AN INJECTION TECHNIQUE FOR *IN-SITU* REMEDIATION OF ABANDONED UNDERGROUND COAL MINES[1]

by

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Abstract. Remediation of underground mines can prove to be a difficult task, given the physical constraints associated with introducing amendments to a subterranean environment. An acid mine abatement project, involving an *in-situ* chemical treatment method, was conducted by the University of Oklahoma. The treatment method involved the injection of an alkaline coal combustion by-product (CCB) slurry into a flooded mine void (pH 4.4) to create a buffered zone. Injection of the CCB slurry was possible through the use of equipment developed by the petroleum industry for grouting recovery wells. This technology was selected because the CCB slurry could be injected under significant pressure and at a high rate. With higher pressure and rates of injection, a large quantity of slurry can be introduced into the mine within a limited amount of time. Theoretically, the high pressure and rate would improve dispersal of the slurry within the void. In addition, the high pressure is advantageous in fracturing or "breaking-down" obstructions to injection. During the injection process, a total of 418 tons of CCB was introduced within 15 hours. The mine did not refuse any of the material, and it is likely that a much larger mass could have been added. One injection well was drilled into a pillar of coal. Normally this would pose a problem when introducing a slurry; however, the coal pillar was easily fractured during the injection process. Currently, the pH of the mine discharge is above 6.5 and the alkalinity is approximately 100 mg/L as $CACO_3$.

Introduction

A remediation project conducted by the University of Oklahoma, in conjunction with the Oklahoma Conservation Commission, investigated the feasibility of treating an abandoned underground coal mine by chemically altering the characteristics of the mine water. A relatively small mine was selected as a demonstration project. Remediation efforts investigated the feasibility of introducing fluidized bed ash (FBA), a type of coal combustion by-product (CCB), with the intent of neutralizing acidity, precipitating metals, and imparting alkalinity to the mine drainage. In order to introduce the alkaline CCB to the appropriate locations, a delivery method had to be devised that could overcome the variety of uncertainties which are commonly associated with a flooded mine environment, Typical obstacles at a mine site include missed wells (those that enter into pillars rather than voids), collapsed mine workings, and/or the storage of materials which create obstructions. If the remediation effort was to be successful, then obstacles could not hinder the treatment process. In addition to the potential obstructions, the treatment strategy required significant dispersion in order to create a buffered region of alkaline material.

A delivery technology was selected that could introduce the alkaline slurry into the mine void under significant pressure and at a high rate. With high pressure and high rate of injection, a large quantity of slurry could be introduced within a relatively short time. Theoretically, the high pressure and rate could improve dispersal of the slurry within the void. Instead of allowing gravity to be the driving force, a pressure gradient is developed which should result in greater movement within the mine. In addition, the high pressure would be advantageous in fracturing or "breaking-down" obstructions to injection. For example, if an injection well is inadvertently located within a coal pillar or in the rubble of a roof collapse,

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the high pressure could potentially clear the obstruction or open a pathway.

The goal of this paper is to convey the results and findings generated from the injection aspect of the study, and also to provide practical information regarding the use of this type of injection strategy.

Background

Project Overview

Numerous treatment methods have been devised to address the adverse environmental impacts associated with acid mine drainage (AMD). However, these developments have historically relied on control devices which fall short of addressing the problem. Control technologies are often expensive (estimated to exceed one million dollars a day nationwide, Kleinmann, 1991), elaborate, and require regular attention. Thus many of the control techniques are impractical in the treatment of AMD from abandoned mine sites.

With respect to underground mines, a more practical approach may be the reclamation of AMD through treatment with CCBS. Water collects within the mine workings to form pools or reservoirs of AMD. If such pools can be treated *in-situ*, the adverse effects associated with their discharge can be avoided or prevented. The introduction of a FBA slurry at strategic locations within the mine void represents one potential method of treatment. The coal combustion by-products will alter chemical conditions in the injection area, thus precipitating dissolved metal species, neutralizing the acid already produced, and imparting alkalinity to the drainage. As a result, the water discharged from the mine will have a reduced metal load, a higher pH, and improved buffering capacity.

