Session 3

Beneficial Uses at the Mine Site

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DEVELOPMENT AND DEMONSTRATION OF CCB BASED STRUCTURAL PRODUCTS FOR MINE USE

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Abstract

Environmental considerations, resulting from the disposal of coal combustion by-products (CCBs) and the impacts of deforestation associated with the harvesting of timber for utilization as roof supports in mines, should become more severe in the future as landfill space and suitable timber reserves become more scarce. To help address these concerns, lightweight, artificial supports such as post and crib elements, utilizing large percentages of coal combustion by-products as aggregate, have been developed for use in underground mines. These structural products show equal or better engineering characteristics as timber and have the potential to replace timber support in underground mines.

CCBs-based ultra-light structural material (ULSM) also has been developed and commercialized for utilization in construction of ventilation stoppings in underground mines. The bulk density of these blocks are in the range of 25 to 40 pounds per cubic foot (pfc) with over 75% CCBs. Efforts are also given to develop and demonstrate large volume CCPs based sub-grade improvement technique for road construction. Soil treated with SIUC fluidized bed combustion (FBC) fly ash developed an immediate bearing value exceeding 25%, with swelling strain less than 1%, over untreated soils and met Illinois Department of Transportation (IDOT) standard specifications.

In this paper, development procedures, engineering characteristics, and beneficial use of CCBs-based structural products are given.

Introduction

Over the past five (5) years or so, the Department of Mining and Mineral Resources Engineering at Southern Illinois University (SIU) has been developing CCBs-based structural products for use in mines. It was thought this would provide the mining industry with better and more uniform quality structural materials throughout the year, reduce deforestation, and allow for the return of CCBs underground. The replacement of wooden cribs and posts was identified as a high priority based on input from the mining industry. Later, the replacement of currently used ventilation blocks (cinder, concrete, Omega, etc.) by lightweight or ultra-lightweight CCBs-based blocks and fill materials were included for development. It was estimated that utilizing these materials in Illinois Basin coal mines would consume about 40,000 – 50,000 tons of fly ash annually.

Research into the utilization of CCBs was divided into two classifications, fill materials and lightweight structural materials. Fill materials developed at SIUC include paste backfill mixtures for underground mine excavations, as well as flowable fills and sub-base stabilizers for the construction industry. Structural materials include ventilation blocks as well as posts and crib elements, the demonstration of which will be the main focus of this paper. Structural materials consisted of lightweight (85-95 pcf) support members and ultra-lightweight (30-40 pcf) ventilation blocks. The lightweight support members consist of 5-inch × 5-inch × 36-inch crib elements at 85 pcf and 6-inch × 6-inch × 96-inch posts at 95 pcf, while the ventilation blocks are 8-inch × 12-inch × 16-inches in size at about 30 pcf.

Review of Pertinent Literature

Fly Ash Types and Usage

Fly ash is the fine by-product of coal combustion that exits from the top of the boiler with the combustion gases and is classified as Class C or Class F by the American Society for Testing and Materials (1994). Class C fly ash is produced from burning western bituminous coal, subbituminous coal, or lignite, while Class F fly ash is produced from burning anthracite coal or eastern bituminous coal. These classes differ mainly in the level of calcium oxide (CaO) present in the ash. Typically, Class F fly ash will contain less than 10% CaO, while Class C fly ash will often contain levels of CaO from 15 to 35% (Wei, Naik, and Golden, 1994).

Over the last several years, interest has been shown in developing new uses for fly ash. These include fill material for mine reclamation (Kim and Cardone, 1997), subsidence control (Chugh et al., 1996), and lightweight, artificial, supports suitable as substitutes for wood products in mines (Chugh et al., 1997).

Characteristics of Wooden Supports

Wood is the traditional material utilized for supplemental roof support in underground mines. It is easy to work with and, until recently, has been in abundant supply and reasonably priced. Wooden support members are relatively lightweight, easily trimmed to length, and fairly durable. Wood, however, has many disadvantages as a structural member. As a naturally occurring material it is subject to wide variances in strength and density, and is subject to seasonal fluctuations in supply. Wood also absorbs moisture and is subject to decay. Because it is a natural product, wood is subject to considerable variance in strength characteristics. Soft spots, knots, moisture content, and voids within the wood will all cause the wood to be weaker than anticipated. For instance, Yu (1987) indicated drops in strength of up to 50% from a two-inch knot for a given specimen. A section of wood may appear to be free of defects to the naked eye, but may include one, or all, of the aforementioned defects.

The strength characteristics of wood are unidirectional; wood products are much stronger when loaded axially, with the grain, instead of 90° to the grain. Biron and Arioglu (1983) reported maximum safe stresses for Class I Oak at about 1,700 psi parallel to the grain (post configuration), and about 425 psi perpendicular to the grain (crib configuration). Yu (1987), and Biron and Arioglu, (1983) identified the moisture content of wood as a major limiting factor on the strength of wood products. In general, as the moisture content of the wood increases, the strength of the wood decreases. For pine, crushing strength decreases about 82% as the moisture content increases from 0% to 50%. This is a significant reduction in strength and will affect the performance of wood when utilized as post or crib members, especially within the humid environment of a mine.

Concrete Supports – Previous Attempts and Results

Anderson and Smelser (1980) investigated the effectiveness of steel-fiber-reinforced concrete (SFRC) crib supports and found them to be significant improvements over their wooden counterparts. Tests of open, SFRC cribs (30-inch $\times$ 30-inch) averaged 2373 pounds per square inch (psi) in compressive strength with an elastic modulus of 0.68×10^6 psi, while wooden cribs of the same configuration averaged 811 psi compressive strength with an elastic modulus of 24.5×10^3 psi. A series of field demonstrations conducted by Smelser and Henton (1983) at seven coal mines and one trona mine demonstrated that SFRC supports were a technically superior and potentially cost effective alternative to wood supports in mines. In all but one of the demonstrations, the supports were used as a direct replacement for wooden supports in the tailgate entries of active longwall panels at mines.

Smelser and Henton concluded that it was technologically and economically feasible to utilize these supports as substitutes for wood cribbing; however, the configuration and dimensions of full-size cribs constructed of these materials affect their ultimate compressive strength and "after-failure toughness."

They determined that supports with solid, smaller cross-sections with fewer joints have the highest strength per unit area with the greatest post-failure "toughness."

Development of Structural Materials

Advantages of Engineered Supports vs. Wood

CCBs-based artificial supports have several advantages over their wooden counterparts. Specifically, CCBs-based supports are much stronger and stiffer than wood products; they are dimensionally stable, will not decay or absorb water, and will not burn. In addition, these artificial supports can be excavated with today's mining machinery, unlike wood, which shreds and becomes wrapped around the cutter head.

Performance Advantages of CCBs-Based Artificial Supports

Figure 1 illustrates the relative performance of 8-inch × 8-inch × 24-inch wooden posts and 6-inch × 6-inch × 24-inch CCBs-based posts, tested axially, while Figure 2 illustrates the relative performance of wooden and CCBs-based cribs.
The CCBs-based posts averaged about 3,000 psi in compressive strength while the wooden posts averaged about 2,300 psi with average elastic modulus of 450,000 psi and 160,000 psi respectively. This demonstrates an improvement of about 30% in unconfined compressive strength and 180% in the elastic modulus. However, the wooden posts demonstrated plastic post-failure characteristics while the CCBs-based posts demonstrated strain-softening post-failure characteristics. The residual strength of the CCBs-based posts, about 40-50% of the compressive strength, was supplied by the reinforcing fibers utilized in the mix.

A comparison of the performance of the crib members, tested in a crib configuration, shows even greater improvements. The artificial cribs averaged 2,400 psi in compressive strength while the wooden crib yielded a compressive strength of around 900 psi. The elastic modulus of the CCBs-based cribs averaged about 300,000 psi while the wooden crib demonstrated an elastic modulus of only about 17,000 psi. This shows an improvement of about 167% in compressive strength and a 1,665% improvement in the elastic modulus.

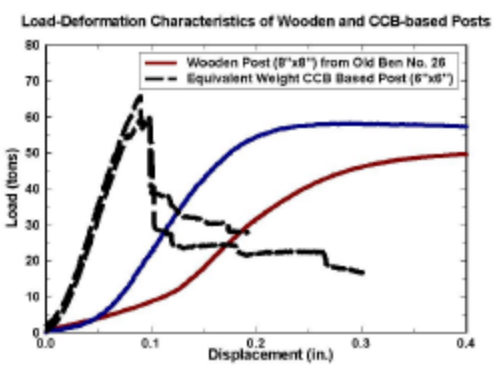

Figure 1. Load-Deformation Characteristics of Wooden and CCBs-Based Posts (Chugh et al, 1997).

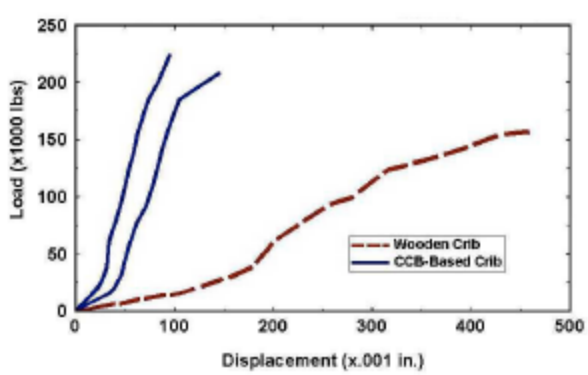

Figure 2. Load-Deformation Characteristics of 2 × 2 Cribs (Chugh et. al, 1997).

Other Advantages of CCBs-Based Artificial Supports

The use of CCBs-based artificial supports in place of wooden supports would help address the problems of deforestation, and seasonal fluctuations in the supplies and cost of supports, as well as disposal of CCBs. In addition, the use of these supports would enhance worker safety, since CCBs-based supports are

substantially stronger and stiffer than wooden supports, are not effected by moisture, and are incombustible.

Since the moisture content of wood adversely affects its strength, wood gradually becomes less effective as a support over time in a humid mine environment. A replacement for wood that shows good time-dependent strength characteristics will enhance safety by providing superior long-term roof support. Wood not only degrades over time, it is dimensionally unstable; it is subject to shrinkage, and supports constructed of wooden materials require periodic retightening to provide an acceptable level of support. Supports manufactured from CCBs-based materials are dimensionally stable; they will not shrink (or swell) over time; they do not absorb moisture and will not decay.

An additional benefit of CCBs-based supports is they will not burn. Composed of about 70% fly ash and 30% binding agents, the finished products are incapable of supporting combustion.

Potential for Utilization

It has been estimated that the substitution of CCBs-based post and crib members in lieu of wood could utilize about 0.25×10^6 tons of coal combustion by-products in the Illinois Basin alone (Chugh, et. al., 1996). This would amount to about 2.5×10^6 tons nationwide, an amount that could double if the materials were utilized in non-coal operations as well. The utilization of CCBs-based artificial supports in place of wooden supports will help address the problems of deforestation, seasonal fluctuations in supplies of supports, non-uniform support quality, and disposal of CCBs and associated environmental problems.

Prototype Fabrication and Field Demonstration Studies

Development of Facilities for Production of Prototype Supports

Laboratory studies resulted in mix development for lightweight CCBs-based structural materials in the 75-105 pcf density range. The mixes typically consisted of about 70% F-fly ash, binders, and appropriate fibers (Chugh, et. al, 1998). Experience gained in the production of laboratory sized specimens was used in assembling a facility for producing full-sized prototype post and crib elements. The facility consisted of a large mixer, mold preparation/handling operations, curing equipment, and finished product storage. The posts and crib members produced in this facility were utilized in two (2) field demonstrations to test the viability of CCBs-based artificial supports in a mine environment. Experience gleaned from the assembly and use of the prototype facility was utilized in the design of a full-size pilot scale facility.

Fabrication of the prototype, CCBs-based artificial supports began during August 1996 and concluded in May of the following year. Approximately 230 crib members (5 inch $\times$ 5 inch $\times$ 30 inch) and 20 posts (6 inch $\times$ 6 inch $\times$ 96 inch) were produced at the facilities for use in two field demonstrations and for characterization testing.

Support Characterization

Engineering properties of the crib elements were obtained utilizing a 600,000 lb. MTS stiff testing machine. Testing of the posts was conducted utilizing a large-scale testing machine, designed by the department staff, located at the research facilities of the Illinois Clean Coal Institute at Carterville, IL. This machine has a capacity of 400,000 lb. and can test specimens up to 7 ft. in length.

Characterization of specimens was accomplished by determining the unconfined compressive strength and elastic modulus as a function of density. Crib members were trimmed to a length of 24 inches and tested in the MTS stiff testing machine under a constant rate of loading, approximately 3000 lb./minute. Posts were trimmed to a length of 7 feet and tested in the full sized testing machine. Poisson's ratio was determined for the crib elements utilizing dial gages setting in the longitudinal direction.

Figure 3 shows the relationship between the unconfined strength, C_o, and the density, ρ, where C_o (cribs) = $142.76e^{0.0304\rho}$, R^2 (cribs) = 0.8207, and C_o (posts) = $364.98e^{0.0134\rho}$, R^2 (posts) = 0.9341, N (cribs) = 19 and N (posts) = 3. A total of twenty-eight (28) crib elements, 5-inches × 5-inches × 24-inches in size, and four (4) posts, 6-inches × 6-inches × 72-inches in size were tested.

Figure 4 shows the relationship between the elastic modulus, E, and the density, ρ, where E (cribs) = $0.5206e^{0.0249\rho}$, R^2 = 0.4724, and E (posts) = $0.7142e^{0.035\rho}$, R^2 = 0.7618 and N (cribs) = 19 and N (posts) = 4.

A significant problem manifested itself during the manufacturing of the prototype supports. Of the twenty (20) posts manufactured, 10 broke immediately after removal from the curing tanks, six were sent underground at Old Ben #26 for the initial field demonstration, and four were set aside for characterization studies. Of the ten posts that were successfully produced, six eventually broke before utilization. The breakage problem was successfully addressed when the concept of a disposable mold, one that remains on the support after completion of the manufacturing process, was introduced. A mold that remains on the support would ensure that any micro-cracks formed during the curing process would not be able to propagate, provide a confining pressure for the CCBs-based structural material under load, and increase the post-failure load bearing capacity of the supports.

Initial studies of CCBs-based supports cast into plastic pipe were very encouraging. The supports, both solid and solid core designs, exhibited performance characteristics very similar to wood products, as shown in Figure 5. Figure 6 shows a full size support utilizing a disposable mold of circular cross-section after failure.

Old Ben Coal Field Demonstration

The first field demonstration of the prototype CCBs-based post and crib elements took place at the Old Ben Coal Company Mine #26, located near Sesser, Illinois, during the months of November and December, 1996. Old Ben #26 was mining the Illinois #6 seam at a depth of about 600 feet with an immediate roof composed of approximately 30 feet of competent gray shale. The coal seam averaged 8 feet in thickness and roof conditions in this area were generally favorable.

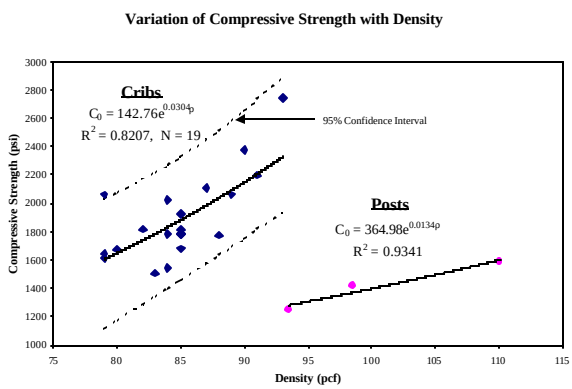

Figure 3. Compressive Strength/Density Relationship.

