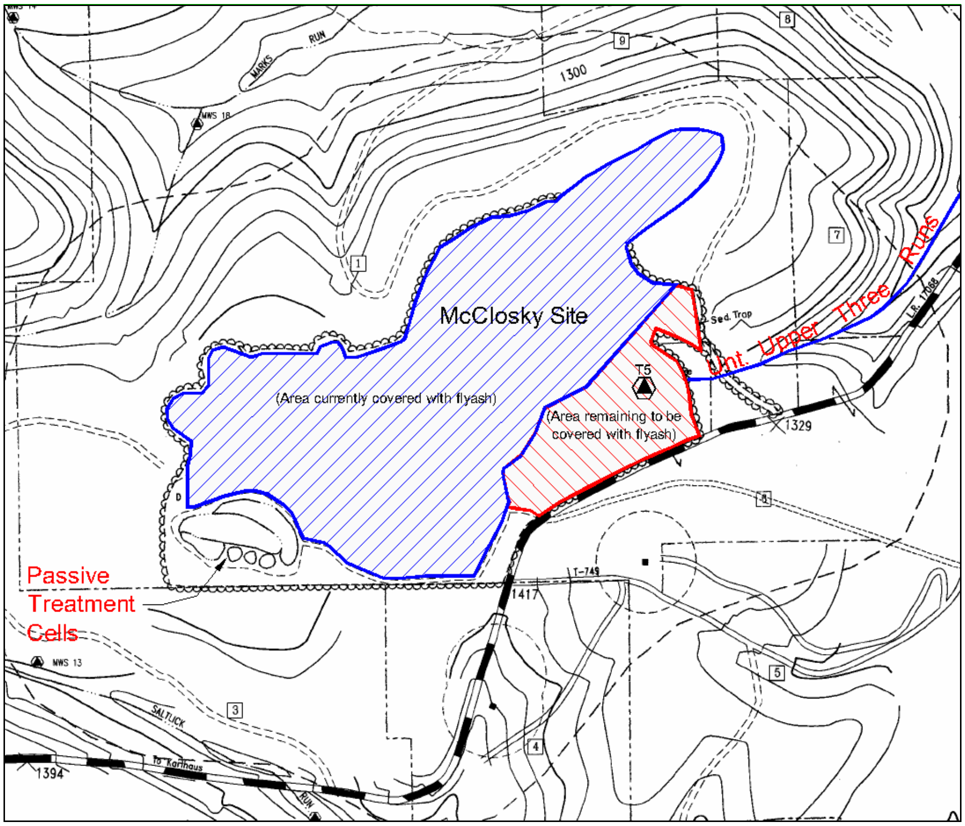


Figure 6.16. Map of McCloskey mine site. Areas already capped prior to 1998 is shown in blue and post-1998 are displayed in red.. T-5 discharge location is included.

The configuration of the reclaimed area of the McCloskey mine site is shown Figure 6.16. The mined area is a hilltop surrounded by drainage to the Saltlick Run and Upper Three Runs watersheds. Scheetz et al., (1997) discussed these and other hydrogeologic constraints and boundary conditions which revealed that there was no apparent horizontal groundwater contribution to the water balance at the site. The rainwater falling directly on the site percolated through the spoils with a detention time of approximately 2 days, with the major portion of the water exiting the site via the seep T-5 and some water exiting at seep T-6. This is consistent with the measured strike and dip varying from N43°E, 4.6° to N42°E, 1.5° for the Lower Kittanning "B" Coal.

6.4.1.2 Low permeability FBC ash cap project concept

The DEP observes that 40% to 50% of precipitation at a surface mine infiltrates vertically into the spoils, furnishing the medium for acid mine drainage production. This suggests that placement of a shallow, relatively impervious barrier as an upper layer of the surface mine backfill would inhibit the formation of acid mine drainage, both by creating an impermeable barrier to atmospheric oxygen and by redirecting the rainfall as uncontaminated surface runoff. An impermeable barrier could be fashioned from a conventional concrete made from Portland cement but the cost would prove prohibitive. However, FBC ash is pozzolanic, thus it has the properties necessary to be formed into a shallow, impervious barrier.

EPA priority pollutants Cr, Cu, Pb, Ni, and Zn are not present at detection limits in the receiving stream, while only a trace of Se is present (Table 6.7). Benthic macroinvertebrate populations have improved substantially since the fly ash application began. This reclamation effort offers the promise of abating pollution in numerous surface mine discharges whose primary hydraulic contributor is vertical flow from rainfall. It is expected that such discharges can be ameliorated to approach discharge limitations, or that the flow rate can be diminished sufficiently to facilitate treatment of pollution in the final discharges with passive systems.

This suggested that placing a FBC ash cap over the reclaimed area would intercept nearly 100% of the water that contributed to the mine drainage flow. In March 1992, the surface mine permit was revised to approve the use of FBC ash grout on site for the purpose of abating the acid mine drainage discharge.

6.4.1.3 Coal ash placement – capping of site

The application of the FBC ash began in July 1992 as a 5 acre experimental project. Prior to ash placement the test plot was evaluated by monitoring infiltration. Fifty five gallon drums (with the tops removed) were filled with clean silica stone, covered with geotextile fabric and buried in the backfill to serve as water collection points. A standpipe was installed which extended from the bottom of the drum to the surface. Water accumulation within the drums was monitored. Water accumulated in the drums on a regular basis. Once the ash cap was in place above the drums, they remained dry. This experiment indicated that an ash cap over the entire site should be successful in inhibiting infiltration below the cap.

The ash was mixed with lime kiln dust at a rate of 90% FBC ash to 10% waste lime by volume. It was spread and compacted primarily by rubber-tired graders over the reclaimed site. The 3 ft. FBC ash cap was applied in accordance with procedures developed by Scheetz under the direction of the DEP (Scheetz et al., 1997). Water was metered onto the fly ash formulation from water trucks during dry months; otherwise, rainfall furnished the necessary water. The FBC ash cap was compacted in 6 in. lifts to a total thickness of 3 ft. The permeability of the ash was determined by laboratory testing to be 10^{-7} cm/sec after a curing time of 515 days. Unconfined compressive strengths of this grant were routinely recorded in excess of 4000 psi during laboratory testing. The topsoil layer was then spread and the area was seeded.

Following completion of the test plot, approval was granted to cap the entire site (Fig. 6.16). By February 1998, an area of 74 acres received the fly ash cap. The cap was applied to a thickness of 3 ft. and covered with 3 ft. of topsoil or topsoil substitute, which in turn was revegetated. An estimated 222,850 tons of fly ash was used to construct that portion of the cap. Between February 1998 and January 2004 an additional 11.3 acres was capped. This included the filling of a 7-acre depression adjacent to the site that was directing precipitation into the backfill. It is estimated that another 35,600 tons of fly ash was utilized during this time period. A total of approximately 300,000 tons of ash was ultimately incorporated into the cap at the McCloskey Operation. In addition to the ash cap, three of the aerobic wetland cells were drained and lined with ash. This was in response to observations that water pumped to these cells was leaking back into the backfilled spoil rather than discharging to the stream.

The ashes approved for use were from several sources; Public Service Electric and Gas Company's Hudson Generating Station in Jersey City NJ; NYE&G Greenwich Plant, Milliken and Goudey Sources, and American Ref-Fuel Company in Essex County NJ; and the Lakeview Coal Bottom Ash Source. Ash from the Piney Creek and Scrubgrass cogeneration facilities and the Lancaster Millable Metals site, all in Pennsylvania, were applied as well. All ashes were approved by the DEP prior to being placed at the McCloskey Operation. Typical chemical characteristics of the ash are given in Table 6.6.

Table 6.6. Typical chemical characteristics of fly ash leachates used at the McCloskey site. (Data provided by B. E. Scheetz from TCLP extracts).

Parameter	Concentration (mg/L)	Parameter	Concentration (mg/L)
Al	0.48	Mn	0.41
As	0.08	Mo	0.53
B	1.05	Ni	0.15
Ba	0.41	Pb	0.65
Ca	970	Sb	1.28
Co	0.03	Se	0.056
Cr	0.07	Si	9.6
Cu	<0.02	Sn	0.61
Fe	0.06	Sr	6.1
Hg	0.004	Ti	<0.02
K	310	Zn	0.04
Mg	35		

6.4.1.4 Results

The chemical quality of the discharge are presented in Figures 6.17 and 6.18. Figure 6.17 presents the historical concentration for sulfate and acidity. Since the capping project began in 1992, sulfate concentrations have decreased by about 50%, from over 4000 mg/L in 1992 to a little over 2000 mg/L in 2004.

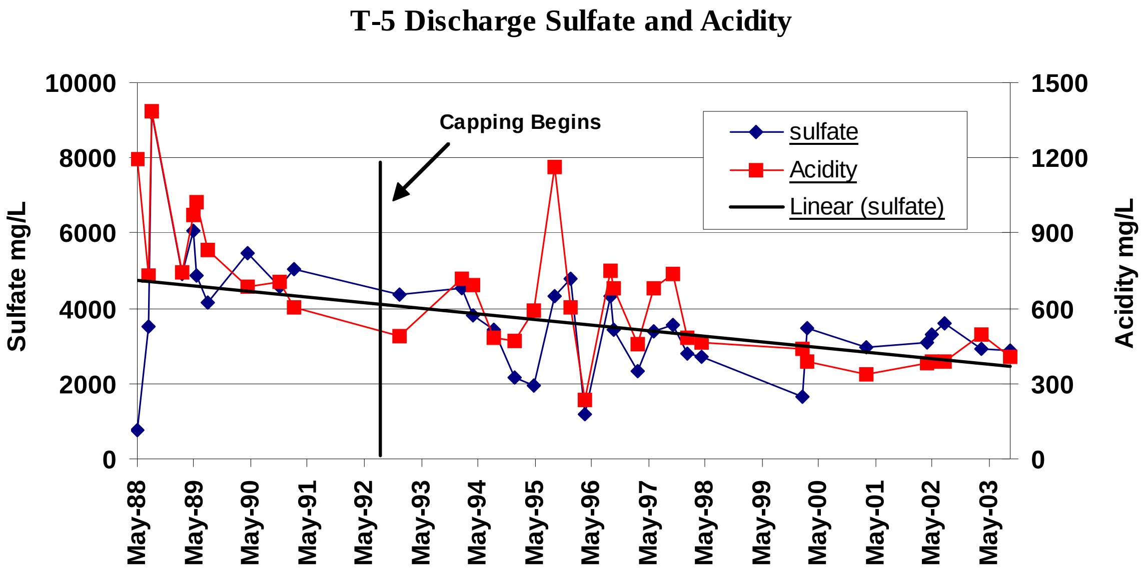


Figure 6.17. Historical quality of the T-5 discharge for sulfate and acidity. Ash placement began in 1992. The trend line for sulfate is included in the graph.