Alkalinity imparted by CCBs tends to be caustic in nature. The caustic alkalinity is in the form of lime (CaO) and calcium hydroxide ($Ca(OH)_2$), which are both slightly soluble minerals. When placed in contact with acid mine water, significant amounts of alkalinity are imparted to the system, which will neutralize the existing acid and increase the pH. Through pH adjustment, metal species will precipitate as hydroxides. As a result, the drainage from the mine will have an elevated pH, increased alkalinity, and reduced metals load. The goal of the injection treatment was to create a highly alkaline buffering zone. The buffered region will treat acid generation from other locations in the mine prior to its discharge. Introducing alkaline materials at strategic locations inside the mine is essential to the success of this *in-situ* remediation. Also, the distribution of the slurry is critical. If the alkaline material does not disperse and create a buffered region, then acidic mine water can pass through the system without being treated.

In other mine injection studies (Petzrick, 1996; Meiers, 1996), when CCB slurries were introduced using gravity feed or low pressure gradients, the injection well refused material after some time period, or the flow was restricted because of obstructions or fiction. According to Petzrick (1996), the manner in which the material is fed into the mine will influence the distance of flow. Continuous injection, as opposed to intermittent injection, appeared to maximize the flow distance. Meiers (1996) reported that the CCB grout material flows in a lava-like manner, displacing the water in the void rather than mixing with it. The objectives of those studies were different from the one proposed by the University of Oklahoma. In the previous studies the mine void was being filled with a grout mixture for subsidence control and/or for the abatement of acid mine drainage (AMD). Subsequently, there were different injection requirements. Our project required relatively even distribution of the slurry; gravity fed mechanisms would probably produce only pockets of alkalinity. In addition, we needed an injection process that would not change the primary flow paths or plug the discharge point. Gravity fed injection methods would probably seal portions of the mine and alter hydraulic gradients.

Site Description

The project site is located in southeast Oklahoma, 160 miles east-south-east of Oklahoma City, near the town of Red Oak ($S^1/_2$, $SE^1/_4$, Section 1, Range 21 east, Township 4 north, Latimer County). The area of interest is located in the Interior Province, Western Region Coal Field (Shannon, 1926), or more specifically, in the Howe-Wilburton Coal District. The district is located in the McAlester Marginal Geomorphic Province (Johnson, 1974) and is in the Arkoma Basin.

Bache and Demnan Coal Company operated the mine from 1907 until at least 1925. Ownership and time of operation were based on several mine maps obtained from the Oklahoma Department of Mines, (Oklahoma City, Oklahoma); however, there is no readily available official record of ownership. All calculations and quantitative estimates are based on measurements from these engineering mine maps and best professional judgement.

The mine was a down-dip slope operation that undermined approximately 46.5 acres. From a mine map dated January 1925, the entire mine volume was estimated to be 8.1×10^6 ft^3. Mine map measurements indicated that approximately 30 to 50 of the coal was left in place to act as support. As a result, the actual mine void volume was calculated to be roughly 5.7×10^6 ft^3. An estimate of the flooded portion of the mine was based on the position of a portal on the mine map. The assumption was made that if the water volume was above the elevation of the portal, then the portal would be discharging acidic water. The portal was not discharging water; therefore, the elevation of the pool was estimated to be below the portal. Based on this assumption, approximately 3.9×10^6 ft^3 of void space are suspected to be flooded (29 million gallons).

When the mine was operational, water drained to the base of the main corridor into a sump room. Here, water was collected and pumped to the surface. Since the mine closed, water has collected and formed a pool. Over the past 70 years, water has accumulated and the pool elevation has risen to a point higher than the elevation of the valley floor. Thus, a gradient was created which allows water to discharge from the mine due to potentiometric pressure, forming an artesion well. The present day seep point is believed to be the remnant of a sump discharge pipe, but there is no record of this feature on any of the maps.