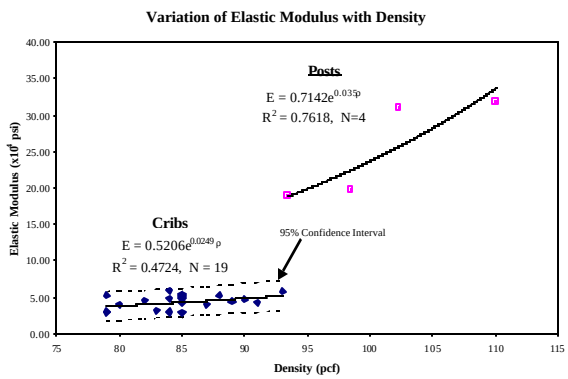

Figure 4. Elastic Modulus/Density Relationship.

Test Area and Instrumentation

The posts and cribs were placed in the tailgate entry, illustrated in Figure 7, of the last longwall panel of the mine; Old Ben Mine #26 ceased operations after this panel was completed. Two cribs and three posts were erected and equipped with load cells designed at SIUC. However, the load data for two posts were unobtainable. Two wooden cribs and one wooden post were equipped with load cells as controls. The outbye wooden crib, located at station 893+00 was damaged during the test and its data was discarded.

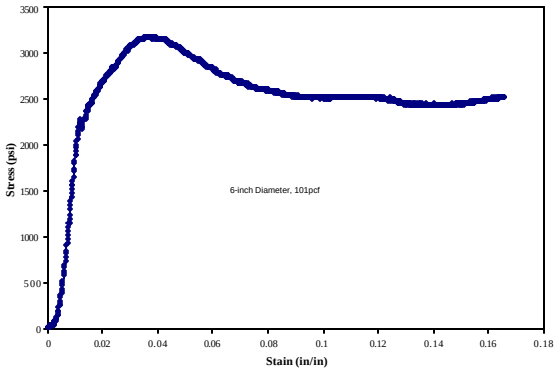

Figure 5. Performance of CCBs-based supports cast into disposable molds.

Figure 6. Full size post cast into a disposable mold.

The load cells, developed as part of this study, are relatively inexpensive, accurate, and durable instruments for measuring dynamic loads in the field. They were designed to be disposable and easily assembled and consist of a 3 ½ inch × 3 ½ inch × 1 inch polyurethane wafer placed between two 7 ½ inch × 7 ½ inch × 1 inch steel plates. The lower plate has ¼ inch diameter holes at each corner where the compression of the wafer was to be measured by use of a bottoming micrometer. The load deformation curve for the polyurethane wafers was determined with the use of the 600,000 lb MTS stiff testing machine at SIUC. The load on each cell was determined by averaging the compression, or displacement, measured at each corner of the load cell. The equation describing the load characterization curve of the polyurethane wafers is Load = 2E+07 × $Disp^3$ – 7E+06 × $Disp^2$ + 1E+06 × Disp.

Field Demonstration #1 - Old Ben Coal Co. Mine 26

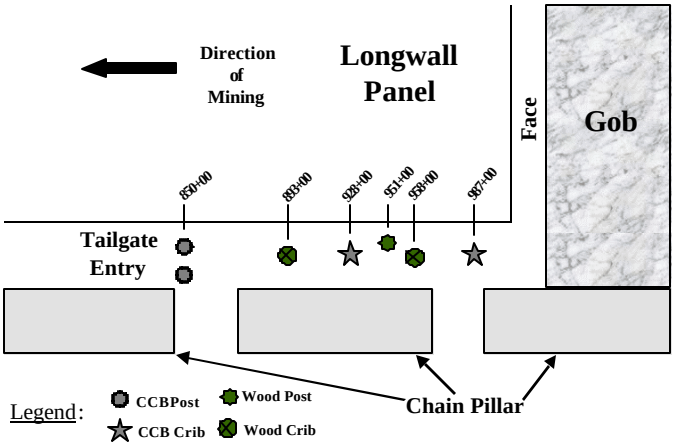

Figure 7. Old Ben #26 Field Demonstration.

For the cribs, one of these load cells was placed at each corner during assembly, approximately halfway between the roof and the floor. For the posts, the load cells were placed between the top of the post and the existing wooden crossbar.

Convergence points, consisting of ½-inch × 18-inch diameter pins driven into the mine floor beneath a roof bolt, were installed adjacent to each post and crib utilized in this demonstration. An extensometer was utilized for measuring the roof-to-floor convergence.

Data Gathering and Analysis

Initial measurements were taken on the load cells immediately after erection of the CCBs-based artificial supports with a second set of measurements taken 2 ½ weeks later. When the longwall face approached to within 200 feet of the inby support, load cell measurements were taken every shift until the face passed the last instrumented support. A bottoming-type micrometer was utilized to measure the compression of the load cells to the nearest 0.001 inch. Convergence measurements were taken with an extensometer to the nearest 0.01 inch.

Mine #26 Demonstration Results

The results of the Old Ben demonstration are shown in Figures 8 and 9. Figure 8 compares the performance of the wooden and CCBs-based cribs as load vs. deformation while Figure 9 compares the performance of the wooden and CCBs-based posts. Load values were obtained from measuring the compression of the polyurethane wafers of the load cells while the deformation values were obtained from the convergence stations.

Worker reaction to the supports was very positive. The time and degree of difficulty in erection of the supports was no different than conventional wooden supports. This was due to the fact that the supports were similar in size and shape to the supports the labors were accustomed to.

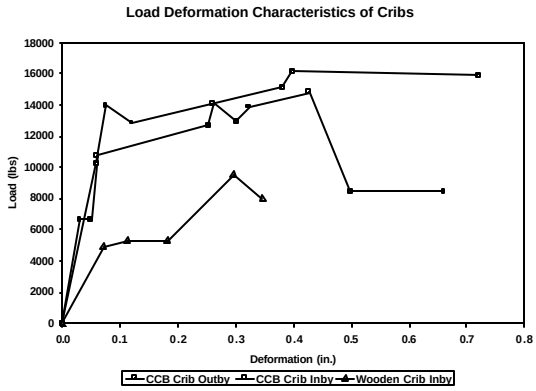

Figure 8. Crib Performance at Old Ben Mine #26.

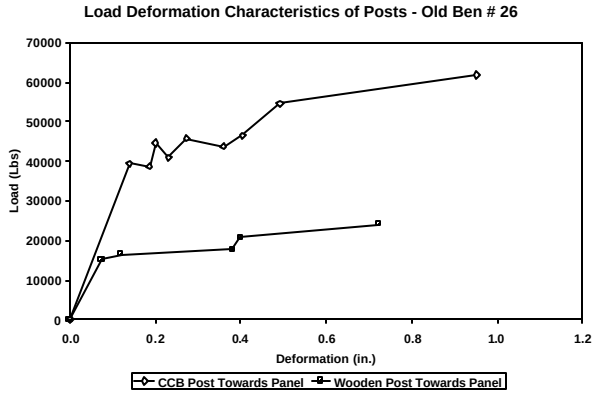

Figure 9. Post Performance at Old Ben Mine #26.

Costain Coal Co. – Pyro Mine Demonstration

The second field demonstration of the CCBs-based artificial supports took place at the Pyro Mine of Costain Coal Co., located near Clay, Kentucky, during the month of June, 1997. For this demonstration, the supports were installed on the headgate of a new longwall panel. This mine is required to fully support all gate entries for ventilation requirements and a bleeder fan is used to provide ventilation to the longwall face; full support of the head and tailgate entries is mandatory for maintaining proper airflow.

Test Area and Instrumentation

The test area at the Pyro mine, illustrated in Figure 10, was located one crosscut in by the longwall setup rooms in the middle entry of the three-entry headgate. This area was chosen because of the severe loading that normally occurs at this location as a new face begins production. Loading of the roof in this area typically occurs at a rapid rate until failure of the main roof, which consists of massive beds of Limestone and Dolomite. Subsidence of the surface area above the panel is an indication that main roof failure has occurred.

The seam height in the test area averaged around 6 ½ feet and roof conditions were generally poor. The immediate roof consisted of weak gray shale that was difficult to support during panel development. Mine management indicated that the maximum depth of a cut was usually only about 10 feet before roof bolting and most attempts at achieving a deeper cut resulted in a major roof fall. Cable type truss bolts are utilized as secondary supports to provide long-term entry stability throughout the mine.

After bringing the artificial crib elements inside, mine personnel proceeded to install the cribs at a single location instead of the three locations planned. The installation of additional conventional cribs out by the test area precluded the disassembly and re-erection of the CCBs-based supports to their preplanned locations. SIUC personnel installed the instrumentation on the supports before longwall operations began, utilizing the same procedures as the Old Ben Mine #26 demonstration.

After erecting the cribs, mine personnel determined that a ventilation wall was required behind the CCBs-based cribs and materials were brought in to complete this job. In the process, two of the cribs were severely damaged by a utility tractor and required reinstallation. Several crib members were cracked or broken and one crib was assembled with broken elements. This is referred to as the "remnant" crib. This crib survived the demonstration, however, and was reportedly still standing as of January 1999.

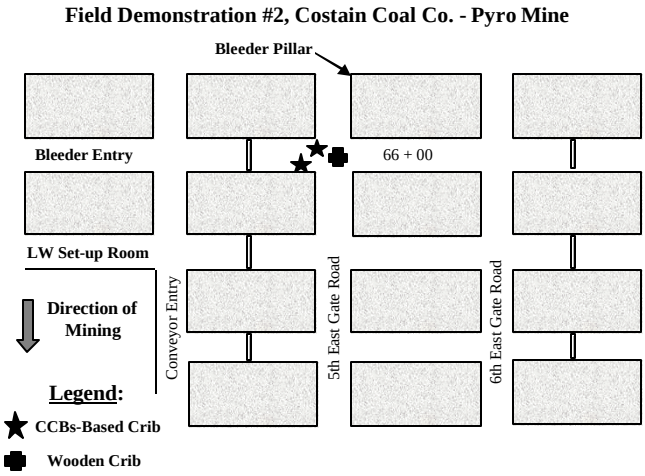

Figure 10. Costain Coal Pyro Mine Field Demonstration.

Data Gathering and Analysis

The cribs were monitored for load and vertical displacement, utilizing the same procedures as the Old Ben demonstration except that monitoring of the supports took place from the startup of the face until subsidence was observed on the surface. Convergence stations were installed adjacent to the monitored supports to determine the amount of vertical displacement; however, the readings indicated that the roof and floor were diverging rather than converging. A closer inspection revealed that the roof in this area was moving laterally, toward the mined-out, or gob area, indicating high lateral stresses in the immediate roof. Approximately 14 inches of horizontal roof movement was observed in this demonstration, precluding the

use of the convergence stations to determine displacement. Without convergence data, the field information from this demonstration was analyzed for load as a function of time and distance of face retreat.

Pyro Mine Demonstration Results

The results of this demonstration can be observed in Figure 11 and Figure 12. Figure 11 shows the loading of the cribs as a function of time while Figure 12 shows the loading of the cribs as a function of face location. In this figure, "0" face distance means that the longwall panel had not begun production. Subsequent, positive distances symbolize the distance that the face had retreated from the setup rooms, away from the cribs.

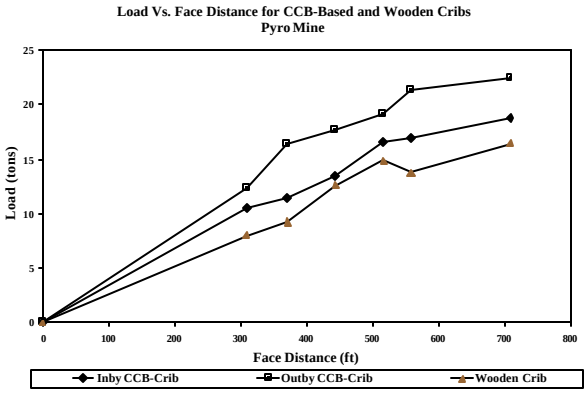

Figure 11. Crib Performance at Pyro Demonstration, Load vs. Time.

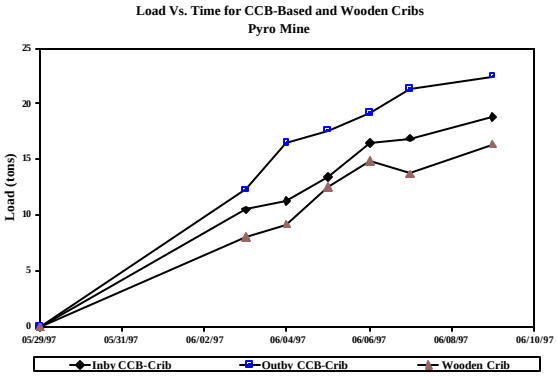

Figure 12. Crib Performance at Pyro Demonstration, Load vs. Face Location.

The observed elastic modulus of the CCBs -based posts were about 1.5 to 2.0 times higher than the wood post and the observed elastic modulus for the cribs was 2.0 to 2.5 times higher than the wooden crib at Old Ben #26.

Mine personnel, both management and labor, were very receptive to use of the supports at both mines since the supports were engineered to be direct replacements for the wood supports currently in use. This enthusiasm was enhanced further when the relative performance of the supports was revealed. Equally important, as of January 1999, mine management at Pyro Mine reported that the test cribs remain intact, despite the failure of most wooden cribs in the area immediately adjacent to the test area.

Mine management at Pyro has expressed an interest in these supports due to the difficulty in obtaining quality wooden supports at a reasonable price during the winter months. The only objection to the artificial supports was breakage. The extremely rough handling the members were subjected to (being run over by a utility tractor) resulted in several broken pieces and management at this operation felt that the supports should be as durable as wood to find acceptance within the mining industry.

Assessment of Field Demonstrations

Field demonstrations of the CCBs -based artificial supports were generally successful and the superior performance characteristics and the potential for utilization as direct substitutes for wooden supports were clearly documented. At Old Ben #26, the CCBs -based cribs supported loads that were, on average, 62% higher than the wooden crib while the CCBs -based post carried over 2 ½ times the load of the wooden post. At Pyro mine, the CCBs -based crib supported loads that were on average 26% higher than the wooden crib.

Development and Demonstration of Mine Ventilation Blocks

The developed blocks are 8 inch × 12 inch × 16 inch in size and have a density of 30-40 pcf. The mix design for the blocks includes about 80% FBC fly ash and F-ash in appropriate proportions, binding agents, and fibers. The strength of the finished blocks ranges from 150-280 psi. The blocks have been subjected to strength and fire propagation tests by MSHA and have been approved for use to construct mine ventilation stoppings. These blocks are shown in Figure 13.

Figure 13. CCBS-Based Ventilation Blocks.

Design and Development of Commercial Scale Facility

Three of the industrial cooperators involved in the research into the development of CCBs-based structural materials, Webb Oil Co., Eagle Seal, Inc., and Woodruff Supply Co., have recently formed a joint venture, Fly-Lite, Inc., to produce CCBs-based products on a commercial basis. Construction of the plant began in December 1998, and limited production scheduled began in late 1999. At the date of this writing, the facility is producing approximately 100 ventilation blocks per day utilizing a batch mode of operation.

Initial production will be about 20 tons per day of fly ash and binding agents, using a batch method. As product demand increases, the process will evolve into the high capacity, continuous operation. Utilizing a batch process during the initial production phase will help minimize waste of materials while training the labor force and making adjustments to the manufacturing process. The plant is designed to process 100 tons per day of dry materials.

The Fly-Lite Plant is designed to produce lightweight post and crib members as well as ultra-lightweight mine ventilation blocks.

Conclusions

Viability of Structural Materials

If CCBs-based artificial supports are to gain acceptance within the mining industry, they must not only posses superior performance characteristics and be cost competitive, but also have similar physical dimensions. These engineered supports must also utilize existing equipment and techniques for installation, and should not require special training before use. In general, the mining industry within the U.S. is very conservative and prefers to maintain the status quo. The general feeling within the industry may be to utilize wooden supports because “that’s the way we’ve always done it.”

Detailed cost analyses have demonstrated that CCBs-based cribs (5-inch × 5-inch × 30-inch) can be manufactured for around $2 while 8-inch × 8-inch × 96-inch posts can be produced for around $15, prices that are very competitive with traditional wooden support members.