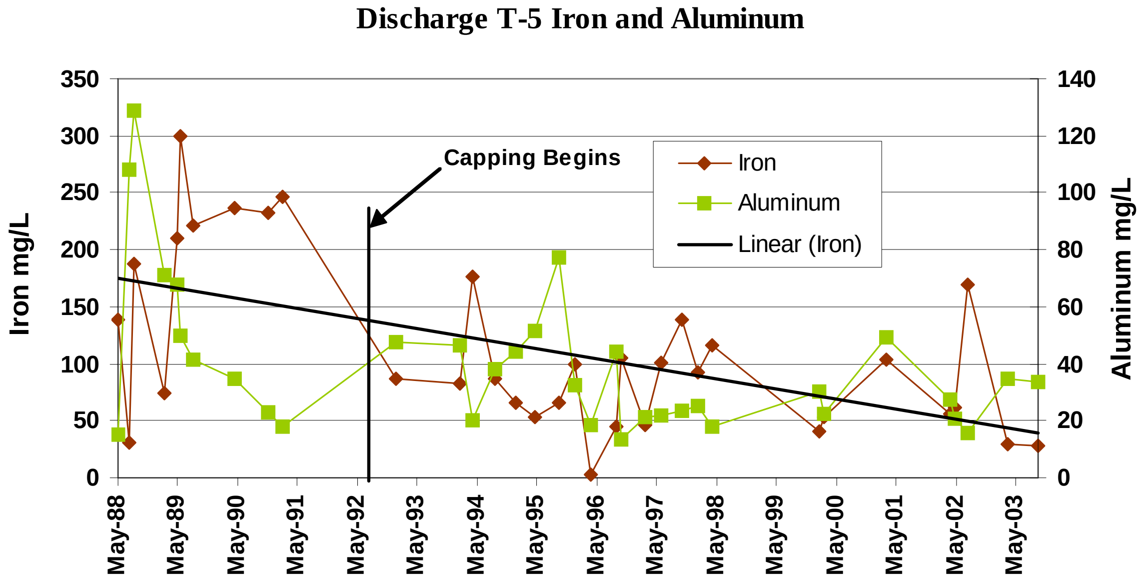


Figure 6.18. Historical quality of the T-5 discharge for aluminum and iron. Although not included, manganese follows a similar trend. The trend line for iron is included.

Being a rather conservative ion in mine drainage, the reduction of sulfate ions clearly suggests that AMD production has been reduced because of the influence of the cap. Acidity also shows a similar decrease in concentration over time. Figure 6.18 shows the historical concentrations of iron and aluminum over time. Similar to sulfate, concentrations of iron and aluminum in the discharge also reflect about a 50% reduction since the beginning of the ash cap.

A secondary objective of the project was to prevent additional pollution as a result of the beneficial use of ash. Evidence of success here includes the chemical quality of the discharge as well as macroinvertebrate and fish sampling in the receiving stream, Upper Three Runs. The results given in Table 6.7 show the absence of EPA priority pollutants from the discharge, which is being mitigated by the fly ash cap. The high concentrations for the parameters commonly associated with AMD, including alkalinity, acidity, iron, aluminum, manganese and sulfates, are attributable to the AMD and not the FBC ash cap.

Table 6.7. Mine drainage discharge quality sampled in 1997. Concentration of AMD parameters for 9/2003 are shown in parenthesis followed by an *.

Parameter	Concentration (mg/L)	Parameter	Concentration (mg/L)
Total Dissolved Solids	5024	Cd	<0.0002
Alkalinity as $CaCO_3$	2 (8.4)*	Ca	326
Acidity as $CaCO_3$	706 (404.8)*	Cr	<0.004
Cl^-	8	Cu	<0.010
F^+	1.7	Pb	<0.001
Fe total	122 (27.6)*	Mg	547
Na	19.3	Hg	<0.001
NH_3 as N	<0.04	Se	<0.007
NO_3 as N	0.43	Zn	2.31
Al	23.7 (33.4)*	Mn	127 (85.5)*
As	<0.004	SO_4^{2-}	3386 (2875)*
Ba	<0.010	pH	(4.2)*

The Pennsylvania Fish and Boat Commission conducted both benthic macroinvertebrate and electrofishing surveys on at least four occasions on Upper Three Runs both upstream and downstream of the fly ash capping project. The results given in Figure 6.19 are for the macroinvertebrates and the electrofishing results are given in Figure 6.20. The water quality and aquatic life in Upper Three Runs has improved significantly since the fly ash cap was placed at the site. No detectable pollution from other EPA priority pollutants has been found in Upper Three Runs.

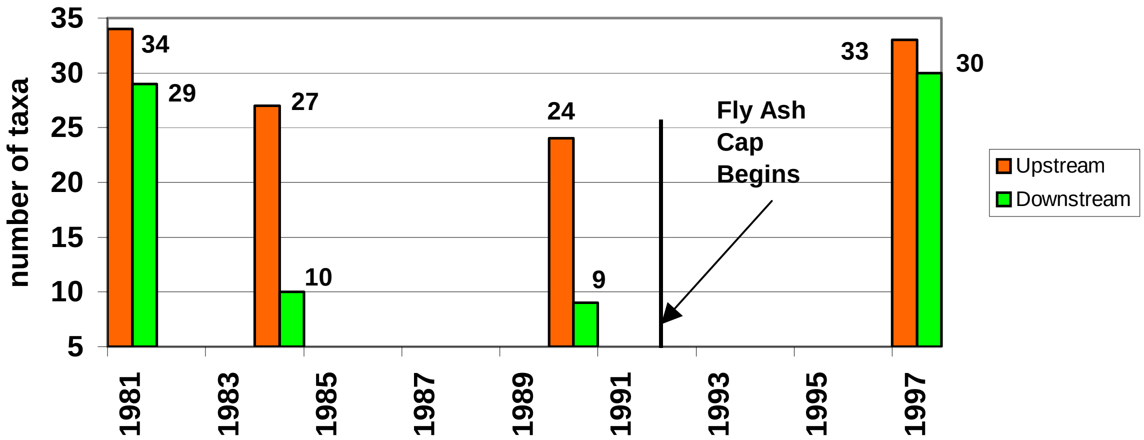


Figure 6.19. Qualitative benthic macroinvertebrate comparison upstream and downstream of discharge

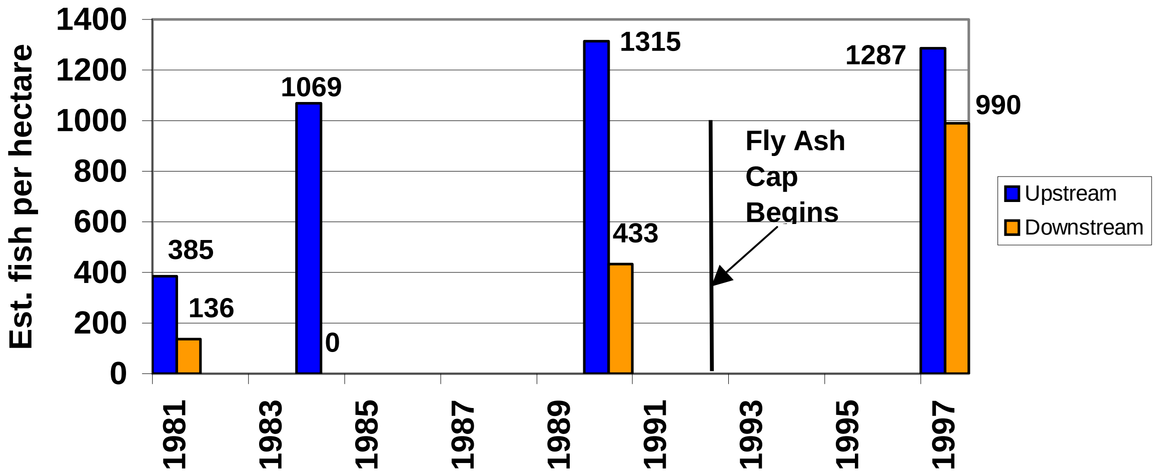


Figure 6.20. Electrofishing results upstream and downstream of discharge.

6.4.1.5 Conclusions

- The fly ash cap at the McCloskey site has enhanced reclamation, abated water pollution, and enhanced the aquatic life in the stream.

- The fly ash cap at the McCloskey site formed an effective barrier that prevents the infiltration of rainwater from entering the groundwater flow regime. Since the horizontal contribution to groundwater flow to the reclaimed spoils being negligible, the fly ash cap has substantially abated the formerly polluted post-mining discharge.

- The fly ash cap at the McCloskey site has not generated secondary problems in the form of EPA priority pollutants in the receiving stream.

This abatement and reclamation project demonstrated the environmentally safe and beneficial use of what otherwise would be considered a waste product. The project clearly demonstrates that a fly ash cap to retard vertical flow would be successful in cases of mine drainage pollution where vertical infiltration of precipitation is the primary source of recharge to a site.

However, if the inflow to a given mine site has a significant horizontal component, retarding the vertical flow from rainfall on the site itself might not be as successful as it has been at the McCloskey site. Insufficient time has elapsed to determine whether, at sites where the natural succession includes plants whose roots might penetrate the cap, a fly ash cap would lose its effectiveness over time or simply limit root zone development.

6.4.2 FBC Ash Grouting of Buried Piles of Pyritic Materials on a Surface Mine – Fran Site.

Effective in-situ abatement technology requires that the source(s) of the AMD production first be located. AMD source location can be done with little difficulty on many surface coal mines using geophysical mapping techniques (Schueck, 1988, 1990) (Schueck et al. 1994). Pyritic materials such as tipple refuse or pit cleanings are often placed in discrete piles and buried. When placed in discrete piles or pods and not properly isolated from infiltrating precipitation or groundwater, severe localized AMD production may result. Under these conditions, geophysical testing method can detect the pods and the resultant AMD plume.