This flooded portion forms a reservoir or pool that maintains a relatively constant hydraulic head. Pool volume fluctuates with rainfall, but without a drastic change in seep discharge. As the pool rises above a certain point or elevation, a modest increase in seep flow is observed. Chemical and physical characteristics of the mine water were monitored over the past two years. A listing of the major chemical constituents and physical conditions are presented in Table 1.

The room-and-pillar extraction method utilized in this mine produced a tiered pattern that resembles a street grid. It consisted of one north-south entry and at least five east-west entries (Figure 1). The north-south entry acts as the main street and bisects the five east-west entries. Each east-west entry or "side street" varies in length from a few hundred feet to a 0.25 mile. For the purpose of description, the entries

Table 1 Average values for chemical and physical characteristics of the mine water at the Red Oak, OK site

Element	Conc. (mg/L)	Parameter	Value
Al	6.2	Temp (°C)	17.2
Ca	62.6	pH	4.4
Fe	192.9	Conductivity (mS)	1.17
Mg	41.9	Turbidity (NTU)	0.1
Mn	6.6	Acidity (mg/L $CaCO_3$)	475

have been named based on location. The north-south entry will be referred to as the "main" entry, and the east-west entries have been numbered in a descending order. The first entry (from the south) is called "1" with the two halves named "1-east"(1E) and "1-west"(1W) depending on the location with respect to the main entry. The names for the second tier are "2-east"(2E) and "2-west"(2W). The naming procedure continues in a similar manner for the remainder of the entries.

Theoretically, if a buffered treatment zone can be created around the seep, then the water discharging from the mine will be of higher quality. In order for this to be achieved, an injection strategy was devised which consisted of six wells positioned around the seep discharge. Originally, seven wells were proposed, but due to economic constraints one well was not drilled. Three wells were placed on the east side of the seep, two wells on the west side, and one almost directly in line. Each of the east and west wells corresponded to a tier within the mine, while the middle well was placed on the main north-south entry. The well placement facilitated the creation of the buffered zone by creating a treatment area 250 feet by 1000 feet, or roughly 5.7 acres. The actual treatment area is difficult to determine given the nature of the mine environment.

<u>Injection Equipment</u>

Injection of the CCB slurry was possible through the use of equipment developed by the petroleum industry for down-hole cement grouting.

This technology was selected because the CCB slurry could be injected into the mine void under significant pressure and at a high rate. High pressure and rates of injection are preferred because a large quantity of slurry can be injected in a short period of time. Presumably, the high pressure and rate would also facilitate dispersion within the void. Instead of allowing gravity to be the driving force, a pressure gradient is developed which may allow greater movement and distribution throughout the mine.

Haliburton Energy Services (Duncan, Oklahoma) was contracted to adapt their down-hole cementing technology to mine injection. The injection strategy was centered around an ADC RCM II (auto density control recirculating cement mixing) pump truck outfitted with dual HT horizontal triplex) 400 pumps. The HT 400 is a piston driven pump with 4.5 inch plungers. The maximum delivery pressure depends on the density of slurry being injected, but upwards of 1,100 psi is possible. A computer (Unipro - II) regulated the density of the slurry and maintained the delivery rate and pressure. Having the ability to vary the pressure setting and rate of injection without delaying operation was particularly advantageous for this application. If an obstruction was encountered, the pressure and injection rate could be adjusted to clear the blockage.

Methods

The remediation design was based on a mine map dated January 1925. The mine map of questionable accuracy but this was the only available source of information. As a result, the injection plan was designed using the map, but development of the project planned for, and expected, the worst-case scenario.

Well Development

The first phase of the treatment depended upon the successful installation of injection wells. The well sites were identified using global positioning system (GPS) technology. Once the locations were identified, an air rotary drill rig was employed to bore $5^1/_8$ inch holes. Six wells were drilled and cased with 2 inch schedule 80 polyvinyl chloride (PVC). Joints of the PVC were connected by threading the casing into galvanized steel collars. Schedule 80 PVC was selected because plastic was not adversely affected by the corrosive nature of the mine water, and the strength of the material could withstand upwards of 400 psi. The ability to withstand pressure was required if a coal pillar was penetrated instead of a void. The pillar would have to be broken-down or fractured using several hundred pounds of pressure.