Marketability of CCBs-Based Supports

The work presented in this paper has demonstrated that CCBs-based artificial supports have superior strength characteristics as compared to their wooden counterparts, and can be produced in sufficient quantities at a competitive price. This work may change some minds within the industry, causing some to take a better look at CCBs-based artificial supports. So far, the response from individuals within the industry that have been exposed to these supports is strongly positive. In addition, by utilizing disposable molds of square cross-section, these supports can be produced in shapes and sizes very similar to existing wooden supports. Field experience has also shown that CCBs-based supports can be cut to length with commonly used hand and power tools and will readily accept a mine spad or screw. No special equipment or tools should be required in the utilization of these products as direct replacements for wooden supports.

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BACKFILLING OF HIGHWALLS FOR IMPROVED COAL RECOVERY

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Abstract

Auger mining of coal highwalls has left billions of tons of stranded coal reserves in the United States Appalachian coalfields because the auger holes render the highwalls unstable. The use of low-cost grout prepared from fluidized bed combustion (FBC) ash to stabilize the overburden strata, combined with modern highwall mining techniques to recover the coal beyond the depth of augering, has the potential to add significant quantities of recoverable coal reserves in the eastern United States. Laboratory testing and field demonstrations conducted for this project demonstrated that FBC ash-based grouts can be prepared and placed in the auger holes with sufficient fluidity and ultimate strength to allow for recovery of the stranded coal. Furthermore, economic analysis indicates that the process can allow coal to be recovered at a significant profit.

Introduction

There are thousands of linear miles of abandoned highwall in the Appalachian coalfields left from contour strip mining, about 25% of which are estimated to have been auger mined to depths of 100-150 feet. Auger mining weakens the face of the highwall and makes the coal beyond the depth of augering difficult to recover (Figure 1a). This "stranded" coal represents a major resource, comprising several billion tons of often high quality reserves. In some areas of Appalachia it is the only significant coal that is left.

Grouting auger holes to strengthen and stabilize the augered highwalls is one method that can be used to recover stranded coal. Portland cement-based grouts have been investigated, but are too expensive. Our concept is to utilize fluidized bed combustion (FBC) ash which is currently being disposed of in Kentucky under a waste back-haul contract. The grout would be prepared using FBC ash and water, and then pumped into auger holes to stabilize the highwall (Figure 1b). Automated highwall mining equipment would then recover the stranded coal to a depth well beyond that of the auger holes (Figure 1c).

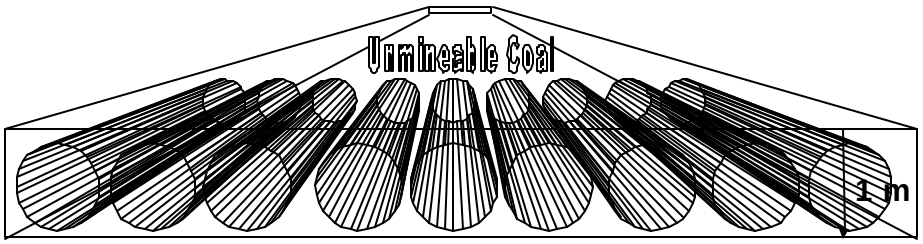
FBC by-products are known to be cementitious when mixed with water and, with sufficient curing, can produce a high-compressive strength material. The calcium sulfate in FBC ash reacts with hydroxide and dissolved glass components to form calcium sulfo-aluminates, the most important mineral of this group being ettringite (Weinberg et al., 1991). Unlike Portland cement-based materials, ettringite is an important cementitious component in FBC-based concrete, grout, flowable fill, etc. (Berry et al., 1991). Ettringite and gypsum formation also contribute to expansion (Jones et al., 1980). In fact for the application described herein, some expansion is desirable.

The project was completed in two phases. Laboratory ash/grout testing, hydrologic monitoring, and evaluation of emplacement methods occurred in Phase I, whereas the field demonstration and economic analysis was completed for Phase II.

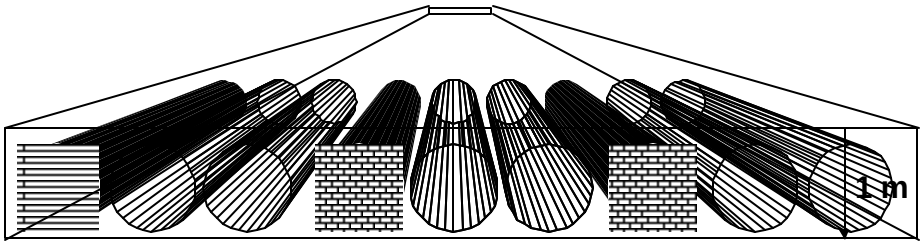
Laboratory Testing Procedures

Materials

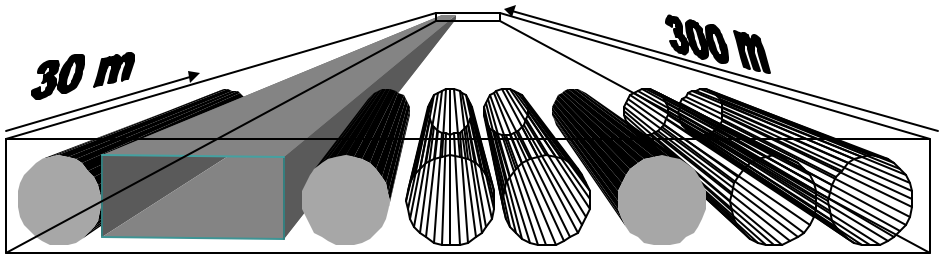
FBC ash originated from the U.S. Generating Co. FBC co-generation facility in Cedar Bay, Florida. The ash was sampled from a receiving and disposal facility in Ivel, Kentucky. Physically, the spent bed material "bed ash" has the consistency of coarse sand. The baghouse material typically referred to as "fly ash" is much finer.



Stage 0 Augered Coal Seam



Stage 1 Grout Fill Every 3rd Auger Hole



Stage 2 Highwall Mine Between Filled Holes

Figure 1. (a) Auger-mined coal extends back about 100 feet and weakens the highwall face. (b) Auger holes are grouted to match highwall mining pattern. (c) Coal is removed to a depth of 1000 to 1200 feet between the grouted holes.

Cylinder Preparation and Curing

The grout samples tested in the laboratory were prepared with ash and distilled water using a paddle-type mixer. Water contents were devised that would provide a range of grout fluidity and strengths. Water:solid ratios ranged from 0.62 to 0.77 (38.3-44.5% moisture). Specimens for mechanical strength testing were formed in several types of cylinder molds, all of which had a length:diameter ratio of 2. The specimens were cured in an enclosed water bath at a fixed temperature with the open top of each specimen above the water-line so that curing occurred in high humidity. Curing temperatures were 50°C, 30°C, and -21°C.

Unconfined Compressive Strength Testing

Unconfined compression testing was selected as the most preferred geotechnical test for this study because it best represents the type of loading that the grout will encounter in an auger hole. A finite element analysis indicated that a compressive strength of 500 PSI would be sufficient to support the rock strata overlying the coal. The strength testing was conducted as per ASTM C 39, C 192, and C 617/C1231, using a triaxial compression machine containing a 10,000 lb. load cell.

Chemical and Mineralogical Characterization

The chemical and mineralogical compositions were determined on the dry ash samples and on the grouts. Chemical analysis comprised major element oxides and SO_3 content, and was conducted in accordance with ASTM D 3177 and D 3682. Free lime was determined in accordance with the procedures of ASTM C 25. Mineralogical characterization was accomplished using x-ray diffraction analysis (XRD). XRD was conducted using a Phillips x-ray diffractometer configured to produce Cu Kα radiation (1.5406Å) at 40 keV and 20ma. Each sample was ground to a powder in a mortar and pestle prior to XRD analysis.

Laboratory Results

Chemical and Mineralogical Composition

The chemical composition of the Cedar Bay fly ash and bed ash is shown in Table 1. X-ray diffraction analysis of the Cedar Bay fly ash and bed ash revealed that although the crystalline phases are similar for the two sets of materials, the distribution of these phases is significantly different (Figure 2; Table 2). The fly ash contains more quartz, gehlenite, and glass, whereas the bed ash has a larger proportion of lime-portlandite and anhydrite. The identification of the crystalline phases was confirmed by optical and scanning electron microscopy, and is consistent with that reported in the literature for similar materials (e.g., McCarthy and Solem-Tishmack, 1994; Iribarne et al., 1994).

XRD spectra of the grout samples are shown in Figure 3. The phases identified are listed in Table 2. Although gypsum occurred in the bed ash-based grout, it was rarely observed in the fly ash grout. This is probably a consequence of the relatively low abundance of lime and anhydrite in the Cedar Bay fly ash. The relative paucity of calcium and sulfate ions and abundance of aluminum in the Cedar Bay fly ash favors the precipitation of ettringite, which is highly insoluble at the high pH (~12.4) of the solution.

Table 1. Chemical Composition of FBC Fly Ash and Bed Ash

Ash Type	SiO2 (%)	Al2O3 (%)	TiO2 (%)	CaO (%)	Fe2O3 (%)	MgO (%)	K2O (%)	Free Lime (%)	SO3 (%)
Fly Ash	33.8	23.7	1.2	28.4	3.6	0.9	1.2	8.1	6.6
Bed Ash	14.9	6.4	0.3	47.9	1.3	2.7	0.4	17.0	29.9

Table 2. Crystalline Phases Identified in FBC Ash and Grout

Mineral Name	Abbreviation	Chemical Formula
Calcite	(Cc)	$CaCO_3$
Anhydrite	(An)	$CaSO_4$
Gehlenite	(Ge)	$Ca_2Al_2SiO_7$
Lime	(Lm)	CaO
Portlandite	(Pt)	$Ca(OH)_2$
Quartz	(Qz)	SiO_2
Ettringite	(Et)	$Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O$
Gypsum	(Gp)	$CaSO_4\bullet 2H_2O$

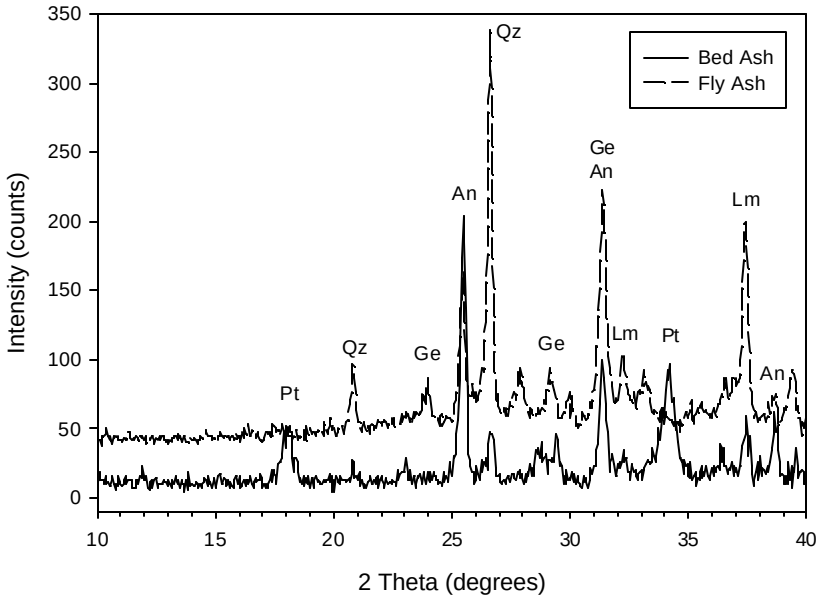


Figure 2. XRD spectra of Cedar Bay bed ash and fly ash.

The effect of curing time on grout mineralogy is shown in Figure 4 for the fly ash grout samples cured at 21°C. Over the course of curing there was a loss of portlandite and an increase in ettringite and calcite abundance; the remaining phases remained more-or-less unchanged. The XRD spectra show that after curing for long periods of time, the distribution of crystalline phases such as ettringite was unaffected by the initial water content. Higher temperatures accelerated the grout curing rate and thus the rate of ettringite and, to a lesser degree, calcite formation, while increasing the rate of decline in portlandite abundance. Curing temperature had no significant effect on final mineral composition of the fully-cured grout samples.

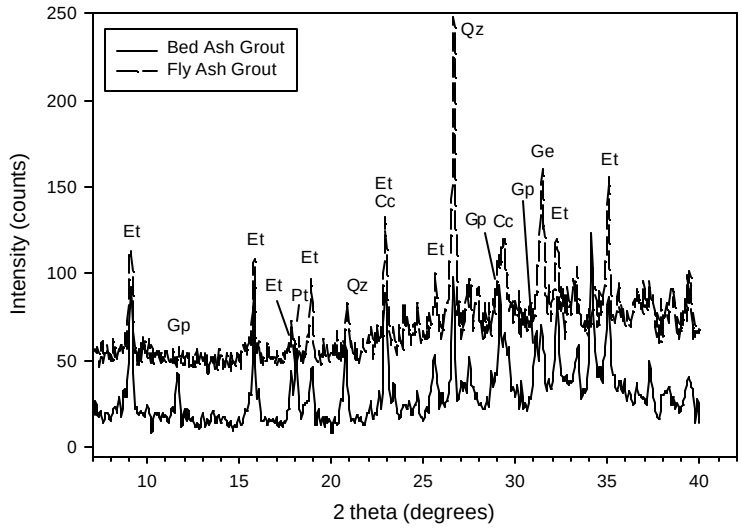


Figure 3. XRD spectra of bed ash- and fly ash-based grouts.

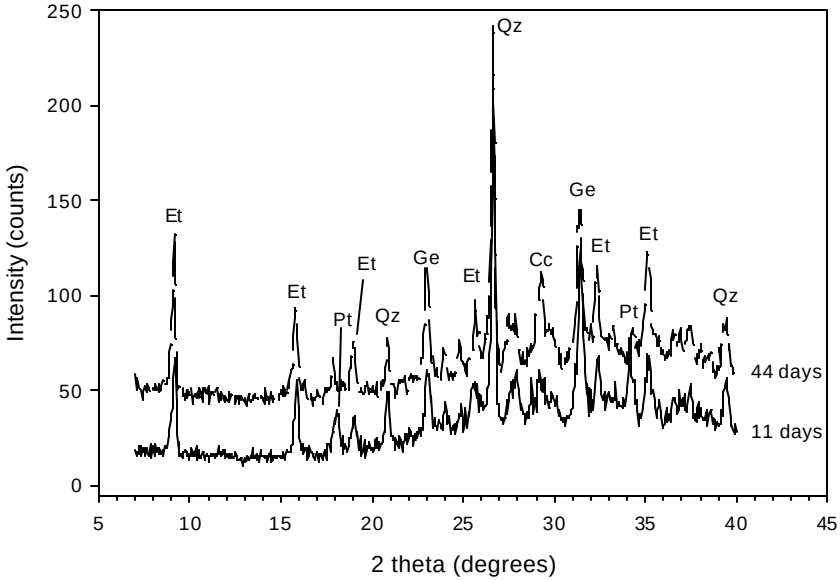


Figure 4. XRD spectra of FBC fly ash-based grouts at different curing intervals.

Unconfined Compressive Strength

The effect of water content on the unconfined compressive strength of the Cedar Bay fly ash grouts was similar to that for Portland cement paste: increasing the water:solid ratio resulted in a significant decrease in strength, probably because of a higher degree of porosity in the hardened grout.

At each water content, the rate of strength gain was considerably increased as the curing temperature increased (Figure 5). The maximum strength was achieved by day 10 and day 25 for the 50°C and 30°C curing, respectively, whereas the grout cured at 21°C continued to gain strength after 100 days. However, the increased curing temperature also caused a slight strength decrease after the maximum was achieved; at 50°C, maximum strength occurred at approximately 10 days, then decreased slightly (Figure 5). At 30°C curing, a similar trend occurred. This held true for all of the moisture contents studied. These relationships are consistent with those published for Portland cement concrete. In general, higher curing temperature increases the early strength of concrete but often adversely affects the longer-term strength, possibly because of greater porosity and more poorly developed physical structure (Neville, 1996).

The laboratory tests suggested that the FBC ash grouts could be formulated at water contents high enough to provide an adequate degree of fluidity, whilst providing sufficient mechanical strength for highwall stablization (i.e., > 500 PSI). However, the data also suggested that elevated temperatures are required for adequate strength to develop within a period of several weeks.