Abatement technology can be applied once the precise locations of the acid producing materials buried within the backfill are determined. The contact of pyrite with oxygen and water is needed to produce AMD. In-situ AMD abatement will result if the pyrite can be isolated from the water and/or oxygen. FBC ash grout was used to isolate pyrite from oxygen and water in this project.

6.4.2.1 Site description

The project site is located in north-central Pennsylvania in the Sproul State Forest, East Keating Township, Clinton County, PA. This 37-acre surface coal mine was mined by the mountain top removal method and reclaimed between 1974 and 1977 under Fran Contracting. The Lower Kittanning coal seam was present in two splits separated by 10 to 20 ft. of clay. Only the upper split was mined, leaving a thick underclay as pavement. The coal was overlain by black shale capped by a sandstone unit. The black shale is pyritic and acid producing. Infiltrating precipitation is the only source of groundwater. Acidic discharges developed soon after reclamation and were first noted after a fish kill in 1978. The discharges (surface and underground), estimated to average 35 gal/min, destroyed five miles of native trout streams. The operator was unable to maintain treatment facilities and forfeited the reclamation bonds.

Buried pyrite-rich pit cleanings and some tipple refuse were found to be producing severe AMD at this site. The pyritic material is located in discrete piles or pods in the backfill, Figure 6.21. The pods and the resulting contaminant plumes were initially defined using geophysical techniques and confirmed by drilling. As demonstrated at the McCloskey site in the previous discussion, isolating the pyritic material from water and oxygen will prevent AMD production.

The AMD discharges from this site are among the worst quality discharges from any surface coal mine in the state. Monitoring wells have been sampled since 1990 to monitor changes in the water quality resulting from grouting efforts. Grouting occurred during the summers of 1992 and 1993.

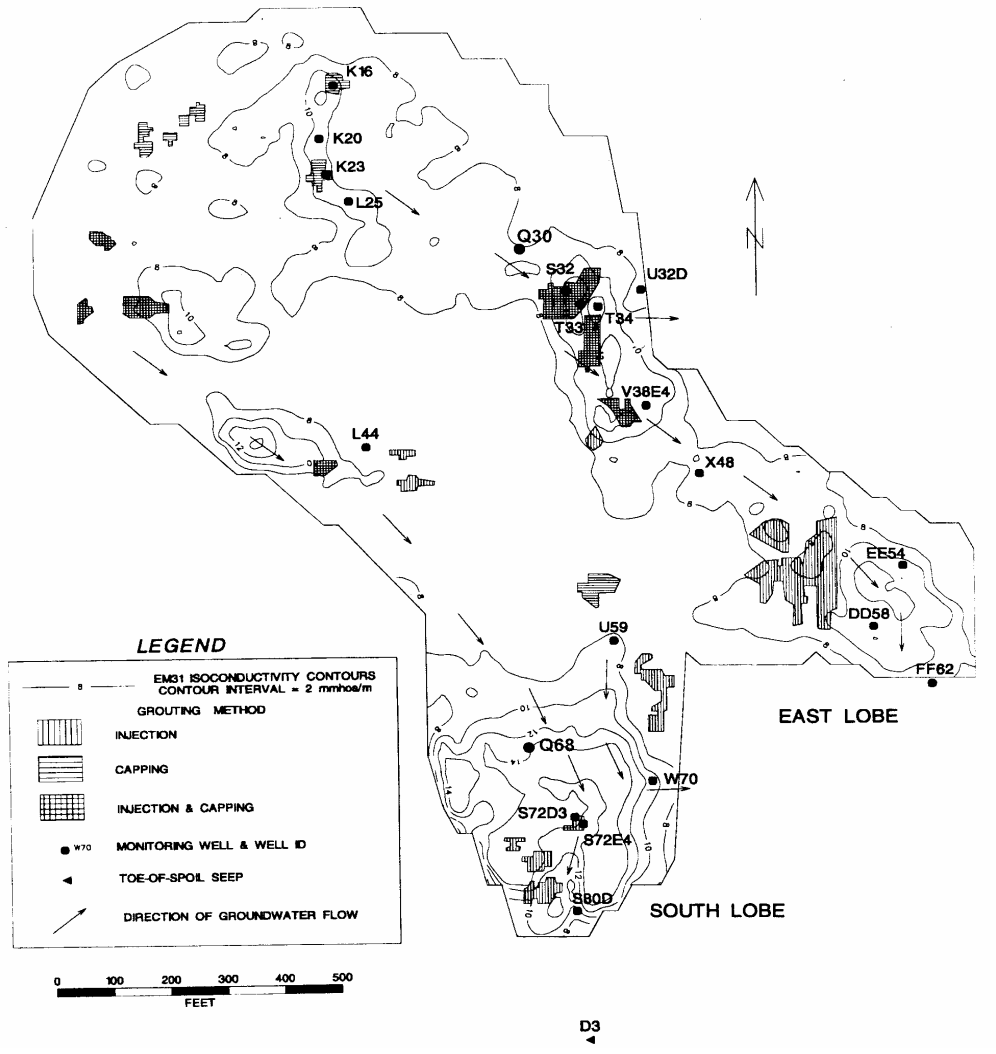


Figure 6.21. Location of buried pods of pyritic materials, sites and types of grout applications and ground monitoring points at the Fran Site, Clinton County.

6.4.2.2 Geophysical investigation and pre-grouting groundwater quality

Several geophysical mapping techniques were used for site characterization. These techniques included electromagnetic terrain conductivity (EM), magnetometry, and very low frequency (VLF). EM was used to map the location of the AMD plumes throughout and off the site. The piles of buried refuse and pit cleanings were located with magnetometry. VLF was used to map bedrock fracture zones beneath and adjacent to the site (Schueck et al., 1994).

EM mapping and drilling data indicated the general groundwater flow path through the site. This is the down-dip direction. The pollutional plumes and groundwater flow direction is indicated in Figure 6.21. EM mapping also indicated pooling of pit water in the down-dip portions of the site behind the low wall. The EM mapping further indicated groundwater pollution plumes leaving the site at three locations where toe-of-spoil (surface) discharges were not present. VLF mapping indicated the presence of fractures in the pit floor, which coincide with the pollution plumes. These fractures apparently channel AMD from the mine spoil to a major joint system beneath the site. The joint system conveys the AMD to Rock Run as base flow, some 250 feet lower in elevation and northeast of the site. A toe-of-spoil discharge, D3, is present beyond the south lobe. The discharge rate of D3 varies from 2 to 85 gal/min and appears as a diffuse seep over a rather large area of about 2 acres. It is at an elevation equal to the lower, unmined split of coal. This discharge flows to the southwest into Camp Run, a tributary of Cooks Run.

Magnetometer mapping was used to determine the locations and configurations of concentrated pods or piles of pyritic materials such as tipple refuse. Magnetic anomalies indicate the aerial extent of the pods of pyritic material buried beneath the surface. In Figure 6.21, polygons are used to indicate the location and extent of the pods of pyritic material and to show the extent and type of grouting applied.

When the magnetic anomaly map was overlain with the EM map, it was observed that conductivity values were highest at or adjacent to the magnetic anomalies, Figure 6.21. The conductivity values gradually decreased in the direction of groundwater flow but showed an increase where the AMD was pooled behind the low wall. This observation is consistent with severe AMD production within the buried pods of pyritic material, followed by dilution as the AMD migrates further away from the pods.

Forty-two monitoring wells were drilled on and adjacent to the site. The wells were located using the results of the combined geophysical mapping. Wells located on the site were drilled through spoil to the pit floor, with depths ranging from 10 to 40 ft. Monitoring wells located adjacent to the site were drilled into the unmined lower split of the Lower Kittanning coal seam. This initial drilling effort confirmed the locations of the pods of refuse and pit cleanings identified with magnetometry. Water quality monitoring was initiated in 1990 and continued through 2001. The grouting occurred during the summers of 1992 and 1993. Sampling of the monitoring wells was done on approximately a bi-monthly schedule from 1990 through 1996, then semi-annually until the present. Water sampling was also performed at the only surface discharge, D3, which is the toe-of-spoil seep located 200 feet south of the site.

Table 6.8 lists pre-grouting water quality for the toe-of-spoil seep and selected monitoring wells, which are considered to be representative of the site (Fig. 6.21). Maximum, minimum, and mean pH values and metals concentrations are presented. These data are based on 13 to 21 sampling events.

The toe-of-spoil seep, labeled D3, and well FF62 represent the pre-grouting water quality which exits the site from the south and east lobes, respectively. Well FF62, located off site and adjacent to the east lobe, intercepts a subsurface discharge plume (as identified by EM survey) suspected to enter Rock Run as base flow. Also, well FF62 samples water in the lower, unmined split of coal. The poor water quality demonstrates fracture communication between the pit floor and lower coal seam. D3 also appears to be coming from the lower coal seam. Comparison of the mean concentrations indicates that the water discharging from the east lobe (FF62) is of poorer quality than that discharging from the south lobe (D3). Drainage from the majority of the pods of pyritic material flows towards the east lobe.

Table 6.8. Pre-grouting water quality from selected groundwater monitoring points. Note the wide variety in concentrations from one monitoring point to the next, especially Well K23.