In order to secure the annulus space, two plastic catchers were fastened to the outside of the casing at 12 and 18 inches from the bottom, respectively. The casing was lowered into the hole, and the equivalent of five feet of medium sized bentonite chips were added. On top of the bentonite, approximately five feet of Portland grout was added and allowed to set for two hours. The casing was suspended in place by the drill rig in order to center the well. After the cement had started to set, several hundred pounds of bentonite chips were added to fill the remainder of the annulus space. At the surface, approximately 8 feet of cement grout was poured to secure the well, and a 4-mch diameter steel pipe, approximately 3 feet long, was set one foot into the cement to act at as a protective surface casing. The 2-inch PVC casing was roughly 1.5 feet above the ground level. A PVC cap was screwed on the top to prevent debris from entering the well, and a galvanized steel lid and lock were used for security.

Injection Equipment Design

For the execution of an error free operation, the appropriate configuration of equipment had to be determined. Factors considered included the delivery and down-loading of FBA, acquisition and storage of water, and the mixing and injection of the FBA slurry. With a pump truck as the nucleus of the process, a description of the arrangement of other equipment follows. Refer to Figure 2 for a depiction of the equipment placement.

FBA. Four field storage bins were tightly grouped east of the cement truck. Each bin could store approximately 500 yd^3 or roughly 37 tons of FBA. All four bins were filled prior to the injection and deliveries were made on an hourly basis during the injection operation. The FBA was pneumatically down-loaded from the trailers into the storage bins.

Water. One 500 barrel (2 1,000 gallons) frac tank was situated on the west side of the cement truck and served as the reservoir for the mixing operation. Water was pumped from the seep outlet using a 5.5 horsepower pump at a rate of approximately 2 barrels/min (84 gal/min). However, the operation would require at least 6 barrels/min (252 gal/min).