Field Demonstration

Site Preparation

The field demonstration site was developed at a surface mine located in Floyd County, Kentucky. The augered highwall was located approximately 50 feet from an active haul road. More than twenty auger holes were uncovered (Figure 6) using earth-moving equipment. The auger holes dipped away from the entrance, which caused some of

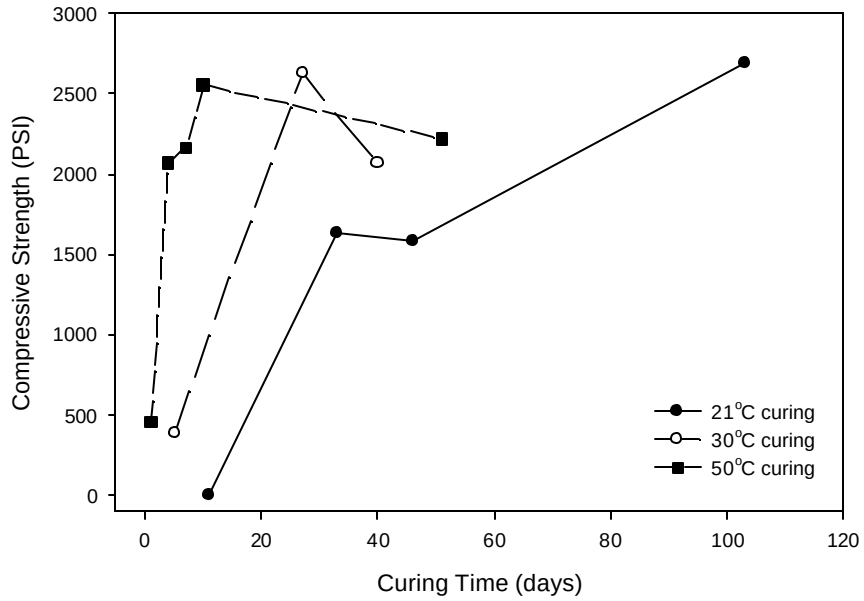


Figure 5. The effects of temperature on unconfined compressive strength of fly ash-based grout prepared with a water:solid ratio = 0.62 (38.3% moisture).

the holes to be completely filled with water towards the back. This is common for auger holes and is caused by the massive auger stem "bottoming-out" of the coal bed within about 100 ft. depth. The standing water was pumped from some of the holes to permit depth measurement and general surveying. Comparison of hole capacity with the actual volume of grout emplaced was used to assess the extent of hole filling.

Grouting Procedure

It was decided to use readily available concrete mixing and emplacement equipment for the field demonstrations. Concrete trucks, of 10 yd^3 capacity, were chosen to mix the grout prior to emplacement. The FBC ash was loaded into the trucks along with a specified amount of water, whereupon the grout was mixed and delivered to the site. The grout was then transferred to a concrete piston pump (Figure 7) that can deliver material at pressure and high rates of approximately 115 yd^3/hr. Hardened agglomerates of fly ash were removed from the grout using a large screen installed on the concrete pump hopper. PVC pipe was connected to the piston pump outlet and inserted into the auger holes. The grout was then pumped through the pipe until the auger hole rejected the material.

The piston pump was mounted on a truck and was equipped with a 90 ft. long extendable, hydraulically -controlled boom. This boom is a desirable feature because it can reach auger holes not immediately adjacent to a haul road. It was also used to withdraw the pipe from the auger hole and move the assembly to the next hole.

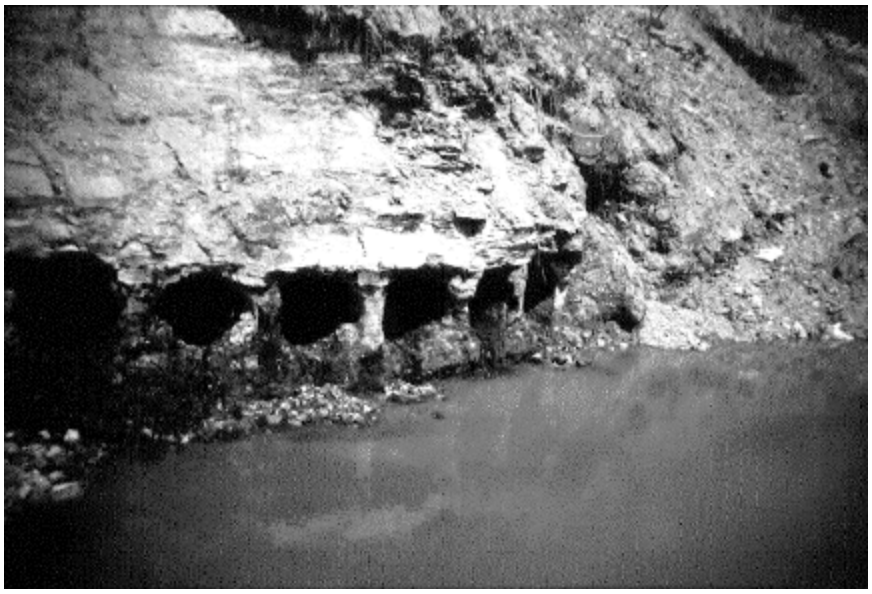


Figure 6. Abandoned highwall containing auger holes. Holes were initially plugged with rock and soil, and were exposed for this project. Each hole is approx. 3 ft. in diameter.

Figure 7. Photograph of field demonstration site, showing mixing truck (left) transferring grout to hopper in the piston pump (right).

Grout Emplacement

The field demonstrations occurred in June and August 1997. Although standing water was pumped from some of the auger holes, it was apparently unnecessary for successful grout emplacement. During grouting of auger holes containing standing water, large amounts of fairly clear water were observed flowing from the hole entrance and from adjacent holes, indicating that the grout effectively displaced water without mixing with it to a significant extent. This worked particularly well when the grout was injected from the back of the hole.

Sandbags were first used as bulkheads at the hole entrances but proved ineffectual at restraining the wet grout. Therefore, additional auger holes were prepared for grouting by removing only the top 6 in. of soil and rock, thus leaving in-place an earthen bulkhead. This bulkhead and the dip of the hole allowed for grouting nearly to the roof. The bulkhead remained intact during grouting and was effective in allowing for greater pressure to be applied to the grout, thus forcing it to the back of the hole.

Moisture contents were obtained at the site using a microwave oven and ranged from 30%-42%. Temperature measurements of the grout were obtained on cylinder samples (prepared for compressive strength testing). These ranged from 45° to 75°C. In addition, a thermocouple apparatus inserted into an auger hole indicated an *in situ* grout temperature of 70°C. Five days after grout emplacement the auger hole temperature was 62°C.

Comparison of the volume of emplaced grout with the capacity of the holes indicated that filling was nearly complete for many of the holes, and suggested that the grout fluidity was sufficient for proper flow. Although several auger holes were successfully filled with bed ash-based grout, it is preferable to use grout containing less bed ash because of the large amount of heat of hydration, and the comparatively low ultimate compressive strengths that are produced.

There was a significant problem regarding the extensive amount of elapsed time (> 1hr.) between truckloads of grout arriving at the mine site. This not only limited the number of holes grouted, but also caused problems with grout stiffening within the mixing trucks, pump, and (partially filled) auger holes between deliveries. It was therefore concluded that the use of concrete mixing trucks be avoided in favor of mixing the grout at the mine site using a mill. Similar techniques have been successful for the injection of FGD-based grouts into abandoned underground mines (e.g., Mafi et al., 1997; Chugh et al., 1997; Petzrick and Rafalko, 1997).

Geotechnical, Chemical, and Mineralogical Monitoring

In addition to cylinder samples prepared during the field demonstrations, cured grout from the auger holes was sampled 194 days and 240 days after the 2nd and 1st demonstrations, respectively. Mining had proceeded to a point where the strata overlying the coal was completely removed thus exposing the grout-filled auger holes. Eleven grouted holes were sampled for physical testing, and chemical and mineralogical analysis.

Representative samples of each grout were cut into prisms, with a height:width = 2:1, for unconfined compressive strength testing. The strength data are provided in Table 3. Comparison of field data with laboratory data (Figure 8) reveals that the range of compressive strengths was very similar for the two data sets. This indicates that the laboratory grout mix proportions and 50°C curing conditions produced material that was similar to the field demonstration grouts and that, more importantly, the compressive strengths exceeded the minimum 500 PSI criterion for proper, safe support of the coal overburden.

After testing for unconfined compressive strength, x-ray diffraction (XRD) analysis was conducted on fragments of the grout samples. These data indicated that the mineralogy of the field demonstration grout was also similar to that of the laboratory-prepared material.

Table 3. Physical Properties of Several Field Demonstration Grouts

Auger Hole No.	Grout Type	Moisture (wt.%)	Strength (PSI)	Wet Density (g/cm^3)
L1	Bed Ash	30.4	944	1.56
L2	Fly Ash	34.3	1334	1.61
L3	BA/FA	40.0	1000	1.67
L8	Fly Ash	38.7	1597	1.59
L10	Fly Ash	36.7	1601	1.60
R2	Fly Ash	34.1	2263	1.79
R4	Fly Ash	39.5	1677	1.79
R11	Fly Ash	38.9	1759	1.58

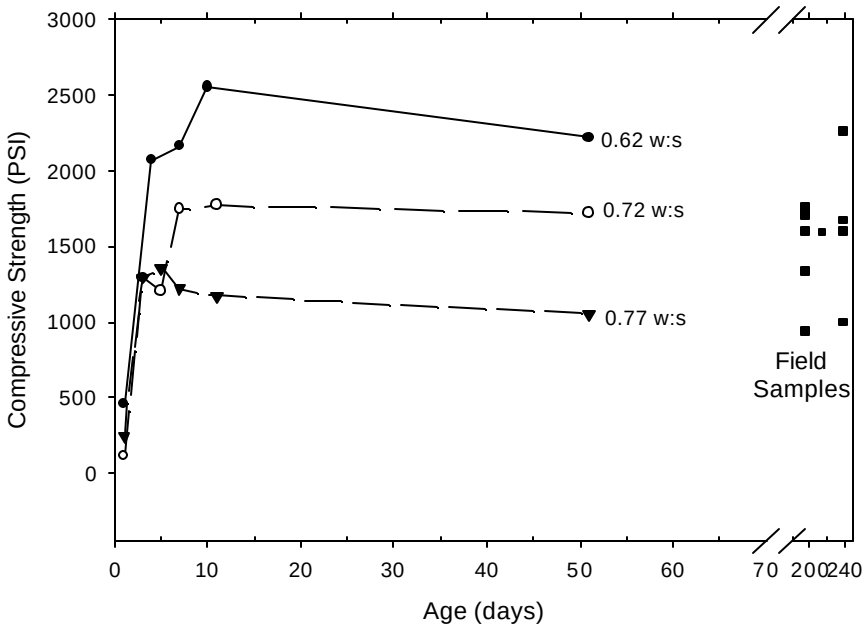


Figure 8. Unconfined compressive strength of lab grouts cured at 50°C, with water:solid ratios between 0.62 and 0.77 (38%-44% moisture), compared with field demo (auger hole) grouts.

Economic Analysis

The final project objective was to evaluate the economics of the concept. A computer program was developed for a basic economic model, and a hypothetical operation was devised to evaluate the feasibility of auger hole filling. The hypothetical mine setup produced a total cost for the auger hole filling operation of less than \$0.20 per yd^3 of coal recovered. This low cost largely resulted from the high proportion of coal recovered per ton of grout placed. It was concluded that grouting should be economically feasible and, when combined with modern automated highwall mining methods, could add significant quantities of coal reserves in the eastern United States.

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GROUT INJECTION INTO AN UNDERGROUND COAL MINE TO CONTROL ACID MINE DRAINAGE AND SUBSIDENCE

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Abstract

This paper presents the results of a study involving the field scale injection of grouts into underground room and pillar mines to control acid mine drainage and subsidence. The grout used is made of Class F fly ash and cement kiln dust (CKD). The mix was developed from several laboratory scale experiments conducted to investigate flow characteristics and strength. Strength requirements for the grout were determined from site specific geologic information and expected stress levels. Starting in the spring of 1999, 40,000 yd^3 of the Class F/CKD grout was pumped into the Longridge Mine in Preston County, West Virginia. Complications due to the mine geometry and recharge to the mine pool have led to the development of new methods for achieving complete backfill in underground room and pillar mines. These new methods and project results will be discussed.

Introduction

Acid mine drainage from abandoned coal mines continues to be the legacy of Appalachian coal mining. Current treatment technologies treat the acid mine drainage after it has exited the mine. Many of these systems are quite efficient but do require substantial flat land in order to be installed. The objective of this project is to evaluate the technical, economic, and environmental feasibility of filling abandoned underground mine voids with a chemically stable grout to control acid mine drainage and subsidence.

Demonstration Project

The Longridge Mine in Preston County, West Virginia is an 11-acre deep mine. The mine void is intercepted by an auger hole that was installed to drain a mine pool so that surface mining could proceed down dip of the Longridge Mine. The auger hole allows a 11,000 cubic yard or 2.2 million gallon mine pool to remain in the Longridge Mine. The auger hole discharged about 100 gallons per minute of acid mine drainage prior to any work at the site.

The Longridge injection began in late January 1999. A total of 3,000 cubic yards of grout was injected into the up dip section of the mine. After two weeks of injection, it was observed that the grout was communicating with the auger hole drainage; grout began to flow from the auger hole that is located 2,000 feet from the injection hole. Grouting ceased while plans were made to stop the grout from leaving the mine. In early April, the project team decided to place a barrier 200 feet down dip from the injection bore hole. The barrier was to be made by pneumatically injected gravel into the mine void from the surface via the Burnett Ejector. A total of 300 tons of gravel was placed into two headings to create a barrier. Three thousand yards of stiff grout (2/5 cement kiln dust to 3/5 class F ash with one bucket of gravel with a solids to water ratio of 3:2) were placed directly up-dip from the barrier. The installation of the barrier decreased the auger hole flow by 90% (from 92 gpm to 9 gpm). Grouting with the prescribed thin grout (1/4 cement kiln dust, 3/4 class F ash with a solids to water ratio of 1:1) continued in holes above the barrier. A total of 12,500 yards of thin grout was placed in the upper cell after barrier construction. The auger hole continued to flow at less than 10 gpm during the spring and summer of 1999.

After the upper cell (Cell 1) was complete, grouting commenced just below Cell 1. While grouting Cell 1, holes were drilled across the mine void to divide it in half. The Office of Surface Mining (OSM) bore hole camera was employed to investigate the mine void. The mine was collapsed and no void could be seen. Thin grout injected below Cell 1 did communicate with the auger hole so a thicker grout mix was employed to stop up the void space in the collapsed barrier. This has worked as 12,000 yards of grout have been placed in Cell 2 with no communication with the auger hole. An investigation of the mine void via the OSM camera on 29 July 1999, indicated that solid grout could be seen 2 feet above the mine roof in boreholes just above the barrier for Cell 2. The auger hole flow is below 5 gpm and has continued to stay at this level through the summer of 2000. Table 1 shows the water quality data from the auger hole before, during, and after grouting.

Conclusions

The placement of a chemically stable grout in underground mine voids is technically feasible and environmentally sound. No adverse water quality affects can be seen from the placement of the Class F fly ash/Cement Kiln Dust grout in the mine. While barium did triple in concentration, it is still well below the drinking water limit established by the U.S. Environmental Protection Agency. Injection costs (labor, water, mixing, pumping) remain below $3.00 per yard. When transportation of cement kiln dust and Class F fly ash are factored in, a cubic yard of grout costs about $12.85 to get into the mine void. A full-scale economic analysis will be completed once injection is complete.