Monitoring Point D3 – Toe-of-spoil seep area combination of all drainage N=16

	Lab	TDS	SO_4	Acid	FeTot	Fe^{3+}	Al	Mn	Cd	Cu	Cr	As	Zn
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	mg/L
Max	2.7	8828	3749	3520	543	385	348	62.3	66	852	269	40	4.2
Min	2.4	4540	1245	2220	183	149	205	28.4	1.9	399	125	4	2.5
Mean	2.49	6475	2751	2995	321	254	268	48.3	25.5	612	200	20.2	3.4

Monitoring Well FF62 – East Lobe – Groundwater discharge zone combination of all drainage N=15

	Lab	TDS	SO_4	Acid	FeTot	Fe^{3+}	Al	Mn	Cd	Cu	Cr	As	Zn
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	mg/L
Max	2.6	12706	5773	6440	1500	1294	562	67.3	167	1110	301	148	7.5
Min	2.2	3404	1272	1940	386	246	114	14.8	29	611	142	25	2.1
Mean	2.32	7970	3477	4088	876	737	256	39.2	83	806	221	69	4.3

Monitoring Well Q30 – AMD production from Lower Kittanning spoil w/ little influence from buried pods N=17

	Lab	TDS	SO_4	Acid	FeTot	Fe^{3+}	Al	Mn	Cd	Cu	Cr	As	Zn
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	mg/L
Max	2.3	26130	11060	10260	2180	1604	789	141	363	2560	778	208	15.5
Min	2.1	13096	3817	7220	300	25	281	34.2	64	2070	501	4	7.5
Mean	2.05	17000	6804	8492	1559	852	628	85.7	172	2336	633	139	11

Monitoring Well K23 – Severe AMD production in pods N=13

	Lab	TDS	SO_4	Acid	FeTot	Fe^{3+}	Al	Mn	Cd	Cu	Cr	As	Zn
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	mg/L
Max	2.2	128205	25110	23900	5690	2320	2440	79	1190	7410	1816	2890	39
Min	2.0	33706	9868	18280	3320	120	281	30.3	128	3360	593	684	10.8
Mean	2.1	46352	15639	21315	5437	1200	1515	60.5	610	5950	1108	1676	27.6

Monitoring Well X48 – Combined spoil and pyritic pods N=14

	Lab	TDS	SO_4	Acid	FeTot	Fe^{3+}	Al	Mn	Cd	Cu	Cr	As	Zn
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	mg/L
Max	2.8	25372	9950	9760	2210	1816	690	125	368	3370	687	493	10.5
Min	2.2	947	4763	3780	342	0	299	7.8	11	1680	492	169	6.2
Mean	2.37	14085	6991	7470	1707	439	492	72.8	227	2543	559	320	8.7

Monitoring well Q30 represents the pre-grouting water quality resulting from the Lower Kittanning spoil with little influence from buried pyritic pods. Q30 is not located directly downgradient of buried refuse or pit cleanings. Monitoring well Q30 is considered a suitable control well to monitor normal water quality variations on the site because it was not influenced by the grouting activities. Flow from Q30 would be toward the south lobe and eventually to the toe-of-spoil seep.

Monitoring well K23 demonstrates that the pods of refuse or pit cleanings can be sources of severe, localized AMD production. K23 is located within a pile of buried tipple refuse. It is located on the up dip portion of the mine site and is also at the upper end of a pollutional plume as defined by EM. The mean concentrations of the AMD parameters at K23 are two to three times greater than the concentrations of the same parameters in Q30 and X48, which represent AMD generated primarily by the spoil alone. This implies that enhanced AMD production from the pyritic material at K23 and similar locations significantly contribute to the degradation of the final discharge quality. The isolation of these subsurface pods of pyritic material from water and/or oxygen was expected to improve the final discharge quality (see Fig. 6.21)..

Monitoring well X48 is located several hundred feet downgradient of piles of pyritic material, but is within the flow path of mine drainage as it migrates through the site towards the east lobe. The water quality sampled from this well would be influenced primarily by the Lower Kittanning spoil as well as some AMD formed in the buried pods of pyritic materials. X48 indicates dilution of the severe AMD as it migrates and mixes with less severe mine drainage.

Certain trace metals also contribute to the pollution from this site. Elevated concentrations of zinc, copper, chromium, cadmium, and arsenic were common in the drainage from this site. The concentrations of other trace metals, such as lead, nickel, and selenium were generally below detection limits.

6.4.2.3 FBC ash grout injection project concept

The primary objective of this AMD abatement approach was to isolate pyritic material from water and oxygen. In sharp contrast to the McCloskey site where the isolation was achieved by capping the entire site, only those piles of buried pit cleanings suspected of causing the most severe AMD were targeted for isolation. FBC ash was the material selected to be used in this isolation approach. FBC ash was chosen primarily because of its pozzolanic (or cementitious) properties as well as for economic reasons.

A grout, composed of FBC ash and water, was used in two different approaches that attempted pyrite isolation. Pressure injecting grout directly into the buried pods to fill the void spaces within the pods and coat the pyritic materials with a cementitious layer was the first approach. In the second approach, pods that would not accept grout because of a clay matrix were capped with the grout to isolate the pyrite from percolating water.

A low viscosity grout was pressure injected into the geophysically identified zones (pods) as a means of encapsulating the pyritic materials with a cementitious coating. Diversion grouting was also used. This approach included capping of some of the pods and limited pit floor paving. The grouting should generate zones of low permeability and redirect groundwater flow, significantly reducing water contact with the pyrite. Although the spoil, particularly the black shale, across the entire site was thought to be acid producing, the grouting effort was limited to only 5% of the site.

Statistically significant water quality improvements have been noted as a result of the grouting, although results are varied. Any water quality improvements resulting from the grouting are expected to be permanent because of the nature of the cementitious grout.

6.4.2.4 FBC ash characterization and grouting operations

The quality of the coal combustion ash is extremely important, particularly when it is being placed into an acidic environment. The characterization of the FBC ash used at the site was completed at the Penn State Materials Research Institute (Zhao,1995). Chemical analysis of the ash is as follows: $A1_2O_3$ - 12.51%, CaO - 38.03%, SiO_2 - 23.91%, SO_3 - 16.02%. The ash was tested using the EPA's Toxicity Characteristic Leaching Procedure (TCLP). All elemental contents of the ash fell within the established guidelines of the TCLP.

Mixed with only water, the FBC ash forms a low strength cement. After 20 days, at a water to solids ratio of 0.5, an unconfined compressive strength of 1920 psi is developed. The compressive strength continues to increase slowly to slightly over 2000 psi in 90 days (Zhao, 1995).

Only those pods of pyritic material identified with magnetometry were targeted for grouting. The grout injection wells were installed on 10 ft centers using 2 1/2 in. perforated, schedule 40 PVC casing. The injection wells were installed in August 1992. Grouting operations began September 1, 1992 and continued through the end of October 1992. The grouting operation resumed in June 1993 and was completed in August 1993. Grout injection wells were located within the polygons indicated in Figure 6.21. The grout was injected using a 650 psi positive displacement pump. The amount of grout accepted by the wells ranged from less than 0.3 to 83 yd^3 . Approximately 4500 yd^3 of grout were used on this project.

Originally, only pressure injection directly into the pods was planned for the isolation of the pyritic materials. However, soon after the grouting operations began, it became evident that this method would not work for all the pods within the site. Several of the piles refused to accept grout. Excavation within these pods showed the pyritic material was within a clayey matrix. These piles were capped with grout to divert infiltrating precipitation. The spoil above the piles was excavated. The excavated area was then pooled with fly ash grout. After the grout hardened, the excavated area was backfilled and regraded. However, the capping alone would not be effective in preventing lateral flow along the pit floor from coming into contact with the pyritic materials. Several of the pods were both capped and grouted. This combined application occurred where several of the wells within the pod accepted little or no grout, Figure 6.21.

Aluminum concentrations in excess of 1000 mg/L at various locations within the spoil suggested that the clay pit floor is a primary source of Al. Therefore, paving areas of the pit floor with a grout slurry was another water diversion technique applied at this site. The purpose was to isolate the pit floor clays from contact with the AMD within the spoil. Success in this approach depends upon a high permeability of the spoil materials covering the pit floor. Well L25 shows the results of the paving activity and is discussed later in this report. The planned pit floor grouting activities were curtailed due to time constraints, ash supply and project funding.

6.4.2.5 Post-grouting water quality monitoring

Grouting occurred during the summers of 1992 and 1993. Water quality was monitored on approximately a monthly basis, April through November, from 1990 through 1995. Then the water quality was monitored on an annual or semiannual basis until 2001. In order to test the effectiveness of fly ash injection on water quality improvement, a series of one-tailed t-tests were computed for the water quality variables sampled from the monitoring wells. A t-test represents a test of significance that compares the mean and standard deviation of one group of samples to that of another to test if both groups came from the same population. The one-tailed t-test further compares not only if there is a significant difference between the two groups but if one group mean is significantly greater than the other. The $p <= 0.05$ level of significance was used as the rejection level of the null hypothesis for all tests. Davis (1986) and Krumbein and Graybill (1965) provide additional information regarding the t-test in geophysical applications.

For the tests, the water quality data for the respective monitoring wells were divided into two groups: the data sampled before fly ash injection occurred and the data sampled after fly ash injection was completed. It was obvious in some of the wells that the grout supernatant was impacting the water quality during and shortly after the grouting effort. These water samples were excluded from the data analysis.

During the summer of 1995, drought conditions existed at the site. The water quality in one of the control wells, L44, changed dramatically. Mean SO_4 values increased four-fold during the summer of 1995 and concentrations of TDS, acidity, Al, and Fe more than doubled. Moderate increases in concentrations of the mine drainage parameters were noted in most of the monitoring wells across the site during 1995. However, the increases were not nearly as drastic as were observed in L44. There were 7 sampling events in 1995, which represents about 25% of the post-grouting sampling events. There were only 8 sampling events since 1995. Because of this strong bias, the sampling events for 1995 were averaged and the average values were considered as a single sampling event. The conclusions within this paper are based on the averaging of the 1995 samples.

Table 6.9 lists the percentage reduction in mean concentrations for several of the mine drainage parameters for the three different applications. The applications included (a) injection only, (b) capping only and (c) a combination of injection and capping. Data are included for wells located both within the pod (IP) and for wells located downgradient (DG) of the pod. The percentage change in concentrations for two control wells, Q30 and Q68, is included for comparison.

Data for the first four wells in Table 6.9 reflect water quality changes resulting from only injection grouting directly into the pod (Table 6.9(a)). There is within-pod water quality data for only one pod that was subjected to grout injection only. There are two wells located within this pod, S72D3 and S72E4 (Fig. 6.21). Both wells exhibited modest reductions in the mean concentrations of the common mine drainage parameters ranging from 29 to 51%. These reductions are all statistically significant. Significant reductions in trace metal concentrations from 36 to 86% were observed as well. This suggests that AMD production was reduced within the pod as a result of the grout injection. Wells EE54 and DD58 are located downgradient of a pod that was only pressure injected. These wells exhibited 22 to 38% statistically significant reductions in mean concentrations of the common AMD parameters with the exception of a non-significant decrease in sulfate concentrations in one of the wells. Significant trace metal reductions were also noted, although percent reductions were less than observed in the within-pod wells. Wells EE54 and DD58 are situated where the flow of AMD from the site created by the Lower Kittanning spoil can influence them, however.