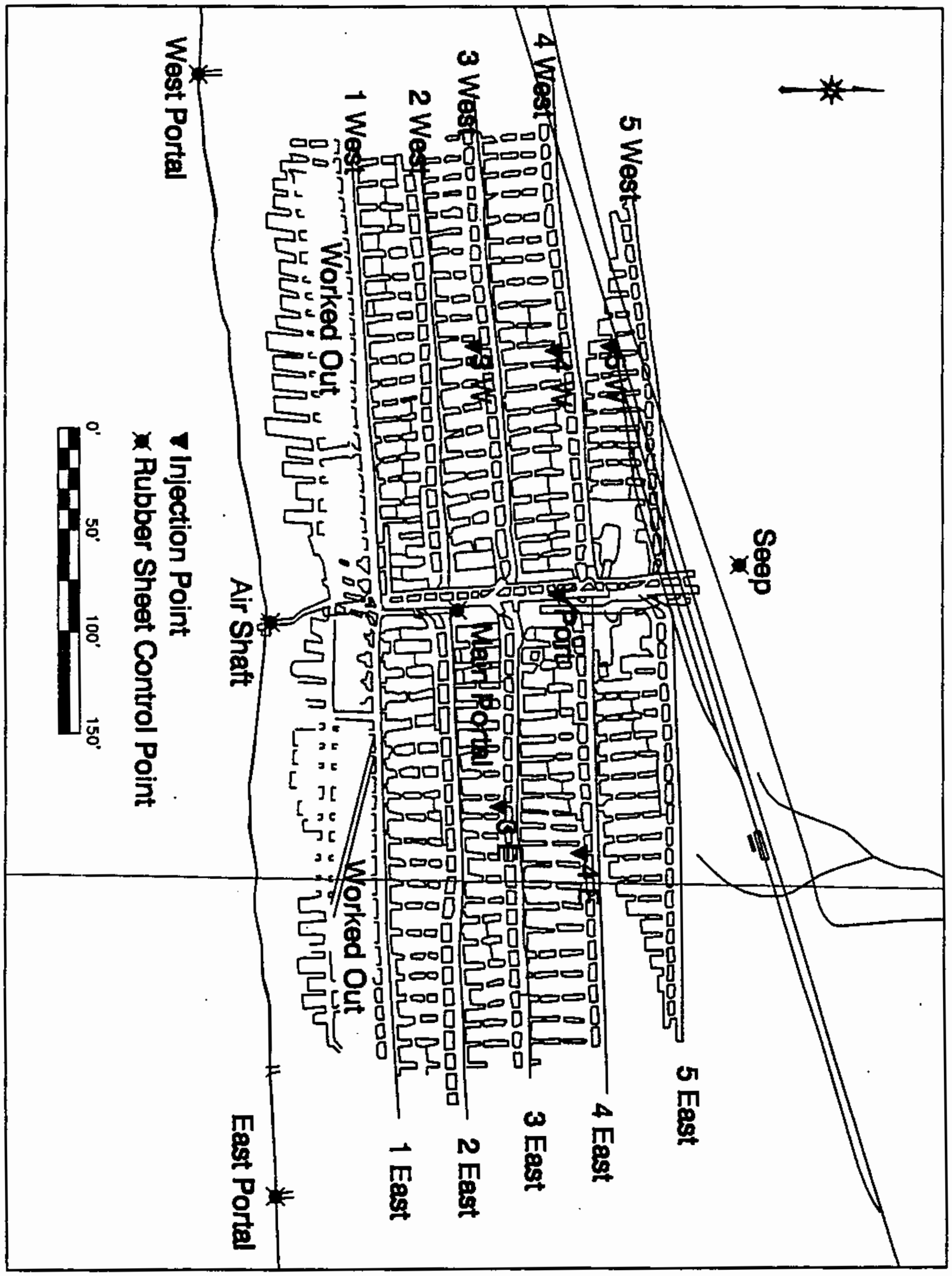

Figure 1 Digitized mine map with locations of the corridors and the injection wells.

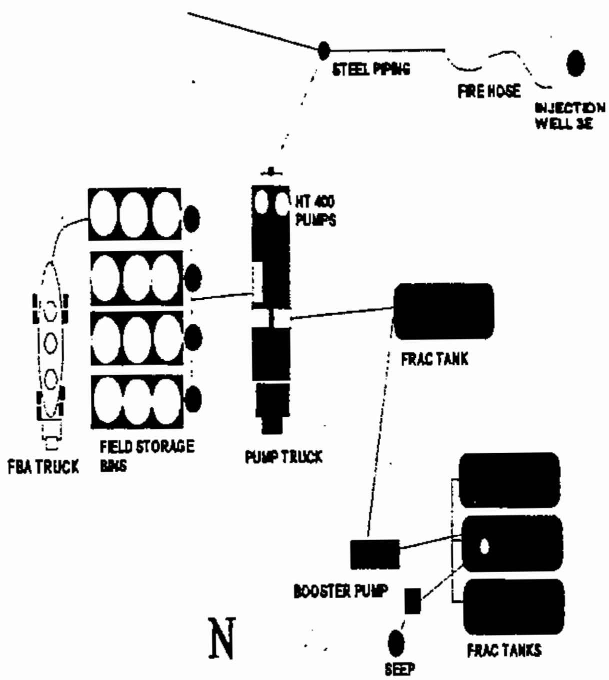

Figure 2. A depiction of the arrangement of the equipment used during the injection process.

Subsequently, a stock pile of approximately 2,000 barrels (84,000 gallons) would be needed prior to injection. Three additional frac tanks would store the necessary volume. They were positioned next to the seep and connected in series.

Injection line. From the south end of the pump truck, the slurry was pumped out through a 2-inch steel line for approximately 150 feet. At this point, a switch tee was added so that the flow could be directed to the well groupings on the east and west side. From the steel line, 3 inch diameter fire hose was used to connect to the wells. Fire hose was selected after a careful review of various piping materials. The deciding factor was the flexibility and ease of moving the line. Any ridged pipe (for example steel) would be difficult to relocate and set up. Plastic quick-lay pipe was an option, but the flexibility and working pressure were not suited for the application. The fire hose had a working pressure rating of 300 psi and test burst of 600 psi. This would handle the anticipated pressures needed to fracture the coal pillar and was within the pressure rating of PVC casing.