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BENEFICIAL USES OF CLEAN COAL COMBUSTION BY-PRODUCTS: SOIL AMENDMENT AND COAL REFUSE TREATMENT EXAMPLES AND CASE STUDIES

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Abstract

Combustion of coal, with high sulfur content, often requires some sort of scrubbing technology be applied so that the emissions meet clean air standards. The by-products produced, often referred to as Clean Coal Combustion By-Products (CCCBs), have unique properties that give them value when properly used for various land application purposes. The keys to a successful beneficial use program are knowing these properties and understanding how to capture them in a beneficial way. In some cases, modification or treatment of the CCCBs must be done to obtain the proper characteristics to achieve a desired end. Also required is an understanding of the regulatory restraints to the use of CCCBs so that we can effectively work within them. We have characterized a large number of CCCBs created by different scrubbing processes. Based on these characterization data, we have designed and conducted laboratory and field scale studies related to land application uses of CCCBs involving agriculture and surface mine land reclamation. This paper summarizes some of the results obtained from these studies. We conclude that CCCBs can be successfully used for land application benefits and may be potentially developed into commercial products. Environmental responses are mostly either not measurable or positive. Observed negative responses are primarily limited to release of metals either directly from the CCCBs or from the treated soil as they are displaced by basic cations (Na, Ca, Mg, etc.) contained in the CCCBs For CCCBs to achieve widespread land application use, we need: 1) education of the general public concerning their benefits, 2) acceptance by regulatory agencies that CCCBs are just as safe as other commonly used land application products (e.g., mineral fertilizers, limestone, various types of composts), and 3) creation of companies or commercial partnerships that focus on the development and marketing of products derived from CCCBs.

Introduction

Coal represents a major natural resource in the United States and a large amount of it is burned each year to produce electricity, heat or other forms of useful energy. Approximately 92.5 million Mg (102 million short tons) of coal combustion by-products were produced in the United States in 1996.

The materials produced in major abundance during combustion of coal and scrubbing of the waste gases include fly ash, bottom ash, boiler slag, and various types of scrubbing by-products. Fly ash is a fine inorganic particulate residue suspended in the flue gases produced when coal is combusted and is collected primarily by electrostatic precipitators. The rapid cooling of the, "ash from the molten state as it leaves the flame," causes fly ash to be predominantly noncrystalline (glassy) with minor amounts of crystalline constituents such as quartz, hematite, mullite, and magnetite. Fly ash particles are extremely variable, however, in size and chemistry due to variability of the coal feedstock and the various types of burners used. In general, fly ash particles are composed of alumina, silica, and iron oxide. They are less than 250 micrometers in diameter, spherical in shape, have a high mechanical strength, and are mostly chemically inert. The shape, fineness, particle size, density, and chemical composition of the fly ash particles determine end-use potential and the properties of the end-use products.

Boiler slag and bottom ash are heavier and coarser than fly ash. Bottom ash, a granular material, is often used as a low cost replacement for more expensive sand in the production of concrete blocks, and in many States it is used as a base in road construction. Boiler slag is granular and sand-like but is shiny black in color and is very hard and abrasive. It is widely used to coat roofing shingles and as a blasting abrasive.

Because burning of coal results in the production of sulfur dioxide (SO_2)(which has been linked to acid rain formation, acidification of soils, and forest decline), the 1990 amendments to the Clean Air Act have mandated a two-stage, 9.07 million Mg reduction in SO_2 emissions by the year 2000. These amendments have spurred the development of SO_2 scrubbing technologies which produce a clean coal combustion by-product (CCCB). Several industry, government agencies, and university programs have conducted extensive studies on the characterization and beneficial uses of CCCB materials and much of this information has been reviewed (Dick et al., 1999; Stehouwer et al., 1998; 1995a; Clark et al., 1995; Korcak, 1995; Norton, 1995; Carlson and Adriano, 1993; Adriano et al., 1980).

In the past, CCCBs were treated primarily as a waste and landfilled; however, landfill sites are becoming scarce and disposal costs are constantly increasing. Provided the environmental impacts are minimal and socially acceptable, land application uses can provide economic benefit to both the producer and the end user of the CCCBs.

The bulk of this paper is extracted from a chapter in a book published by the Soil Science Society of America (Power and Dick, 2000). This book deals with all types of by-products including CCCBs and other related by-products such as gypsum (Dick et al., 2000; Ritchey et al., 2000)

Properties of Clean Coal Combustion By-products and Their Impacts on Land Application Uses

Two major forms of CCCBs are produced during the removal of SO_2 from flue gases. Dry CCCBs are produced by any of several technologies developed for retrofitting on existing coal burning facilities. New fluidized bed combustion boilers are the most common source of dry CCCBs. They are collected using various particulate emission control devices. Dry CCCBs are highly variable in their characteristic properties. We have analyzed more than 50 samples collected from different sources located primarily in Ohio (Stehouwer et al., 1995a).

A second type of CCCB, and by far the largest volume produced, is a wet flue gas desulfurization by-product. In general, once the flue gas is discharged from the boiler, it is fed through a dust collector to remove fly ash and then introduced into a scrubber. In the scrubber, the flue gas contacts slaked lime or limestone slurry which absorbs SO_2. If additional air is injected with the flue gas, production of almost pure gypsum results. There are numerous uses of gypsum including production of wall board and land application uses (Ritchey et al., 2000). If air is not forced into the absorber, a slurry cake of CCCB is created containing a mixture of calcium sulfite and calcium sulfate. This slurry cake must be dewatered by centrifugation or vacuum filtration prior to its use. The slurry cake is then generally further processed or fixated by adding dry fly ash to increase solids content along with some additional lime. This causes a pozzolanic or cementitious reaction to occur which strengthens or hardens the material.

Each scrubbing process yields materials that have different properties that will affect their end use potential. Properties of CCCBs that can either enhance or reduce value for various land application uses are summarized (Table 1). Consequently, not all CCCB materials are equally suitable for all possible beneficial uses. Specific beneficial uses of CCCBs must be designed to take maximum advantage of those properties that enhance the value of the CCCBs and to minimize the properties that reduce value. Obviously, information on the mineralogical, engineering, and chemical properties of CCCBs is essential in designing a beneficial use program.

Data on the types and amounts of minerals in dry CCCBs (Table 2) is often the most informative when planning potential beneficial land application uses. For example, those interested in using CCCBs to capture their pozzolanic properties will want to know the relative amounts of CaO, $Ca(OH)_2$, and fly ash. Fly ash, by itself, can increase compressive strength, durability, and workability while decreasing permeability, shrinkage, and segregation of many materials with which it is mixed. These benefits are due to the fineness, spherical nature, and size distribution of the fly ash particles which allow better filling of voids and reduce the need for water. Both wet and dry CCCB samples, containing fly ash and CaO or $Ca(OH)_2$, will exhibit cementitious properties that can be useful for various engineering applications such as embankment stabilization or roadbed construction.

For agronomic land application uses, the trace mineral content and minerals that provide neutralization potential are most important. The neutralization potential can be determined by titration and is generally expressed as a percentage of calcium carbonate equivalence (ASTM, 1990). Mean calcium carbonate equivalency (CCE) values measured for materials obtained from each of the various dry CCCB processes ranged from 24.8% to 65.2% (Table 3).
The four large volume wastes from coal-fired boilers c fly ash, bottom ash, boiler slag, and wet scrubber CCCBs c were exempted in 1988 from hazardous waste regulations under Subtitle C of the Resource Conservation and Recovery Act (RCRA) (USEPA, 1993). This exemption was reaffirmed in 1993. Instead, the regulations of these by-products was left to the individual States. The American Coal Ash Association (Washington, DC) has taken the lead in working with CCCB producers and States in developing guidelines for the use of these materials. For other types of CCCBs, particularly the fluidized bed combustion boiler by-products, the American Coal Ash Association and the Council of Industrial Boiler Owners are assisting the U.S. Environmental Protection Agency in creating a database of chemical and physical properties to also exempt these sources from the RCRA regulations.

If we consider the major components in most of the CCCBs that are currently nonexempt, we can begin to understand what their potential environmental impacts may be. The sorbent used in most scrubbing processes is hydrated lime ($Ca(OH)_2$), limestone ($CaCO_3$), or dolomite ($CaMg(CO_3)_2$). These materials have been used by farmers for centuries, at rates of 20 Mg/ha (8.9 tons/acre) or greater, to alter soil pH from an acidic value to a value near neutral (pH 7). Thus, their introduction during the scrubbing process should not result in any harmful environmental impacts of the resultant by-product. The product of the scrubbing reaction is primarily $CaSO_3$ and this material, when applied to aerobic soil environments, is rapidly converted to gypsum ($CaSO_4\$2H_2O$) which also has a long history of use as a soil amendment (Ritchey et al., 2000). Fly ash is the mineral residue from the coal that is burned and its chemical properties will depend on the source of the coal. Combustion of coals that are high in Boron (B) may produce fly ash or CCCBs that contain sufficient concentrations of this element to caution against land application due to B phytotoxicity. This problem can be reduced by allowing these materials to weather, to leach out the B, before land application.

If there is a concern in land applying CCCBs, it is that during the SO_2 scrubbing reaction, a potentially harmful element or compound may be sequestered or concentrated in the reaction by-products. Because there is little information or baseline data available, many states are requiring environmental impact information before approving CCCB materials for land application uses. Due to a lack of clear regulatory guidelines we have adopted the 503 Rules (USEPA, 1993) to help us assess the risks involved for land application uses of CCCBs. The 503 Rules were developed to regulate land application of biosolids and are not directly applicable to CCCBs. CCCBs are essentially 100 percent inorganic and amorphous whereas the 503 Rules were developed for organic materials which mineralize in soil. Thus, the use of the 503 Rules, when applied to CCCB materials, probably imposes a stricter level and greater margin of safety than when applied to land application of biosolids.

If a total chemical analysis of the CCCBs is done, one can compare the concentrations in the CCCBs sample with the concentration limits as defined by the 503 Rules. Stehouwer et al. (1995a) and Clark et al (1995) have reported detailed elemental concentrations of a range of CCCBs. It is also possible to calculate the loading rates of the various elements by multiplying the application rates by their concentrations in the CCCBs sample and comparing these values with the 503 cumulative loading limits.

Toxicity characteristic leaching procedure (TCLP) tests are commonly used to characterize the potential toxicity of waste products. This procedure was developed to determine the potential mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic waste materials. The results of applying the TCLP tests to six CCCB samples indicated that, in all cases, the TCLP concentrations were well below the drinking water limits. This is not surprising because the alkaline material in the CCCB samples causes the pH to be above 7 and precipitates metals, thus removing them from solution, or precluding them from entering the solution phase.

Case Studies of Clean Coal Combustion By-product Land Application Uses

Agricultural Uses

To justify CCCBs use in agriculture, any addition to the soil must clearly benefit the environment (i.e., soil, water, or air) or the crop (Korcak, 1998). Potential benefits of applying CCCBs to soil are both chemical and physical in nature. Physical benefits include increased water infiltration and aggregation of the soil. Chemical benefits of land applications of CCCBs include its ability to supply essential plant nutrients, modify the balance of nutrients, or adjust the pH to a more optimum level.
As previously stated, there are several properties of CCCBs that can be captured for beneficial use when they are used as an agricultural amendment. Many soils in the United States are limiting in one or more essential plant nutrients that are required in trace amounts for optimum crop growth (Adriano et al., 1980; Dick et al., 2000). For example, CCCBs may serve as supplementary sources of Ca, S, B, Mo, Se, and other trace elements. Proper rates are often site specific and studies are required to match the proper rate of CCCBs to be applied to the land to the need of the crop.

Selenium is one element that is not required by most higher plants but is an essential element for animal growth. Since Se is often limiting in animal feed, it is added as a supplement to improve feed efficiency. The problem is that Se is needed only in very low concentrations, and it can become toxic if concentrations in the diet are not properly controlled. Recommended food and feed concentrations to provide adequate Se for animal growth range from 0.2 to 1.0 mg Se/kg plant material and concentrations above 5 mg/kg can cause Se toxicity (Mengel and Kirby, 1987). Use of CCCBs can supply Se to plants, and when the plants are subsequently fed to animals, this Se can help overcome deficiencies. It is important, however, that Se concentrations in the crop growing in soil amended with CCCBs are in a proper range so that the feed can be safely used.

Soluble salts also can be a problem when fresh CCCBs are land applied unto agricultural fields. If the material used to scrub the sulfur dioxide contains dolomite, magnesium sulfate is created during the scrubbing process and this material can be an especially important contributor to salt problems. The problem of high soluble salt concentrations can be minimized in several ways. Surface application, without incorporation, separates the CCCBs from the germination seed and reduces the salt effect. The surface layer of CCCBs can, in addition, also act as a mulch to conserve soil moisture. Applying the CCCBs at times when the crop is dormant (e.g., in the fall of the year after crop harvest and before a new crop is planted), also provides time for salts to be flushed from the treated soil. Weathered or stockpiled material, from which a substantial portion of the soluble salts have been leached, also may provide a solution to the salt problem. One study has shown that weathered ash could be used up to rates of 131 Mg/ha (58 tons/acre) while salt-related problems occurred at 87.2 Mg/ha (39 tons/acre) for the fresh ash (Martens and Beahm, 1976).

Boron is an essential plant nutrient but also can easily become toxic if applied at excessive rates. Boron concentrations greater than 1 mg/L in the soil solution may be toxic to sensitive plants (Bohn et al., 1979). However, concentrations of several tenths mg/kg may indicate deficiency. Boron toxicity is primarily a problem the year of application only (Ransome and Dowdy, 1987). Boron is very soluble and can be easily leached away so that toxicity problems can be easily avoided with proper testing and if time is permitted for natural leaching to occur in the field prior to planting of a crop.

Benefits of CCCBs as an agricultural amendment also may be attributed to changes in the chemical, physical, and microbiological properties of the soil. The benefits that can be captured related to soil chemistry are changes in pH and additions of essential plant nutrients. These have already been discussed. Physical changes of the soil, after CCCBs treatment, would include changes in the distribution of soil particle size, increased pozzolanic activity and possibly increased soil dispersion. To overcome many of the chemical and physical problems of CCCB use, work is needed to develop equipment that can apply the CCCBs at precise rates and precise locations within the soil profile. Jacobs et al. (1991) found that when a coal ash was banded into the soil at a 45 degree angle to the surface, corn roots were concentrated at the ash band, which was water saturated after rain occurred. Corn yields were increased in the ash-banded plots. The ash may have increased yields by supplying essential plant nutrients and by holding water for longer periods of time, than the natural soils, thus reducing drought problems. Additional work on this and

other creative ways to apply CCCBs to soil may indicate even greater land application benefits to agriculture.

The effect of CCCBs application on the microbiology of the soil/plant system is largely unknown. This microbiology is very complex and represents an area that is ripe for further study.

The preceding paragraphs highlight some of the general issues related to beneficial uses of CCCBs. The following sections will provide specific examples or case studies where CCCBs were used in agriculture and in surface coal mining. We will focus on things learned to optimize the benefits of the CCCBs while maintaining the quality of the environment.

Agricultural Limestone Substitute. Many CCCBs contain a substantial amount of neutralizing potential, either as $CaCO_3$ or CaOH. In addition, once a pH adjustment has been made, the coal ash in some CCCBs exhibit a large buffering capacity which provides resistance to further pH change. CCCBs also contain essential plant macronutrients and micronutrients.

Rates of CCCBs to be applied to soil for pH adjustment can be easily determined by matching the soil=s lime requirement with the total neutralizing potential (expressed as calcium carbonate equivalency or CCE) of the CCCBs. Both analyses are commonly provided by university or other commercial testing laboratories and analytical procedures have been published (Thomas, 1996; Sims, 1996). For example, if a soil test indicates that 10 Mg/ha (4.5 tons/acre) of $CaCO_3$ is required to achieve a final soil pH of 7.0 and the CCE value of the CCCB is 50%, then 20 Mg/ha (9.0 tons/acre) of the CCCB will need to be applied to the soil.