Table 6.9. Percent reductions in mean concentrations as a result of the three grouting applications.

(a) Application: Injection Grouting Only

Well	Loc*	TDS	SO_4	Acid	Fe	Al	Mn	Cd	Cu	Cr	Zn	As
S72D3	IP	**39%**	**51%**	**41%**	**36%**	**40%**	**47%**	**86%**	**50%**	**44%**	**43%**	**72%**
S72E4	IP	**39%**	**51%**	**38%**	**38%**	**29%**	**44%**	**84%**	**48%**	**45%**	**38%**	**81%**
EE54	DG	**26%**	**38%**	**23%**	**28%**	**24%**	**33%**	**81%**	**25%**	*16%*	**28%**	**62%**
DD58	DG	**22%**	*23%*	**25%**	**28%**	**26%**	**34%**	**84%**	**27%**	**30%**	**30%**	**51%**

(b)Application: Capped Only

Well	Loc*	TDS	SO_4	Acid	Fe	Al	Mn	Cd	Cu	Cr	Zn	As
K23	IP	**32%**	**33%**	**26%**	*12%*	**34%**	**9%**	**77%**	*20%*	**33%**	**36%**	**59%**
K20	IP	**61%**	**70%**	**66%**	**64%**	**60%**	**48%**	**93%**	**61%**	**65%**	**62%**	**81%**
U59	DG	**31%**	**46%**	**35%**	**28%**	**38%**	**34%**	**85%**	**43%**	**43%**	**33%**	*49%*
L25	DG	**51%**	**54%**	**61%**	**61%**	**52%**	**64%**	**82%**	**54%**	**60%**	**60%**	**75%**

(c) Application: Grouted and Capped

Well	Loc*	TDS	SO_4	Acid	Fe	Al	Mn	Cd	Cu	Cr	Zn	As
T33	IP	**67%**	**68%**	**70%**	**79%**	**73%**	**66%**	**92%**	**79%**	**79%**	**70%**	**90%**
T34	DG	**92%**	**92%**	**93%**	**90%**	**93%**	*19%*	**95%**	**96%**	**96%**	**92%**	**91%**
V38E4	DG	**37%**	**44%**	**47%**	**42%**	**47%**	**43%**	**88%**	**50%**	**51%**	**42%**	*10%*

Application: Control Wells – Far or indirectly downgradient from grouting activities

Well	Loc*	TDS	SO_4	Acid	Fe	Al	Mn	Cd	Cu	Cr	Zn	As
Q30	Far	*11%*	*16%*	**14%**	*7%*	*2%*	*-9%*	**56%**	*9%*	**27%**	*-55%*	*33%*
Q68	Ind	*-5%*	*-17%*	*-1%*	*7%*	*10%*	*20%*	*74%*	*5%*	*8%*	*0%*	*-61%*

Negative values indicate a percent increase in mean concentration. Statistically significant changes where P <=0.05 are indicated in bold. Changes that were not statistically significant are shown in normal italics print. Control wells Q30 and S68 are included for comparison.

*Location IP = In-pod; DG = Downgradient; UG=Upgradient; Far=Far From; Ind=Indirectly Downgradient

Table 6.9(b) represents those pods that would not accept the pressure injected grout and were therefore capped. Wells K20 and K23 are located within a pod that was only capped. The worst quality found on the entire site before grouting operations was at well K23, Table 6.8. Despite the poor water quality, statistically significant decreases in the common mine drainage parameters, ranging from 9 to 66%, were observed. Statistically significant reductions in the concentrations of most of the trace metals, ranging from 33 to 93%, were also observed. A downgradient monitoring well, L25, displayed similar reductions. On another area of the site a well downgradient from a pod that was only capped, U59, exhibited reductions in the mine drainage parameters from 34 to 46% and trace metal reductions from 33 to 85%.

Table 6.9(c) represents the situation where pods were both injection grouted and capped. Well T33 is located within a pod that accepted grout quite well, but was capped as an assurance measure. Significant decreases in mean concentrations range from 66 to 79% for the mine drainage parameters and from 70 to 92% for trace metals. Well T34 is immediately downgradient of this pod. Except for manganese, all parameters exhibited reductions in concentration in excess of 90%. The data suggest a reduction in AMD production within the pod and minimal migration of mine drainage from the pod toward the discharge points. Well V38E4 is situated downgradient of another pod which was both grouted and capped. Improvements noted here are less dramatic than in well T34. In well V38E4 significant reductions in concentrations of 37 to 43% were noted for the mine drainage parameters and from 42 to 88% for the trace metals. Grouting of this pod was somewhat less successful than the grouting of the pod at the T33 well location. However, the results are similar to the downgradient well observations for the grouted only situation, wells DD58 and EE54.

For the first year or so after the grouting was completed there were few observed decreases in SO_4 concentrations and there were even increases in some of the wells. However, most of the wells show a decrease in the concentrations of the other mine drainage parameters. The lack of reduction in SO_4 concentrations is not consistent with the premise that AMD production was reduced as evidenced by the reductions of the other mine drainage parameters. Dissolution of sulfate salts across the site is believed to be the reason for the lack of change in sulfate concentrations. Precipitates on the black shales found both on the above and below the ground surface were abundant on the site. Other studies indicate these are likely sulfate salts, most commonly pickeringite, $MgA1_2(SO_4)_4\ 22H_2O$, and halotrichite, $Fe^{+2}A1_2(SO_4)_4\ 22H_2O$ (Cravotta, 1994) and Nordstrom (1982). Re-dissolving of these salts would explain the observations. The continued, longer term monitoring appears to support this hypothesis. For all but one of the wells shown in Table 6.10 statistically significant reductions in SO_4 concentrations ranging from 33 to 92% over time demonstrates a reduction in AMD production as a direct result of the grouting when compared to the two control wells shown in the same table.

Using either total dissolved solids (TDS) or SO_4 as a surrogate measure for comparing the three grouting techniques, Table 6.9, it is quite evident that a combination of both injection grouting and capping of the pods produced the best results. The capping of the piles was the second most successful technique and the injection grouting alone was the least successful. The operator's inability to control grout placement with pressure injection likely reduces the effectiveness of this technique. With the pressure injection directly into the pods, the number and spacing of the injection wells can be controlled, but the path that the grout follows cannot. Pseudokarst conditions exist within mine spoil and the grout will follow the path of least resistance. During the grouting operations, it was not unusual for grout to be injected into one injection well only to surface two or three injection wells away, skipping the intermediate wells. The exceptionally wide variation in the amount of grout each well would accept was further testimony to this phenomenon.

The location of the pod with respect to the location of any perched water tables within the backfill likely influences the result that the combination of techniques works best. Capping only provides protection from infiltrating precipitation. If the pod that is only capped is in contact with water moving across the pit floor, AMD production will likely continue. Conversely, pods that are only injected with grout may not effectively be shielded from infiltrating precipitation.

There has been concern over the use of FBC ash because of the possibility of trace metals leaching from the ash once it is in place. The monitoring of this site should lay these concerns to rest. Trace metals concentrations are not normally determined in routine mine drainage analysis. However, they were determined on this project and their concentrations are presented in Table 6.10 for several of the wells. It should be noted that the concentrations of these metals produced on the site prior to FBC ash introduction are often orders of magnitude higher than the concentrations of the same metals, which leached from the ash in the TCLP. Of perhaps greater significance is the fact that the grouting reduced the trace metal concentrations more that it did the concentrations of the common mine drainage parameters. Cadmium concentrations were reduced most of all, universally. Even where mine drainage parameter reductions were modest at best, Cd reductions were major (wells EE54 and DD58, Table 6.9). Arsenic concentration reductions were generally only 5 to 10% less than that of Cd. This was followed by nearly equal reductions of Cu and Cr at about 30% less than that of Cd. The smallest reductions were noted for that of Zn, being about 5% less than that of Cu and Cr, but still significant.

Opponents of the use of FBC ash for AMD remediation argue that As will leach from the ash and pollute the groundwater and receiving streams. The monitoring data from this site refute those allegations. Just the opposite appears to be the actual case. What is also necessary to bear in mind in this case is that the ash injected into this site for over 10 years has been in daily contact with AMD with a pH ranging from 2.4 to 2.7, an exceptionally strong acid solution not normally found on mine sites. If the ash can prevail under field conditions this severe and rigorous, it is unlikely that the ash will create problems under much milder conditions found elsewhere.

Those metals found to be present at below detection limits were deleted from further testing at the request of the laboratory for economic reasons. It cannot be stated with certainty that trace metals are not leaching from the FBC ash, but it can be stated that there has been a significant decrease in the trace metal concentrations found at the site as a result of using the ash. In this case, the benefits of using the FBC ash far outweigh the concerns with respect to metals leaching from the ash.

It has been questioned whether post-grouting reductions in concentrations of the AMD parameters are a result of AMD abatement or a neutralization of the AMD by the alkaline ash grout. The noted reductions in SO_4 concentrations strongly suggest that AMD abatement is the dominate mechanism occurring here. During the grouting operation it was common to note spikes in calcium concentrations along with significant rises in pH and dramatic reductions in concentrations of other mine drainage parameters due to neutralization reactions. If the supernatant was still present and was responsible for the changes, then it would be expected that there would be statistically significant increases in calcium concentrations wherever there was a significant decrease in the concentrations of the other parameters. That is not the case. The data in Table 6.9 show significant reductions in concentrations of the mine drainage parameters regardless of whether the calcium increased or decreased. Also, the noted spikes in pH usually disappeared within a few months to two years after grouting, indicating a flushing of the supernatant. Subsequent increases in calcium concentrations are thought to result from leaching of the grout.

The concentrations of ferric iron generated from the pods of pyritic material must also be considered when considering the effect that severe AMD generated within the pods has on the rest of the site. Garrels and Thompson (1960) have shown that pyrite is rapidly oxidized by ferric iron in the absence of oxygen and at low pH values.