The fire hose was attached to the injection wells by fixing an adapter set up on each well. The set up consisted of a 6-inch nipple followed by a ball valve. A tee was placed on top of the ball value and a pressure gauge was fixed in one of the openings. A U-shaped adaptor, referred to as a "double wing", was then attached on the top opening of the tee.

Injection Process

Approximately 80 tons of ash would be injected into each well. In order to maximize the movement of the material, an injection scenario was proposed. To start, seep water would be injected until 10 barrels (420 gallons) were flushed through the system. A 10 lb/gallon density mix would then be introduced to test the pressure in the hoses and to determine if the mine was accepting the material. After roughly 20 barrels (840 gallons), a 12 lb/gallon slurry would be injected until 300 barrels (126,000 gallons) were pumped in the mine. The 10 and 12 lb/gallon slurries would then be alternated, at their respective volumes, until the entire mass of FBA was injected. The premise for this strategy was to flush the FBA material out from around the injection point and to promote dispersion of the material. After the 80 tons of FBA were injected, mine water would then be used to flush the hose and casing before moving to the next well.

Results and Discussion

Field Results and Discussion

Preparation for the injection began on July 15, 1997. Frac tanks were delivered and filled using water from the seep. The land owner cleared brush and leveled the ground for the placement of equipment. Four field storage bins were set in place and were prepared to receive FBA. On July 16, the first phase of the FBA delivery began. Six loads, or 147 tons, of FBA were delivered. The remaining quantity of FBA was delivered during the injection. The pump truck was brought to the site and all of the equipment connected. A trial injection was conducted using water to test the integrity of the system. On July 17 the actual injection process began.

Injection. Injection of the FBA was a learning experience for both the University of Oklahoma and Haliburton. Neither party had used CCBs in an application such as this. Certain minor changes and modifications were required during the application, but the actual delivery aspect of the project was a success.

The placement and organization of equipment worked well throughout the process. The entire mass of material was injected into the mine without any refusal. The high pressure and rate of application were effective at breaking-down a coal pillar and removing obstructions. As a result of the preparatory efforts, the entire injection process required 15 hours, with 13 hours of actual injection time. During that period, 418 tons of ash were injected, which equates to 32 tons/hour. The average rate of injection was roughly 110 yd^3/hr, but a maximum rate of 375 yd^3/hr was observed.

The use of the fire hose proved to be an effective means of delivering the slurry. Pressures were maintained within the working range of the hose without major problems. The hose was easy to move between injection wells. The amount of downtime between wells ranged from 10 to 20 minutes depending on the distance.

Pressure at the pump truck was maintained between 250 and 300 psi and the rate of injection was held between 7 and 8 barrels/min. Pressures at the well head were monitored to estimate how the mine responded to the input of material. Well head pressures varied depending on the individual well. In general, the pressure fluctuated between 0 and 20 psi, but the well located in the coal pillar had consistently higher pressure readings. During the fracturing process, mine water was pumped against the coal pillar. Pressure readings at the truck increased slightly above 300 psi during the initial few seconds of the injection before leveling off. In fact, the fracturing process occurred so fast that the well head observer did not notice any measurable change in pressure. Although the coal pillar was easily fractured, the higher pressure (>60 psi) observed at the well head during the injection may indicate that the fractured pathway was constricted or sinuous. Subsequently, there may have been significant friction and resistance to flow.

There did not appear to be a clear correlation between the pressure at the well head and the density of the material injected. Nor was there a direct correlation with the rate of injection and pressure observed at the well head. Rather, pressure increases and decreases could not be correlated to a specific cause. Meiers (1996) observed pressure increases followed by sharp decreases during an injection project. He concluded that the pressure would increase until the gout entered another room or void. Perhaps something similar was occurring at this site. The pressure may have increased when an obstruction was encountered or something hindered the flow path. The drop in pressure was observed when the obstruction was removed or a flow path was created.