A CCCB with a CCE value of 60% and containing 129 g/kg of magnesium (as $CaMg(CO_3)_2$) was tested as a limestone substitute at three different sites in Ohio. The Wooster site was the most acid with a pH of 4.6. The amount of CCCB applied was 0, 1/2, 1, and 2 times the lime requirement rate as determined by standard soil tests. The actual amount of CCCB applied at the maximum rate (i.e., two times the lime requirement) was 70 Mg/ha (31 tons/acre). This CCCB by-product consisted of a 40:60 (wt/wt) mixture of bed and cyclone materials from a pressurized fluidized bed combustion (PFBC) process and had a particle size distribution similar to conventional agricultural limestone. Approximately 25% of the cyclone portion of the by-product was the mineral dolomite ($CaMg(CO_3)_2$). The B concentration was approximately 190 mg/kg. Nutrient concentrations were adjusted by applying fertilizers. The CCCB was applied in September 1992 and alfalfa (*Medicago aestivum* L.) was planted that fall and corn (*Zea mays* L.) was planted the next spring.

Alfalfa yields were increased slightly in 1993 (a very dry year) and more significantly in 1994 by application of the CCCB to the soil when compared to the untreated control. Unfortunately, an agricultural limestone treatment was not included to compare with the CCCB response. Corn yields were not significantly increased and this is probably due to corn being more tolerant of acid soil conditions than is alfalfa. Alfalfa and corn tissue elemental concentrations remained within sufficiency ranges for Mg, S, and Mo and were increased in the alfalfa grown on the CCCB treated soil, as compared to the untreated control soil, in 1993 but not in 1994. Although there was some evidence of increased concentrations of B in alfalfa tissue resulting from the CCCB application, these concentrations remained well below phytotoxic levels. Molybdenum concentrations also increased substantially, although this is commonly observed when acid soils are limed. This increase was thought not to be due to Mo in the CCCB material applied. Tissue concentrations of Al and Mn decreased in all samplings which can be directly attributed to the increased soil pH.

Other results of this study can be summarized as follows. The Mg-containing CCCB was an effective soil liming material when applied according to standard CCE and soil tests. It neutralized soil acidity within the depth of incorporation and sustained a near neutral soil pH. Surface application of the CCCB also affected subsoil chemistry. The downward movement of Mg and sulfate was the main mechanism for this effect even though a large amount of $CaSO_4$ was present in the CCCB. The much greater solubility of epsomite ($MgSO_4 ! 7H_2O$) resulted in much greater and more rapid transport of Mg than Ca. Because there was more Mg than sulfate in the CCCB, sulfate was depleted in the surface soil before Mg. Following depletion of sulfate, transport of Mg and Ca decreased substantially

because their solubility was then controlled by their respective carbonate forms. The effect of the CCCB on subsoil chemistry also depended on the base-status of the subsoil. In a high Ca status subsoil, movement of Mg and Al from the surface decreased subsoil Ca and increased subsoil Al. In a subsoil with high Al concentrations, movement of Mg and sulfate from the surface decreased subsoil Al and increased subsoil Mg. A CCCB containing Mg, thus, may be more effective than gypsum in ameliorating subsoil Al phytotoxicity.

A second experiment was begun at Wooster in 1997 and involved the use of a specific CCCB that contained expanded vermiculite clay and had a CCE of 46%. This CCCB was applied in the spring of 1997 at a rate based on the soil=s lime requirement to achieve pH 7 (18.3 Mg/ha or 8.2 tons/acre CCCB) and alfalfa was planted. Results after one year (Figure 1) showed that the CCCB significantly increased alfalfa yields compared to the untreated control. The yields on the CCCB treated plots (both with and without added fly ash) were higher than when soils were amended with agricultural limestone. This suggests there was a benefit obtained from applying the CCCB in addition to only pH adjustment. This benefit is probably due to the presence of trace elements contained in the CCCB.

Obviously not all CCCBs are candidates as agricultural limestone substitutes for land application uses. Factors that may preclude their use are heavy metal concentrations that exceed the EPA 503 regulation limits, high B content, high soluble salt content and low acid neutralizing potential (Carlson and Adriano, 1993; Clark et al., 1995; Stehouwer et al., 1995a). Use of a material with a low CCE value would require much higher rates than are normally recommended (usually 10 to 50 Mg/ha which is equivalent to 4.5 to 22.3 tons/acre). Applying CCCBs for mine land reclamation, where soils are often severely degraded and contain very high levels of acidity, would be a situation where recommended rates would need to be increased.

If CCCBs are weathered prior to their application to soil, many of the problems related to excessive B and salt concentrations can be avoided. Weathering also, however, decreases the liming benefit of the CCCBs. In all cases, especially where food crops will be grown, a careful chemical analysis of the CCCBs should be made prior to their application.

The very small size of fly ash or CCCB particles makes material handling considerations a very important part of any beneficial land application program. When dry CCCB materials are applied to soil using a commercial limestone spinner spreader, excessive dusting occurs. A drop box spreader or any other spreader that can evenly apply the CCCB to the soil surface without dusting could be used. Wet CCCBs are also difficult to handle because they are formed as a paste-like material. After mixing with fly ash and lime, the material agglomerates into large chucks (5-30 cm diameter). These chunks will plug most lime spreaders, but are easily broken up by a manure spreader. We have found that when high rates of CCCBs are applied to soil for reclamation of abandoned surface coal mines, which often also require an organic amendment, it is possible to combine these two materials. For example, a CCCB mixed with a biosolid or yard trimmings compost creates a granular material that has excellent spreadability with minimum dusting.

Coal Mine Spoil or Coal Refuse Treatment

There has been a recent trend for coal mining companies in the Eastern United States to both sell coal to an end user and to remove or dispose of the coal combustion by-product once the coal is burned. The most obvious use of the CCCBs is to return it to the mine where the coal originated. There are also many abandoned (or orphaned) mine lands that often are located near an active mine that can benefit from land application of the CCCBs (Sutton and Dick, 1987). In the following section, we describe several uses of CCCBs that are specific to the coal mining industry.

Several projects have been conducted in Ohio to investigate the use of CCCBs for reclamation of highly degraded mine soils or areas where coal refuse has been deposited and accumulated (Stehouwer et al., 1995b and 1995c). The project for which we have the most complete information is an abandoned clay and coal mine site, located near Dover, OH. This site was regraded during the summer of 1994 and the treatments were applied in the fall of 1994 just prior to seeding with a mixture of grasses and legumes. Approximately 1.2 m (4 feet) of overburden were placed above an impermeable clay layer and three treatments, each replicated two times, were then applied to the

overburden. They included: (1) 112 Mg/ha (50 tons/acre) of agricultural limestone mixed into the overburden and then 20 cm (8 inches) of resoil material placed over the overburden and treated with an additional 45 Mg/ha (20 tons/acre) of limestone; (2) 280 Mg/ha (125 tons/acre) of CCCB (an atmospheric fluidized bed combustion material) incorporated to a depth of 20 cm (8 inches); and (3) 280 Mg/ha (125 tons/acre) of CCCB plus 112/Mg (50 tons/acre) yard waste compost also incorporated to a depth of 20 cm (8 inches). The quality of both surface water and drainage water, representing that which leached downward to the clay layer and then laterally to the tile drains, was measured.

All three treatments improved surface water quality. Changes in pH, soluble Al and sulfur concentrations before, during and after reclamation are shown in Figure 2. Calcium concentrations were also increased by the CCCB treatments, as compared to the resoil treatment, due to the gypsum in the CCCB material. Tile water was near neutral and Al concentrations were generally less than 3 mg/L. With the exception of B, trace element concentrations in surface and tile water generally remained very low and were unaffected by treatments. Mean concentrations of As, Ba, Cd, Cr, Cu, and Se were below detection limits or below primary drinking water standards. Boron is associated with the coal ash component of the CCCB. Although B concentrations were increased compared to the resoil treatment, they were below phytotoxic levels.

Biomass production was greatest for the topsoil (i.e., resoil) treatment (Figure 3) but all treatments provided almost complete ground cover, thus protecting the site from erosion. Long-term effectiveness of the CCCB treatments is being studied to learn whether CCCB materials can create conditions that are ecologically sustainable and to ensure the site does not revert to the toxic and vegetation free environment present prior to reclamation.

Groundwater quality was also monitored at the Fleming site. In addition to groundwater wells, lysimeter clusters were installed to provide a more rapid or initial estimate of the effect of CCCBs on groundwater quality. Interstitial water in the application area had pH values more than one unit higher and specific conductance more than 8 S/m higher compared to a control area or where a borrow topsoil was used in a traditional reclamation procedure (Haefner and Rowe, 1997). Other elements with concentrations higher in the interstitial water beneath the CCCB application area included SO_4^{2-}, Cl, F, Ca, Mg and B. Sixteen months after reclamation was completed, there was no evidence that CCCBs had adversely affected the chemistry of groundwater beneath the reclamation area—even in shallow groundwater.

Clean coal combustion by-products can be mixed with pyritic overburden to help neutralize acidity and buffer pH at a level high enough to prohibit formation of additional acidity. It can also be mixed with coal refuse, i.e., material high in sulfur content that is washed from the coal. Sometimes as much as 50% of the raw coal is removed in this washing process and the coal refuse may contain S concentrations that approach 20% due to the enrichment of pyrites (Daniels et al., 1995; Buttermore et al., 1978). Coal refuse disposal is a major problem because copious amounts of acidity are created in the refuse and is released as acid mine drainage (Daniels et al., 1995; Martin, 1974). This acid drainage must be collected in ponds and treated.

Much of our early work involved treating coal refuse with dry CCCB materials that contained approximately equal amounts of ash, unreacted sorbent and reaction by-product (mostly $CaSO_4$ and $CaSO_3$). Dissolution of $CaSO_3$ increases water pH by consuming hydrogen ions during formation of bisulfite ion (HSO_3^-). Calcium sulfite is also an efficient reductant, limiting the concentrations of dissolved O_2 and ferric ion in the solution that equilibrates with the coal refuse. These reducing reactions are rapid and have large equilibrium coefficients and when pH is less than 8, the presence of $CaSO_3$ in a slurry can maintain dissolved O_2 below 10 mg/L. Decreasing pH greatly accelerates the dissolution and oxidation of $CaSO_3$ in water (Tseng and Rochelle, 1986; Masson, 1986) so that the inhibitory action of the SO_3^{2-} is eventually lost. Under acid conditions, SO_3^{2-} will also react to form sulfur oxide gases such as SO_2 and SO_3, which can be toxic to plants (Clark et al., 1995). Therefore, the optimum combination for inhibiting formation of acidity is to combine the use of $CaSO_3$ with a material that will result in an initial adjustment in pH to above 5.0 and preferably to 6.5 or higher.

Pyrite oxidation and acid production are also inhibited by the sulfite species SO_3^{2-}, HSO_3^- and H_2SO_3 found in CCCBs. These species are toxic against *Thiobacillus ferrooxidans*, *Thiobacillus thiooxidans*, and *Leptospirillum*

ferrooxidans which are the main bacteria known to be involved in catalysis of pyrite oxidation (Hirose et al., 1991, Hurtado et al., 1987; Sugio et al., 1994 and 1995; Takeuchi and Suzuki, 1994).

We recently began a series of experiments to determine the effectiveness of $CaSO_3$ to inhibit acid production in coal refuse or mine spoil. These tests included: (1) a slurry experiment; (2) a lab-scale column (2.5 cm i.d. x 13 cm length) leaching experiment; and (3) a large-scale greenhouse (30 cm i.d. x 112 cm length) column leaching experiment. The fresh coal refuse used was generated by the gravity separation method and had a mean particle size >0.95 cm (classified as a coarse refuse) and contained 17.5% S. Calcium sulfite was synthesized in our lab and calcium $CaSO_3$-based wet CCCB was obtained from the American Electric Power plant located near Coshocton, Ohio. The composition of this CCCB sample was 64% $CaSO_3$, 10% $CaCO_3$, 9% $CaSO_4$, and 17% fly ash.

In the slurry experiment, we incorporated 0.1 g to 0.2 g of $CaSO_3$ every three days into a freshly ground (<2 mm) coal refuse slurry (1 g refuse in 100 ml water) maintained under normal oxygen (21%) and reduced (1%) O_2 partial pressures. The reduced O_2 partial pressure was tested because when coal refuse is buried and capped, the levels of O_2 are much lower than found at the surface and the effectiveness of the $CaSO_3$ treatment may be greater and longer lasting under such conditions. At both O_2 partial pressures, $CaSO_3$ prevented a decrease in pH.

In the lab-scale column leaching experiments, $CaSO_3$ (6.4 g) and a CCCB material (10 g) containing $CaCO_3$ and fly ash were applied to 50 g fresh ground (<2 mm) coal refuse. The columns were leached (1 ml/h) with 20 ml water weekly for the initial 13 weeks and biweekly for the last 14 weeks. We found $CaSO_3$ inhibited the onset of acid production for about one month and produced at least 36% less total leachate acidity than the control during the 27 weeks of the test (Figure 4). The CCCB inhibited acid production more effectively than $CaSO_3$ alone and this seemed to be mainly due to a positive synergistic effect of the $CaSO_3$ with components of the CCCB (i.e., $CaCO_3$, fly ash, and possibly $CaSO_4$). Iron and $SO_4$2-leaching also indicated pyrite oxidation inhibition by $CaSO_3$ and this inhibition was increased by the CCCB.

The positive synergistic interaction of $CaSO_3$ with CCCB components is due to the great dependence of dissolution, oxidation, and speciation of $CaSO_3$ in water on the pH, the O_2 content, and the concentrations of various metal ions. At the equilibrium pH of a solution containing $CaCO_3$ (about 8.0), the rate of dissolution and oxidation of $CaSO_3$ is just rapid enough to maintain dissolved O_2 below 10 mg/L resulting in inhibition of pyrite oxidation. Fly ash has small particle size (<0.05 mm), large surface area (>1 m^2/g), and various metal oxides. Small sized particles can fill the pore spaces in coarse coal refuse and thus retard oxygen diffusion from the atmosphere into the coal refuse. In addition, the large surface area can adsorb protons and various metal ions and buffer pH which, in turn, can decrease sulfite oxidation kinetics.

In the greenhouse column leaching experiment, we incorporated 5.5%, 11%, and 22% CCCB into the surface (0 to 15 cm) layer. To the middle (50 to 65 cm) layer of the same columns, we applied an additional 1.25%, 2.5%, and 5.0% CCCB, with the low to high rates in the middle layer matched with the low to high rates of CCCB applied to the surface layer, respectively. The columns were leached with water (0.5 liter water applied twice with two hours between each application) weekly for the first 13 weeks, biweekly for the second 14 weeks, and monthly for the last 12 weeks (total 39 weeks). The CCCB applied at the highest rate significantly (P # 0.01) increased leachate pH and decreased leachate acidity compared to the control (Figure 5). The inhibitory effects of the CCCB on acid production in the coal refuse decreased with decreasing amounts of the CCCB and with time. During the initial 27 weeks, the high rate of CCCB also significantly (P # 0.05) reduced concentrations of various elements especially As, Fe, Ni, Pb and S, and Zn (Table 4).

From the above experiments, we concluded that $CaSO_3$ and $CaSO_3$-based CCCBs can effectively inhibit acid production in coal refuse containing high concentrations of pyritic sulfur. This inhibition can be improved by initially adjusting the pH to at least 5.0 and restricting O_2 diffusion into the coal refuse. The pH adjustment can be made by addition of $CaSO_3$-containing CCCBs that are also alkaline. Oxygen diffusion in coal refuse can be inhibited by addition of fine particles such as fly ash to fill the pore space in coal refuse or placement of soil and vegetation covers on the surface of coal refuse to separate coal refuse from the atmosphere. An even stronger inhibitory effect

of $CaSO_3$ on acid production in coal refuse can be achieved by placing $CaSO_3$ or $CaSO_3$-based CCCB at depth. Oxygen concentrations decrease rapidly with depth and any O_2 in percolation water will be rapidly removed when it passes through the buried $CaSO_3$ layer. Prolonged existence of $CaSO_3$ at depth of coal refuse would also be important when the toxicity of dissolved sulfite species to the bacteria involved in pyrite oxidation is considered.

Other Uses

This paper is not a comprehensive review of all known or potential land application uses of CCCBs. Some uses of CCCBs described (Table 5) have been developed and tested only in the most preliminary manner. Even greater use can be envisioned as many of the regulatory and material handling barriers that restrain CCCBS use are overcome. With imagination and a detailed knowledge and understanding of the properties of CCCBs, additional uses will undoubtably be discovered and developed in the future.