According to the monitoring well data, Fe^{3+} concentrations from these pods commonly exceeded 1000 mg/L with pH values close to 2.0. Once the water exits the pod, such as the K23 location, it must migrate through 1500 ft of spoil before discharging from the site. The Fe^{+3} is available to rapidly oxidize pyrite located along its flow path to the discharge point. Reduction in Fe^{+3} formation should thus result in reduced pyrite oxidation. Although not shown in Table 6.9, reductions in Fe^{3+} concentrations closely paralleled those of total Fe.

Considering that the overburden on the site is acid producing, as demonstrated by the control wells such as Q30 and Q68, it is necessary to examine the changes in the water quality that discharges from the site to evaluate the overall effectiveness of the grouting effort. When reviewing the data, it is important to keep in mind that only 2 of the 37 acres (5% of the site) were directly affected by the grouting effort. Table 6.10 presents the pre- and post-grouting mean concentrations for several of the parameters tested, along with the percent reductions. A negative value indicates the concentrations increased rather than decreased.

There are three monitoring wells and a toe-of-spoil discharge which intercept AMD discharge plumes, as identified by the EM mapping, Figure 6.21. All of these wells are located along down-dip portions of the mine site and reflect the quality of water leaving the site from the lower split of the Kittanning seam. However, all three wells indicated a wide range in water quality, both before and after grouting. During the spring, the water quality is historically much better than during the summer and fall months. The lower split of the Lower Kittanning seam extends beyond the limits of the mining on the north and west sides. The winter snow pack is normally up to five feet thick. It appears that as the snow pack melts water infiltrates to this lower split of coal and migrates down dip, diluting the AMD intercepted by the monitoring wells. Even with this scatter, statistically significant reductions in mine drainage parameters of greater than 45% were noted for these wells. These improvements are notable considering that the total area affected by the grouting was only 5% of the surface mined area. The improvement in the quality of the discharge D3 is not nearly as dramatic as the monitoring wells. However, as can be seen in Figure 6.21, there was little actual grouting completed upgradient of this discharge. Additional work upgradient of the D3 discharge was planned, but was terminated due to time, ash supply and funding constraints.

Table 6.10. Pre- and post-grouting mean concentrations of mine drainage constituents and percent reduction in mean concentration for wells and toe of spoil seep located in discharge plumes. For locations refer to Figure 6.21.

Monitoring Well FF62												
Condition	Lab	TDS	$S0_4$	Acid	Fe tot	Al	Mn	Cd	Cu	Cr	Zn	As
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	μg/L
Pre-grout	2.3	7970	3477	4088	876	256	39.2	83.6	806	221	4270	69
Post-grout	2.6	4235	1749	2151	411	132	18	25	610	133	2321	27
Reduction	**-13%**	**46%**	**50%**	**47%**	**53%**	**48%**	**53%**	**69%**	*24%*	**39%**	**45%**	**60%**
Monitoring Well S80D												
Condition	Lab	TDS	$S0_4$	Acid	Fe tot	Al	Mn	Cd	Cu	Cr	Zn	As
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	μg/L
Pre-grout	2.4	9951	3500	5096	937	394	45.5	108.5	1542	394	4754	56
Post-grout	2.9	4914	1825	2148	343	193	22.4	18	576	156	2139	14.8
Reduction	**-23%**	**51%**	**47%**	**58%**	**63%**	**51%**	**51%**	**83%**	**63%**	**60%**	**55%**	**74%**
Monitoring Well W70												
Condition	Lab	TDS	$S0_4$	Acid	Fe tot	Al	Mn	Cd	Cu	Cr	Zn	As
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	μg/L
Pre-grout	2.6	9689	3695	4611	735	397	49.4	60.2	985	221	4931	19.5
Post-grout	3.0	3000	1630	1657	165	133	15.8	83	395	102	1559	17.8
Reduction	**-16%**	**69%**	**56%**	**64%**	**77%**	**66%**	**68%**	**80%**	**60%**	**54%**	**68%**	8%
Toe of Spoil Discharge D3												
Condition	Lab	TDS	$S0_4$	Acid	Fe tot	Al	Mn	Cd	Cu	Cr	Zn	As
	pH	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	μg/L	μg/L	μg/L	μg/L
Pre-grout	2.5	6451	2451	3022	326	289	48.6	37.6	743	200	3455	20.2
Post-grout	2.53	5351	1815	2445	276	240	39.9	18	654	186	3062	17
Reduction	-1%	17%	**28%**	**19%**	15%	**16%**	**17%**	**52%**	**11%**	7%	**11%**	11%

Statistically significant % reductions are indicated in bold. A negative value indicates a % increase.

6.4.2.6 Chemical interactions between AMD and FBC ash grout

Monitoring well L25 provides a fairly clear picture of the chemical changes that occurred as a result of the ash injection into an acidic environment. L25 is located in the AMD plume downgradient of the pod of pyritic material at the K23 location. Pre-grouting water quality indicated the presence of severe AMD. Three injection wells were drilled within 50 feet of well L25 to accommodate a pit floor paving experiment. Only the bottom of the casing was open so that all of the injected grout would be directed to the pit floor. The two adjacent wells accepted a total of 90 yd^3 of grout and a third located 50 ft downgradient accepted 20 yd^3 . In addition to the grouting, a "dry" ash cap was placed at the end of September 1993 within 30 feet of well L25. During the two grouting seasons, ash that had gotten wet and formed large clumps was cast to the side of the mixing bin. During final site cleanup, this ash was buried in its dry state adjacent to the cap placed over the pod intercepted by well K23 (Fig. 6.21). This ash would be subject to leaching by infiltrating precipitation.

The following graphs illustrate the chemical changes that occurred when the grout interacted with the AMD. The first graph, Figure 6.22, depicts the changes that occurred to pH. Prior to the grouting, the mean pH was 2.3. Grouting occurred during June 1993. The pH increased immediately to 8.9 because of the highly alkaline supernatant. Over the next several months, the pH value gradually dropped. In 1994, the mean pH was 2.8. The pH was back to pre-grouting levels by 1996.

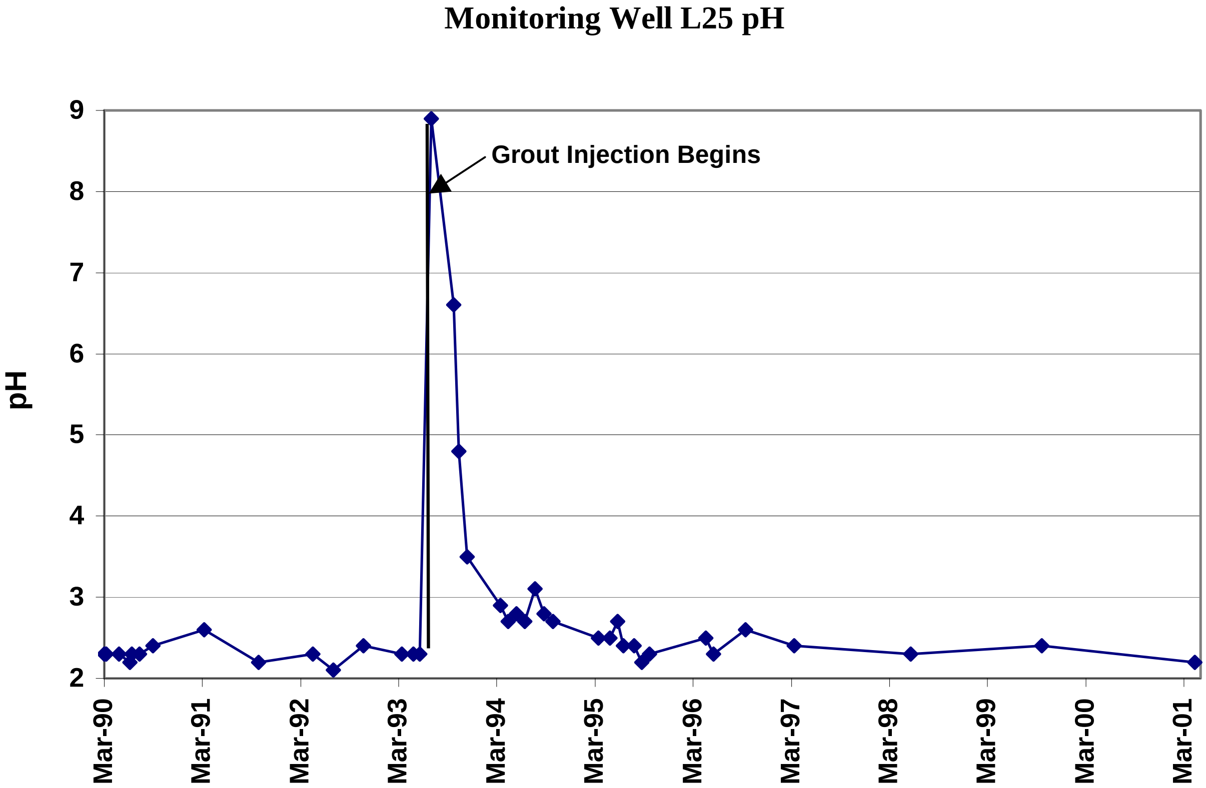


Figure 6.22. Response in pH monitoring well L25 to pit floor grouting effort.

Figure 6.23 is a graph of SO_4 and acidity concentrations over time. These two variables likewise show a response to the grout supernatent. Sulfate concentrations averaged 6496 mg/L prior to grouting. After grouting, the concentrations were close to 1500 mg/L for the next four months. Since that time, the SO_4 concentrations have risen, but are presently 2900 mg/L, much lower than the pre-grouting levels. The effect of the drought conditions in 1995 are clearly evident in the graph, where concentrations of virtually all constituents increased dramatically for all wells. Acidity levels also dropped dramatically as a result of the supernatent. In fact, the alkalinity concentration 90 days after the grouting was 766 mg/L. Similar to sulfate, the acidity concentrations spiked during the 1995 drought, but returned to and remain at below pre-grouting levels. Overall, there have been reductions in concentrations of 54% and 61% for sulfate and acidity, respectively, as a result of the grouting effort.