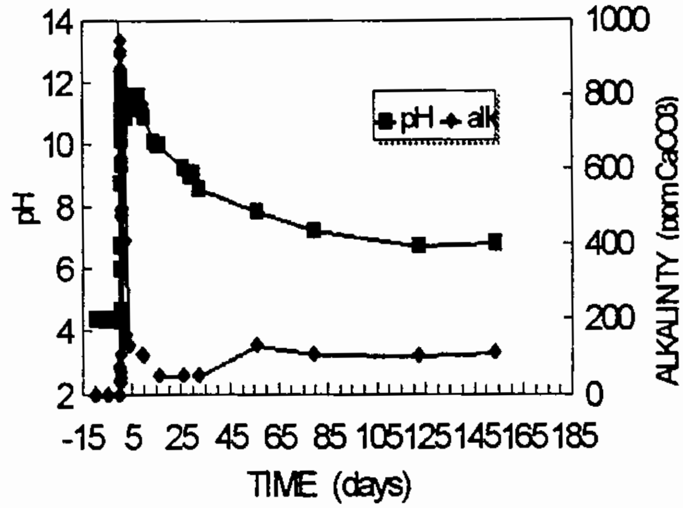

Figure 3. The relationship of pH and alkalinity concentration with respect to time for the mine seep.

One major problem, which detracted from the success of the project, was the generation of dust. The system was designed to completely contain the FBA in the storage silos and pneumatically transfer the material to the pump truck. Unfortunately, the field storage bins were not appropriately equipped with dust collection devices. During the downloading process, excess FBA would blow out on the ground when the bins were full. This resulted in temporary periods of significant fugitive dust emissions.

Clogging of the injection pumps was a problem that limited the efficiency of the injection process. Since FBA is a mixture of fly ash material and bed ash particles, the size distribution can vary significantly. At least one load of FBA was delivered which contained an unusually high percentage of gravel--sized particles. These particles settled out in the injection lines prior to the pump forming a mass of material that restricted flow. When clogging occurred the operation was temporarily stopped while the lines were cleared.

Chemical Alteration

During the 15 hours of injection the pH of the discharge water increased from 4.3 to 12.2. Alkalinity also increased from 0 to 950 ppm as $CaCO_3$. The drastic changes in pH and alkalinity were expected given, the caustic nature of the CCB material. Previously conducted laboratory experiments indicated that there would be elevated pH and alkalinity; however, what would occur in the mine environment was uncertain. After the sharp increase, the pH and alkalinity of the mine discharged began to decrease within hours of the injection. A decrease was anticipated, but the magnitude of the drop was not (Figure 3). After 153 days, the magnitude of pH drop and the alkalinity concentration appeared to have stabilized. Presumably, the treated water is approaching equilibrium with carbon dioxide in the mine head-space. Firm conclusion cannot be drawn at this time because of the lack of data and reduced flow. Discharge from the mine has not returned to seasonal base flowlevels.

Summary

In general, this procedure was effective at achieving the goal and needs of this project. A method was required which could be versatile and powerful given the uncertainties associated with the working environment. Down-hole grouting technology developed by the petroleum services industry was selected because a CCB slurry could be injected into the mine void under significant pressure and at a high rate. With a higher pressure and rate of injection, a large quantity of slurry could be introduced into the mine within a limited amount of time. Theoretically, the high pressure and rate could improve dispersal of the slurry within the void, but there was no way to determine this practically. Instead of allowing gravity to be the driving force, a pressure gradient was developed which allowed for greater movement of material within the mine. Also, the high pressure was effective at breaking-down obstructions to injection. A well which was drilled into a coal pillar, instead of the mine void, was easily fractured. During the injection process, a total of 418 tons of FBA was introduced without significant resistance. In fact, it is likely that a much larger mass of material could have been added. The overall effect on chemical alteration of the mine water is uncertain at this time. More data and further evaluation are needed before any conclusions can be made.

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