Summary and Conclusions

Large amounts of CCCBs are created each year. If their properties are properly exploited, CCCBs can provide many economic benefits to both producers and end users. The key to a successful beneficial use program is knowing the properties that can be utilized, understanding the regulatory restraints to their use, and then to work effectively within these restraints.

This chapter summarizes some of the properties that provide economic value to CCCBs and also some of the properties that must be carefully considered before land application uses can move forward. Case studies present examples of how CCCBs can be successfully used as a commercial product. Use of CCCBs in agriculture, coal extraction and processing, as an engineering or construction material, and for other less developed uses, demonstrate the value of the these materials.

What is needed next is: (1) education of the general public of the benefits of using these by-products; (2) an acceptance by regulatory agencies that CCCBs are just as safe as other commonly used land application products (e.g., mineral fertilizers, limestone, various types of composts); and (3) the creation of companies or commercial partnerships that focus on the development and marketing of products derived from CCCBs.

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UNDERGROUND PLACEMENT OF COAL PROCESSING WASTE AND COAL COMBUSTION BY-PRODUCTS BASED PASTE BACKFILL FOR ENHANCED MINING ECONOMICS

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Abstract

Development of paste backfill mixes, composed of over 70% coal combustion by-products (CCBs), has potential applications for reducing ground movements and acid mine drainage problems. This concept also can be used to extract about 5-8% more coal in a room-and-pillar mining area from current values of about 56%. The mined-out panels are subsequently backfilled to minimize subsidence potential. At the demonstration mine site, Crown III Mine, in Illinois, the pillars were designed for short-term stability of 1-2 years. The mined-out areas were backfilled from the surface with gob-, CCBs-, and fine coal processing waste (FCPW)-based backfills containing 65%-70% solids to minimize short-term and long-term surface subsidence risk. The concept has the potential to increase mine productivity, reduce mining costs, provide a beneficial use for large volume CCBs, and improve the environment and mine health and safety.

Two injection holes were drilled over the study panel at a demonstration mine to inject coal processing waste and coal combustion by-products. A mixing plant was built to mix various compositions of CCBs and gob with water to create paste backfill for pumping underground. At the demonstration mine, about 9,293 tons of backfill were injected. The backfill flowed uniformly about 300 ft from the point of discharge.

Background

The term "paste" backfill refers to a high solids concentration (70-90%) and pumpable slurry with the consistency of a paste. The paste backfill has the advantages of reduced pumping requirements for excess water, quicker and higher final strength and stiffness, and homogeneous mix consistency. Since weak floor strata in Illinois Basin coal mines are water sensitive, paste backfill offers significant advantages over a conventional slurry backfill. This project is evaluating the concept that the extraction ratio in a room-and-pillar panel can be increased from current values of about 56% to about 64% with short-term stability of one to two years. A CCBs-based paste backfill can then be injected from the surface upon completion of all mining activities in the panel, which will set up relatively quickly and minimize future surface subsidence movements and acid mine drainage. Management of CCBs, higher extraction ratio underground, and minimal environmental costs then significantly improve mining economics.

The more specific objectives of the project are:

1. Demonstrate that environmentally benign pumpable paste backfill mixtures containing 65% to 70% solids can be developed using FCPW (fine coal processing waste or coal slurry), gob, and CCBs (coal combustion by-products).
2. Demonstrate that the reduction of pillar sizes is possible without significant surface movements if the panel is subsequently backfilled.
3. Demonstrate that gob- and CCB-based paste backfill can flow at least 300 feet from the injection borehole.
4. Study flows characteristics of paste backfill in entries and crosscuts during the pumping process and evaluate the extent to which entries and crosscuts are fully backfilled away from the injection point.

5. Study shrinkage, durability, and strength-deformation properties of the pumped backfill as curing progress.
6. Study impacts of backfilling on surface movements.
7. Perform industrial engineering and cost studies for paste backfill placement in an active mine.
8. Evaluate environmental impacts of paste backfill placement in an active mine.

This project is a cooperative effort between the industry, university, and the State and Federal government. The State's Office of Coal Development and Marketing and the Federal Energy Technology Laboratory are actively involved in the project. For the purpose of this concept demonstration, Crown III Mine of Freeman United Coal Company developed a small panel (hereafter called the backfilling panel) with eight entries with 80 ft by 60 ft (center-to-center) pillar sizes and 20 ft entry width (Figure 1). The pillars were designed for short-term stability of 1-2 years. Secondary mining was done in this panel to increase the extraction ratio from 50-55% to 65%.

Two injection holes were drilled over the study area to inject paste backfill consisting of coal processing waste and coal combustion by-products into the panel. For this purpose, a plant was built to mix about 10% F-ash, 50% FBC, and 40% gob with water for pumping underground. Underground backfilling was started on August 11, 1999 through the primary borehole and subsequently on October 13, 1999 through the secondary borehole. Altogether 9,293 tons of backfill were injected underground and it flowed in all directions from the point of discharge. The backfill flowed as a sheet covering the entire width of the opening. A maximum flow distance of 300 ft was observed underground.

Underground visits were made periodically to measure roof-to-floor convergence to obtain the general conditions of the roof and floor. Underground roof-to-floor convergence in the backfilling panel taken in March 1999 showed a convergence of 1.8 inches in the center of the panel. It was also found that in some intersections roof falls occurred and those areas might be inaccessible in the future.

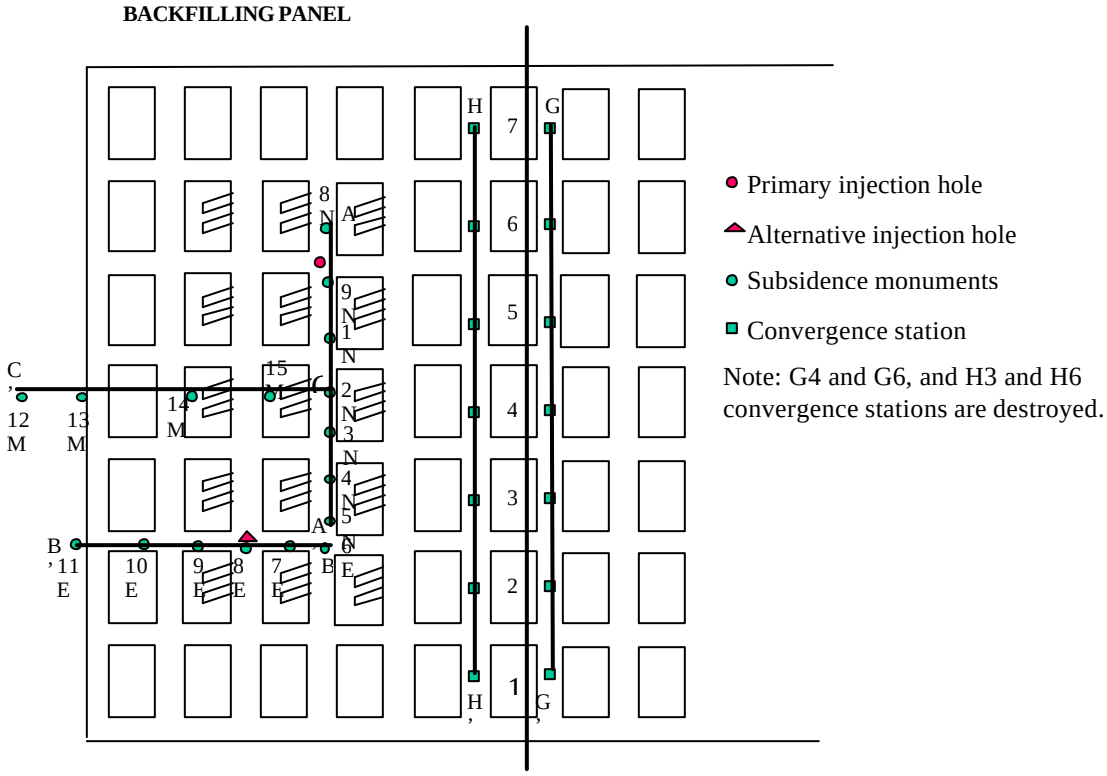

Figure 1. Location of underground convergence stations and surface.

Pertinent Previous Work

Large volume management of CCBs (coal combustion by-products) in underground mines to control subsidence and acid mine drainage has significant possibilities, particularly in Illinois where high sulfur coals at shallow mining depths are exploited and protection of prime agricultural lands and groundwater resources is crucial. A cooperative research agreement between the U.S. Department of Energy and Southern Illinois University at Carbondale was initiated in 1993 to develop blind backfilling technologies to manage CCBs and FGD (flue gas desulfurization) by-products in underground mines to control surface subsidence (Chugh et al, 1996). A paste backfill grout made of 48% scrubber sludge, 52% fly ash/bottom ash mixture, and 2 to 3% lime was used for hydraulic backfilling. About 8,062 tons of grout were injected into an abandoned coal mine near Pawnee, Illinois. Monitoring of ground movements before and after backfilling has indicated that the rate of vertical surface displacement after backfilling is much lower (in the range of 4 mm after six months of backfilling operation). Recent measurement (January 2000) indicates that no measurable vertical downward ground movement has occurred for the last one year.

Underground backfilling operations have been carried out using mine tailings, slurry mixes, cement mixes, and CCBs. Several researchers have performed backfill operations in abandoned mines to reduce surface subsidence (Whaite and Allen, 1975; Maser et al., 1975; Petulanas, 1988). Slurry backfilling, fly ash-cement sealant, and high volume fly ash were used in those studies. Enhanced extraction ratio and acid mine drainage control studies have also been performed in the United States as well as in other countries (Palarski, 1993; Gray et al., 1995; and Chugh 1996).

Paste Backfill – Previous Experience in Illinois

As indicated earlier, a paste backfill may be defined as a high solids concentration (70-90%) and pumpable slurry with a paste like consistency. The ASTM slump for a paste backfill may range from larger than zero to less than 12 inches, with bleed typically less than 4%. Since the solid and liquid phases do not separate significantly over a short period of time in a paste backfill, it is easy to refluidize the fill in a pipeline and start pumping operations. A small proportion of fines, typically less than 20 microns, is required to develop a paste backfill (Brackebusch, 1994). Since a paste backfill has low water content, it should be beneficial for mines with weak floor strata.

Chugh et al. (1998) demonstrated the development of a CCBs-based paste backfill to fill an abandoned mine panel near Pawnee, Illinois. The backfill was composed of scrubber sludge, F-ash, bottom ash, and 1-2% lime. The solids concentration was over 70%, with bleed less than 3%, and ASTM slump height of 9 to 10 inches. Compressive strength values of over 400 psi were achieved. Strength and elastic modulus of cured mixes can be varied depending on the composition and proportion of different elements. Over 8,000 tons of the designed backfill were pumped with flow distance of at least 200 feet.

Development of CCBs and CPW Based Paste Backfill Mixes in the Current Study

The goal of this study was to investigate if a paste backfill can be developed with CCBs and CPW so that potential acid mine drainage problems can be minimized. Based on the coal company interests, paste backfill development was limited to CCBs and coarse coal refuse (gob) only. The gob was crushed to minus 1/4-inch size before using it as part of the paste backfill development in the laboratory, and minus ¾ inch in the field demonstration.

Several paste backfill mixes were prepared in the laboratory using different compositions of FBC ash, F ash, and gob. The main idea was to develop a mix that will flow at least 300 ft from the point of discharge and possess about 300 to 400 psi compressive strength with elastic modulus of 20,000 to 25,000 psi. In addition, environmental characteristics must be suitable to minimize acid drainage development.

Characteristics of Gob and CCBs

Crown III Mine supplied gob (coarse coal refuse of coal processing rejects) and FBC (fluidized bed combustion) fly ash. As the size of gob varied between -4 inches to +28 mesh, the as-received gob was crushed

in the laboratory to sizes less than 0.25 inches. However, in the field demonstration, gob was crushed using a jaw crusher to a maximum size of 0.75 inch. Particle size distribution data show that about 62% (by weight) of gob particles are finer than 0.1 inch for field crushed samples as compared to 90% (by weight) for laboratory crushed samples (Figure 2).

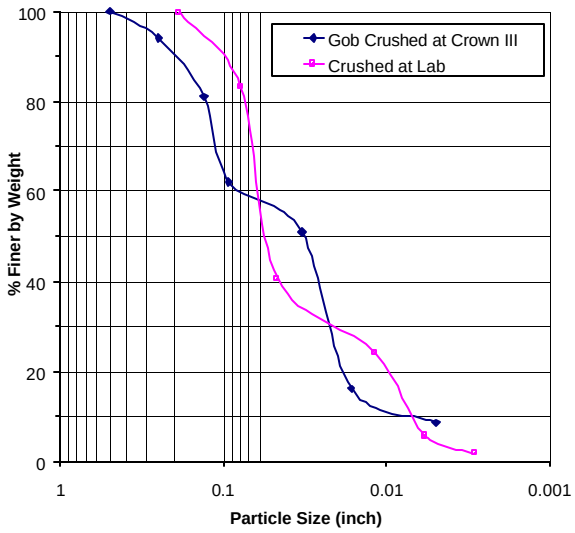

Figure 2. Particle Size Distribution for field and Laboratory Crushed Gob Samples.

F-type fly ash was obtained from the Coffeen power plant. Water content in the F-ash ranges from 9 to 16% but it could increase to 22% if ash is rain soaked. The moisture content of the as-received materials, particle sizes, and calcium carbonate equivalent (CCE) values of the raw materials (gob, FBC, and F-type fly ash) were determined (Table 1). CCE values indicate that the proportions of FBC fly ash will dictate the CCE of the mix. By thoroughly mixing crushed gob, a potential acid producing material, with FBC fly ash, a highly alkaline material, it is possible to neutralize acid forming potential of the gob.

Table 1. Selected Physical Properties of Mix Components.

Properties	Gob	FBC fly ash	F-type Fly ash[+]
Mean particle size	0.09 inches	33.2 microns	32.6 microns
As-received moisture	9.0 %	0.0 %	16.0%
CCE	9.3%	75.0%	3.7%
Paste pH	3.2	12.8	8.8

[+]: From Coffeen power plant

Mix Development and Characterization

Eighteen (18) preliminary mixes were made using water to make a grout of slump between 9.0 to 10.0 inches. Proportions of gob and FBC were varied from 25% to 75%. The ratio of F-type fly ash to FBC fly ash was kept in the range of 0.0 to 1.2. Figure 3 shows the bleed of freshly prepared grouts for slump values in the range of 9 to 11 inches. Low bleed values (1% to 3%) suggest that the developed mix may be a suitable paste backfill.

Cylindrical samples of cured grouts were tested for compressive strength at 7-day and 28-day curing. All the samples were cured at room temperature and humidity. Tables 2 and 3 show mix components and the engineering properties for different mixes.

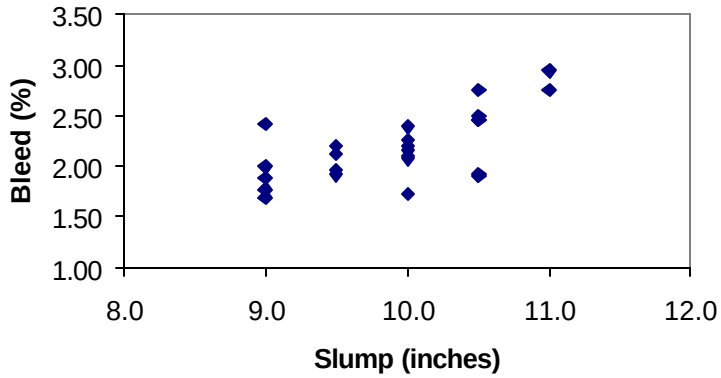

Figure 3. Relationship Between Slump and Breed.