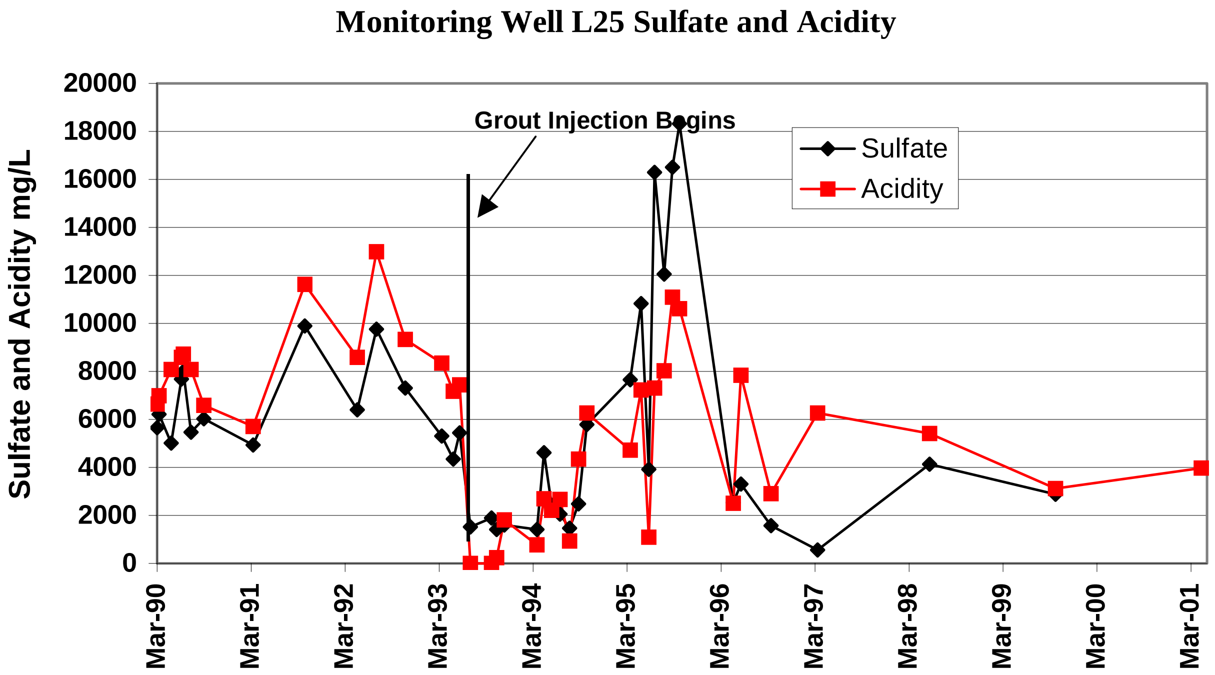


Figure 6.23. Sulfate and acidity response to pit floor grouting effort. Note the temporary effect of the drought during 1995.

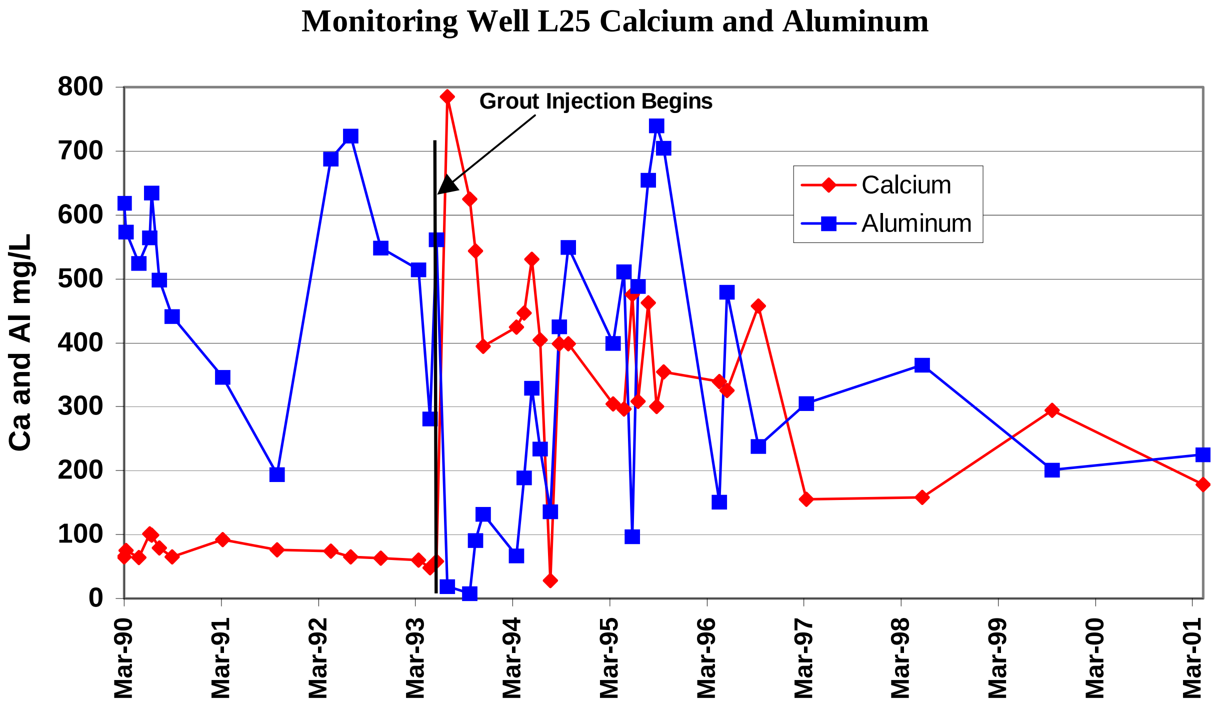


Figure 6.24. Calcium and aluminum response to the pit floor grouting effort. Note the general inverse relationship between Al from AMD and Ca, primarily from the grout.

The long-term response by aluminum suggests that pit floor paving may be effective in reducing leaching of the clays. Calcium and aluminum concentrations are included in the graph shown in Figure 6.24.. Shortly after grouting, A1 concentrations dropped to a low of 8 mg/L and have since rebounded, but are less than half of the pre-grouting concentrations. Although not shown on the graph, concentrations of iron and manganese closely paralleled that of Al. Calcium shows a rather different behavior. The mean Ca concentration prior to grouting was 72 mg/L for well L25. After injection, the concentration rose sharply to over 700 mg/L as a result of the supernatant. Since then, the mean concentration has returned to about 200 mg/L, above the pre-grouting value.

Based upon testing performed in the laboratory by the Penn State Materials Research Institute, there is an explanation for the increase in calcium. Within the grout, the calcium is normally present in three chemical phases. These include, in the order of decreasing solubilities, calcium hydroxide (log K=-5.05), calcium aluminum silicate hydrate (log K=-8.16 to -22.54), and calcium aluminum sulfate or ettringite (log K= -111.2). The high calcium concentrations are most likely a result of the dissolution of the calcium hydroxide. The calcium aluminum sulfate and the calcium aluminum silicate hydrate are likely to leach over time, but at a much slower rate than the calcium hydroxide. These reactions are similar to what would be expected if Portland cement had been injected instead of the fly ash .

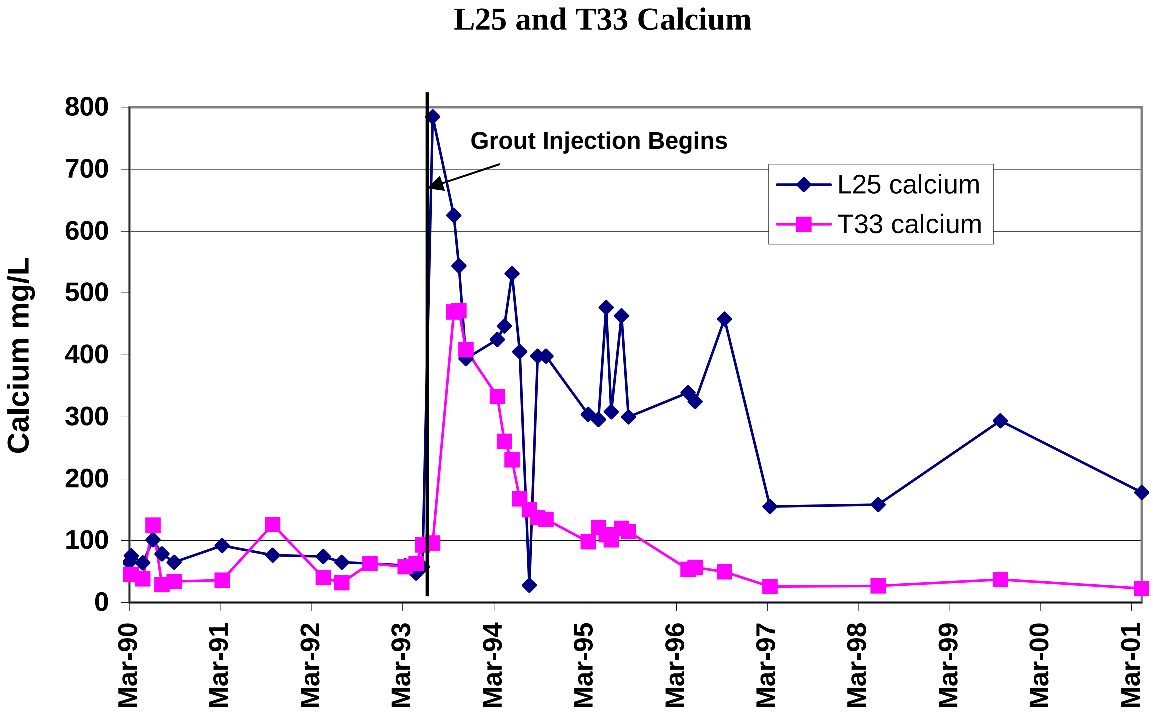


Figure 6.25. Long-term calcium concentrations in two monitoring wells.

The long-term increase in calcium that was noted in well L25 is not a universal occurrence at this site. The opposite was observed in monitoring well T33, an in-pod well where the pod was both grouted and capped, as shown in Figure 6.25. For both wells, the grouting occurred during the summer of 1993. An immediate increase in calcium from the supernatent was noted in both wells. The increased levels of calcium were noted for three to four years after the grouting. After that, the concentrations leveled off. The post-grouting calcium concentration in T33 is less than that observed during the pre-grouting period, the opposite of what occurred in L25. As a whole, there have been both increases and decreases in calcium concentrations and there is no consistent pattern that has been established with respect to grouting technique.

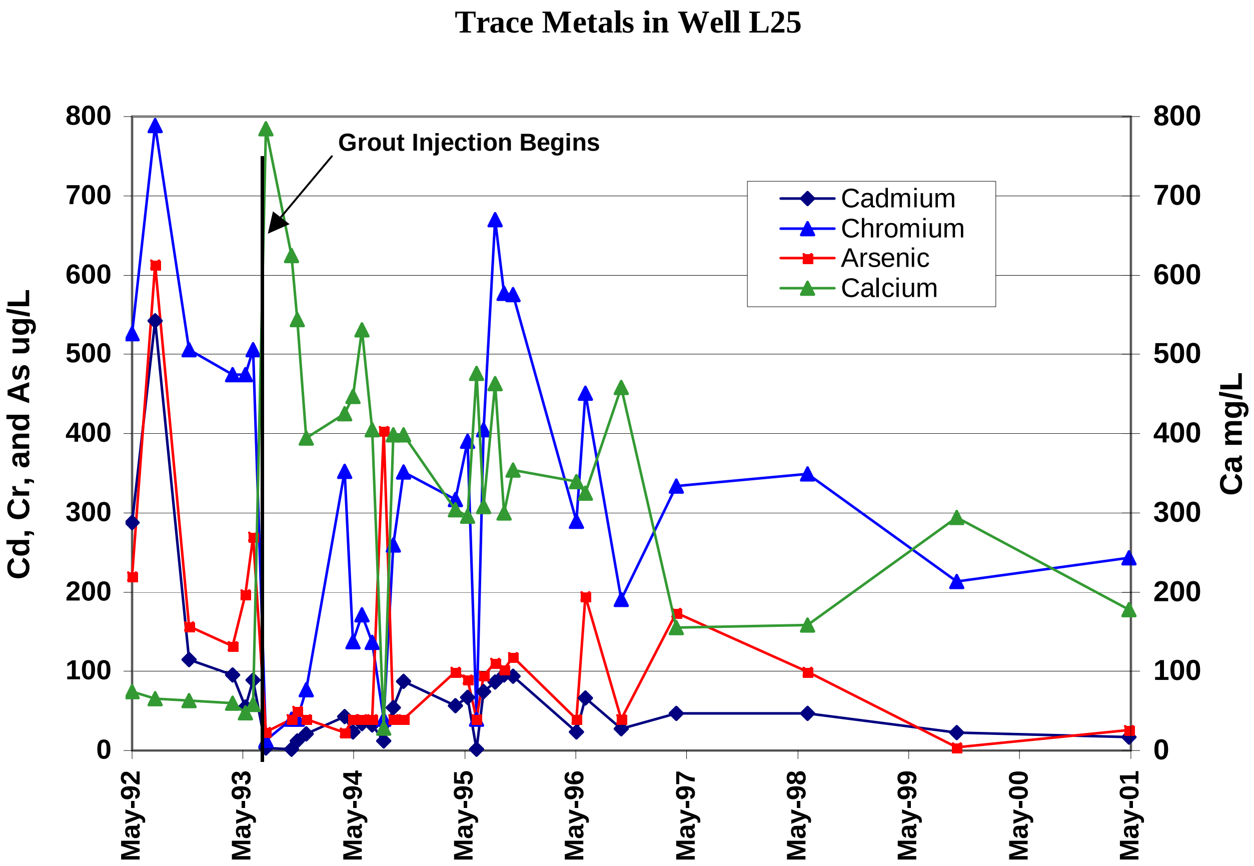


Figure 6.26. Long-term behavior of Cd, Cr, and As in well L25.

The final graph, Figure 6.26, illustrates the behavior of the trace metals cadmium, chromium and arsenic over time and provides evidence that the source of the trace metals is the spoil, not the FBC ash. Throughout the history of sampling on this site, arsenic, chromium and cadmium behaved in similar fashion. Following the injection of the grout in June 1993, the concentrations of these metals decreased dramatically because of the neutralizing effect of the supernatent. As the supernatent was flushed from the area, the concentrations of the trace metals rose somewhat, but remain well below pre-grouting levels. Note that, before grouting, trace metal concentrations fluctuated while calcium concentrations remained relatively constant. As stated earlier, calcium concentrations are more than twice as high post-grouting as they were pre-grouting. Post-grouting fluctuations in calcium concentrations are also quite noticeable. Note that, especially since 1997, there is an inverse relationship between the trace metals and calcium. If the FBC ash was the source of the trace metals, one would expect a direct relationship, i.e.

trace metal concentrations would rise when calcium concentrations rose. This is not happening and suggests that the leaching of the calcium from the FBC ash suppresses the dissolution of trace metals from the spoil

6.4.2.7 Summary of In Situ Grouting of the Fran Site

The pods of pyritic material were treated with FBC ash grout in three ways: 1) injection only, 2) capping only, and 3) both injection and grouting. Based on the water chemistry, the combination of injection grouting and capping produced the most favorable results, followed by capping only. Injection grouting produced the least favorable results. The combined approach inhibits contact between water, oxygen and pyrite by limiting infiltration as well as diverting lateral flow around the pods. Injection limits contact via lateral flow, but may not inhibit vertical infiltration. Capping is most applicable in situations where the pods are located high in the spoil and above the level of water table fluctuations within the backfill.

The inability to control final grout placement is a major drawback of the injection process. Pseudokarst conditions became established during backfilling operations (Hawkins, 1998). Because the gout is a viscous fluid, it will tend to flow into high permeability zones when pumped into spoil under pressure. If the permeability within the pod is low, the injected grout may flow away from the pod instead of filling the voids within the pod as intended or the well will accept very little grout. When this happens, AMD abatement will be limited or will not occur at all.

The placement of the grout in the capping operation is controlled by the operator and is a direct approach. The ability to control infiltration zones is dependent upon the area of excavation and grouting. This approach is appropriate where the pyritic material does not come into contact with water moving along the pit floor.

Use of the FBC ash grouting techniques on this site resulted in an overall improvement in water quality. Although the percent reduction in mean concentrations varies, concentrations of the common AMD parameters generally decreased by 45 to 65% and reduction of trace metals were usually higher. This is significant because the grout application occurred on only 5% of the site. The research effort was to designed demonstrate that FBC ash grout could effectively reduce the severe AMD production within the pods of pyritic material buried within the spoil. The noted water quality improvements indicated this goal has been met; however, the degree of improvement is somewhat less than what the researchers had hoped for. Any changes in water quality, which resulted from the grouting, are expected to be permanent because of the pozzolanic nature of the grout. It was known that the entire site generated AMD and there was no pretense of eliminating all AMD production. Despite less than total success at AMD abatement, the authors view injection grouting as a viable AMD abatement technique is worthy of application on sites which meet certain criteria. This technology is perhaps best indicated for those sites which would normally produce net alkaline drainage but improper placement of refuse or pit cleanings has resulted in an acidic discharge. The use of FBC ash is also recommended on active surface mines and refuse disposal sites as a preventative measure. FBC ash grout can be used in a controlled approach on active sites. The ash grout can be applied directly to or mixed with refuse and pit cleanings to create monolithic structures capable of diverting water away from the pyritic materials.

6.5 CONCLUSIONS

1. Coal ash has been used in many abandoned mine hazard abatement projects in Pennsylvania in the past 35 years by state and federal government agencies. Most of these projects involved the use of pulverized coal powerplant ashes (PC ash), mixed with Portland cement (and sand or other aggregate material in some cases) to form grout mixtures that were pneumatically injected through boreholes into abandoned underground mines. In the Centralia Mine Fire in the Anthracite Region, starting in 1969, and numerous other anthracite and bituminous mine fires, many thousands of tons of the ash/cement grouts were injected to form barriers to attempt to control the mine fires. While these noncombustible ash barriers may have been effective in controlling the spread of the fires, they have not been successful in completely extinguishing the mine fire in most cases. However, the use of coal ash in these cases has not been shown to cause pollution of the mine pool or other groundwater degradation.

2. Coal ash cement grout mixtures have been used in numerous mine subsidence control projects in the anthracite and Bituminous Region. Most of these subsidence control projects used PC ashes that were injected through boreholes into abandoned underground mines, where the ash cement grout was either in direct contact with the minepool or in a groundwater flow path hydrologically connected to the minepool and/or mine drainage discharge points from the underground mines. Although many of these projects were completed with PC ash prior to the regulatory requirement to adjust the pH to a range between 7.0 and 12.0 for mine reclamation purposes, no cases of groundwater pollution related to this coal ash use have been reported. The widespread use of these coal ash cement grout mixtures has been effective in controlling mine subsidence and protecting homes and other structures on the land surface.

3. Coal ash, particularly FBC ash, has been used successfully in the Sharp Mountain Reclamation Project to make a cement-like grout that has structural properties suitable for plugging or bridging mine voids and cropfalls. The strength of the grout mixture is enhanced with the addition of Portland cement, cement kiln dust or other similar materials. Grout strengths are variable depending on the calcium content in the ash. Additional reinforcing materials such as rebar can be added to provide structural support (tensile strength) and the grout mixture can be adjusted to a consistency that allows it to flow freely these materials.

4. Coal ash can be used successfully as a bulk fill material for backfilling cropfalls and other mine subsidence features where little on-site material is available. Coal ash is available in abundance in the Anthracite and Bituminous Regions and it can be an economically viable alternative to importing other materials.

5. The use of coal ash in AMD abatement at the McCloskey site in Clearfield County, through the construction of a coal ash capping layer on the surface of the backfilled

surface mine, has significantly reduced infiltration of groundwater through the backfill and thereby substantially abated the post-mining AMD discharge. The improvement in water chemistry demonstrates abatement and the reduction in flows demonstrates the ability of an ash cap to serve as an infiltration barrier.

6. The coal ash cap at the McCloskey surface mine site has not generated secondary pollution problems in the receiving stream, and has allowed the population of a stream by fish which otherwise wouldn't support fish.

7. The use of an FBC ash cement grouting techniques to encapsulate the buried pods of pyritic refuse material at the reclaimed Fran surface mine site resulted in an overall improvement of the water quality of post-mining discharges. Generally, the mean concentrations of acid mine drainage parameters decreased by 45-65%, which represents a significant reduction in the pollution load to receiving streams. This project showed that there is a potential future for in situ grouting which requires more development.