Strength values (28-day cured) of more than 300 psi are not achievable unless the proportion of gob is less than 50%. Addition of F-type fly ash in the mix reduces the strength value unless the gob proportion is low (25% to 45%). It is found that the strength of cured grouts peaks when the ratio of F-type fly ash to FBC fly ash is around 0.2 and the proportion of gob in the mix is 45% or less. Preliminary mix design suggests that mixes with gob proportions in 40% to 45% range and the ratio of F-type fly ash to FBC fly ash not in excess of 0.2 are good candidates for achieving a 28-day cured strength in the range of 400-500 psi.

Table 2. Proportions of raw ingredients of four final mixes.

Components	Mix ID 25	Mix ID 18	Mix ID 21	Mix ID 26	Mix ID 27
Gob, %	25	40	45	45	45
FBC fly ash, %	62.5	50	55	46	40
F-type fly ash^{+}, %	12.5	10	0	9	0
F-type fly ash^{++}, %	0	0	0	0	15

$^{+}$: From Coffeen plant, $^{++}$: From Meredosia plant

Field Demonstration of Paste Backfilling

Field demonstration was performed at Crown III Mine of Freeman United Coal Company. A special room and pillar panel was developed for this purpose to enhance coal recovery by 8-10% by secondary mining and subsequently backfilled using the developed backfill mixes. A description of the backfilling operations is given in the following sections.

Mine Characteristics, Additional Recovery Plans, Subsidence, and Underground Convergence Monitoring

Figure 1 shows the study panel including borehole locations, surface deformation monuments and underground convergence points. A typical mining panel is 600 ft wide. For the purpose of the demonstration, the mining company developed the backfilling panel with eight entries and 60 ft by 40 ft pillar sizes. The entry width in the backfilling panels was 20 ft. In the backfilling panel, secondary mining was done to increase the extraction ratio from 50-55% to about 65%. Three rows of pillars in the backfilling panel were split with two cuts 18-ft wide and 20-ft deep (Figure 1).

Table 3. Properties of final mixes.

Properties	Mix 25	Mix 18	Mix 21	Mix 26	Mix 27
7-day strength, psi	479	243	168	430	149
28-day strength, psi	523	523	492	579	299
7-day elastic modulus, psi	22,407	20,000	19,433	26,452	9,000
28-day elastic modulus, psi	36,822	27,000	37,156	33,750	11,387
Water requirement for 9-inch slump, %	40	36	39	40	42
Bleed at 9-10 inch slump, %	1.1	1.6	1.6	1.6	1.1
CCE, %	45	44	41	36	32
Density of fresh grout, pcf	109				
Density of 28-day cured grout, pcf	90				

Surface subsidence movement stations along line A-A', B-B' and C-C' were installed at variable intervals (Figure 1). Measurement of vertical ground movements started prior to secondary mining and the last measurement was recorded on August 12, 1999. After that period most of the monuments were destroyed due to vehicle movements, digging of surface trench, etc. Since this area was eventually ponded with coal combustion by-products, no more surface movements could be collected in this area.

Underground convergence stations numbered G1 through G7 and H1 through H7 were monitored periodically to measure underground movements (Figure 1). A convergence station consisted of a roof bolt head and a square head bolt, vertically beneath the roof bolt, anchored into the floor. It is designed to measure the roof-to-floor convergence using a convergence rod. Underground roof-to-floor convergence monitoring could be carried out until March 23, 1999. Some of the convergence stations were damaged due to roof falls and reaching other measuring stations became unsafe. As a result, the underground monitoring program was abandoned.

Mixing and Underground Placement Plant

Figure 4 shows the schematic of the mixing plant at Crown III Mine. Three hoppers were used to load FBC, F-ash, and gob into three conveyor belts, which fed the main belt. By controlling opening width of hoppers and speeds of respective conveyor belts, the final dry mix of 53% FBC, 33% gob, and 14% F-ash was obtained. Characteristics of various components of the mixing plant are given in Table 4. This mix is similar to the mix ID 18 which has considerable strength and stiffness and is also designed to control acid mine drainage. At the pug mill, water is added to mix solids; then the paste backfill is pumped into the injection hole.

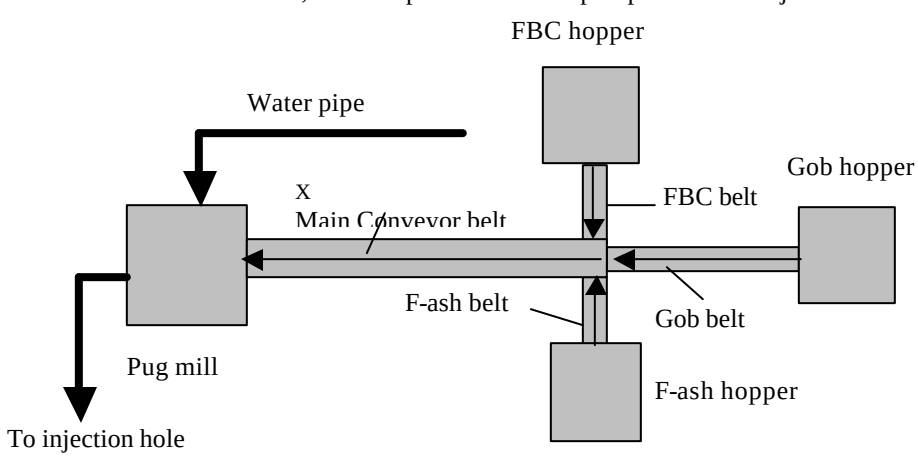

Figure 4. Schematics of mixing plant at Crown III Mine.

The peak-mixing rate in this plant was designed not to exceed 100 ton/hour of solids and 40 ton/hour of water. This mix provides about 11 inch of slump height. The plant was operated with a water addition rate of 138-152 gals per minute to obtain a mix of at least 11-inch slump. It was difficult to maintain a constant feed rate of solids into the pug mill.

Table 4. Characteristics of conveyor belts.

Belt	Length (ft)	Speed (ft/min)	Capacity (ton/hour)	Weight (lb/ft)	% Weight
Gob	32.5	66.7	30.02	15.00	32.99
FBC	18.83	23.1	48.51	70.00	53.32
F-ash	19.83	17.8	12.46	23.33	13.69
Main	60.83	66.7	90.99	108.33	100

Specially, the composition of three components varied slightly depending on the amount of material in the different hoppers. Moisture content in these components also changed based on weather conditions. Due to the higher water content in gob and variable gob particle size, strength of the field mixes ranged from 131 to 280 psi, which is lower than that of laboratory mixes of 400~500 psi.

Underground Placement of Mixes

Underground placement of CCBs was carried out through two boreholes as shown in Figure 5. Primary borehole was located near the mixing plant and was used to inject material under gravity. For the secondary borehole, a concrete pump was used to transport material from the mixing plant to that borehole. Mixing plant was operated in two shifts with three men working per shift.

Underground Backfilling Operation Through Primary and Secondary Borehole

Figures 6 shows the daily rates of backfilling operation through the primary and secondary borehole. In this figure day 1 to 13 refers backfilling through primary borehole and day 14 to 17 signifies pumping through the secondary borehole. The daily and hourly average rate of backfilling through primary borehole was 627 tons (452 ton of solids and 175 ton of water) and 117.1 tons/hour (83.5 ton/hour of solid and 33.6 ton/hour of water), respectively. About 8159 tons (5873 tons of solid and 2286 tons of water) of mix were injected underground though the primary borehole until the hole was blocked. Net operational time was 68.4 hours with an average of 3 hours per shift.

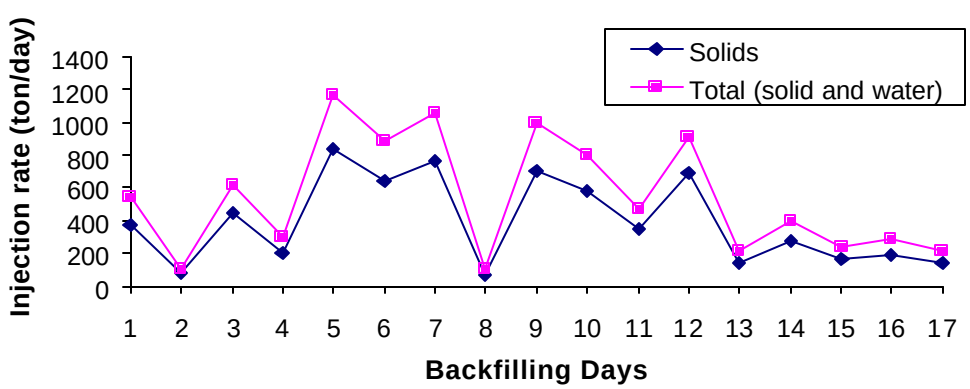

Figure 6. Daily backfilling rate through primary and secondary boreholes.

The study panel was permanently sealed after the backfilling operation was completed through the primary borehole. It delayed the backfilling operation through secondary borehole and also Freeman United Coal Company had to prepare for filling this area with CCBs for the winter season. As a result, only four days of

operation were possible through the secondary borehole as shown in Figure 6. Within these four days, 1134 tons (773 tons solid and 361 tons water) were placed underground in 14.4 net hours of operation. The hourly average rate was 79 ton/hour (54 ton/h solid and 25 ton/h water). These rates are lower than those in the primary hole due to the size restriction of the concrete pump. Altogether using both holes, about 9293 tons of solid and water mix were injected underground. The overall water to powder ratio was about 0.40 with 11-inch slump height.

Underground Flow Characteristics

It was found that the mix flowed in all four directions, especially toward the west and southwest. Mine entries were filled to within 1 ft of the roofline within 30-ft in all directions from the primary borehole. The backfill flowed a maximum distance of 300 ft with a gradient of two degrees as shown by the shaded region in Figure 5. It also was observed that the mix flowed uniformly as a sheet and did not form any channels. There was hardly any separation between solids and water. High volume of gob in the mix did not impede underground flow behavior. Moreover, the strength of mix after twenty-four hours of curing was enough to sustain the weight of a human being. Underground observers had no problem walking over the thick sheet of mix.

Vertical Ground Movements and Underground Roof to Floor Convergence

Prior to the backfilling operation, roof-to-floor convergence and surface subsidence data were collected periodically. Rate of vertical surface movements was about 0.5 to 0.6 inch per year. The average downward movement over two years was 1.16 inch and it was uniform over the entire panel (Figure 7). There ware no significant differential movements over the entire backfill panel. However, just after backfilling, the surface had to be prepared for land filling with CCBs. Thus, no ground movement measurement could be recorded after backfilling.

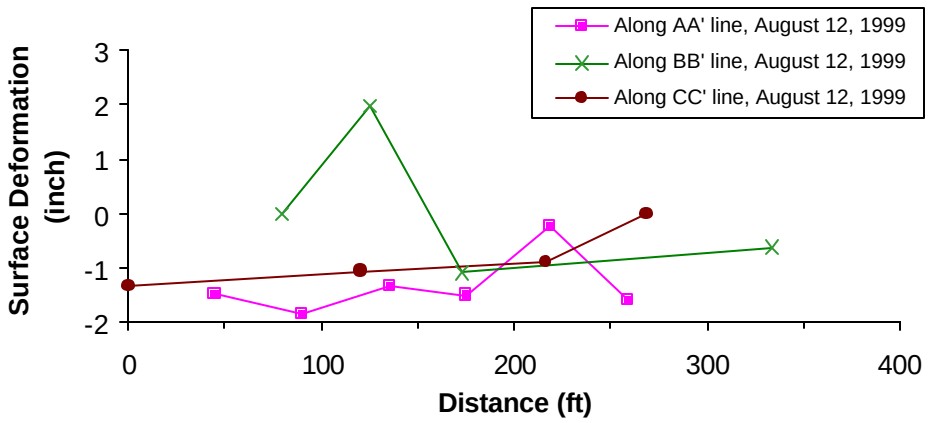

Figure 7. Vertical ground movement over the backfill panel.

Underground roof-to-floor convergence data taken after 18-months of secondary mining in the backfilling panel indicates that about 2.0 inches of convergence had occurred at the center of the panel (Figure 8). This is because of heaving associated with weak floor strata. Also, the roof shale above the coal seam sags over a period of time and increases roof-to-floor convergence. A few roof falls also occurred at intersections.

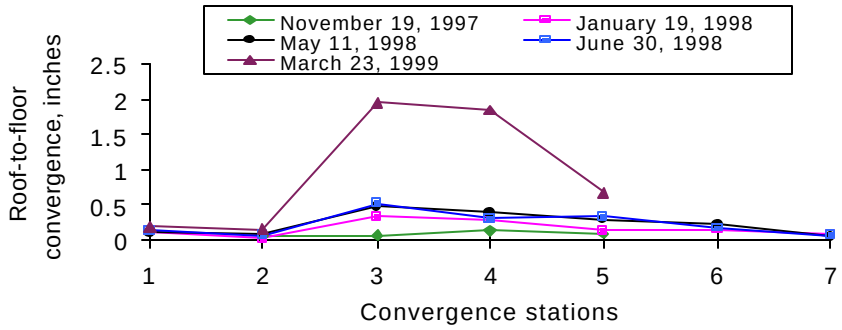

Figure 8. Roof to floor convergence at the study panel after one and half year of secondary mining.

Economics of Underground Management

Economic analysis of backfilling for all panels was performed by Freeman United Coal Company (Caldwell, 1999). Preliminary analyses indicate that the proposed technology and concept have potential to enhance economics of underground mining in Illinois. In performing these analyses, capital requirements of equipment, ash plant, ash/slurry pond, and other operating costs such as land, royalty, trucking, road, and site development, etc. were considered. Additional more detailed analyses are currently underway by the Company.

Conclusions

The concept of paste backfilling using CCBs and CPW has potential to enhance mine economics through higher recovery and reduced environmental impacts such as mine subsidence, and acid mine drainage. Paste backfill material composed of gob, FBC fly ash, and F-type fly ash was successfully developed and demonstrated for use at the demonstration mine site. Over 9,000 tons of material were injected underground through two boreholes. The overall water powder ratio was close to 0.4. Underground flow behavior was excellent without much separation of solids and water. A high amount of gob in the mix did not impede flow behavior. An underground visit revealed that material flowed a distance of about 300 ft as expected. Material flow was uniform and sheet-like.

Backfill material provides lateral support to the coal pillars increasing their effective width and reducing the effective opening height. This improves long-term pillar strength and thus reduces potential for long-term surface movements. The underground management of by-products also will be economically beneficial to both the mining and the electric utility companies. Integrating gob and FBC (a highly alkaline material) thoroughly can minimize environmental concerns associated with the acid-producing gob. In this study, the pH of filled mixes ranges from 9.47 to 10.0 with a CCE value of 2-kg/ m ton. When placed underground, a cured mix of gob and FBC fly ash should have little oxidation potential, which should further reduce the acid producing capability of gob.

Economic analyses of underground management of coal processing wastes and CCBs were done by the mining company (Freeman United Coal Company) and preliminary analyses indicate an economic potential for the concept and technology.

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Figure 5. Underground condition of the panel after backfilling.

RE-MINING WITH CCBs AT THE BROKEN ARO DEMONSTRATION SITE

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Abstract

Re-mining has the benefits of recovering an energy reserve not usually accessible because of abandoned underground mines. The hidden dangers of abandoned underground mines during re-mining include: mine gases, unstable roof, volumes of acid water, and unstable highwall. However, re-mining offers exposure of the acid mine drainage (AMD) source and dewatering of the mine complex. Additionally, re-mining allows for simple placement of a continuous mine seal that would be effective for multiple openings and additional entries. Re-mining of the coal reserve is not economically feasible for the coal company due to AMD responsibilities. Thus, a joint effort between Ohio DNR-Division of Mines and Reclamation, R&F Coal, and American Electric Power allowed for a controlled test site to evaluate re-mining as an AML restoration and AMD abatement technique.

An abandoned underground mine complex last mined in 1910 in Coshocton County, Ohio, Broken Aro Mine is located on Woodbury wildlife area, seven miles west of Coshocton. The site forms the headwaters of the Simmons Run Watershed. This paper will present the planning and completion of the re-mining effort and the flue gas desulfurization material (FGD) seal placement. Preliminary and post-mining water quality monitoring is used as an indicator as to the effectiveness of the AMD abatement. Included in the environmental assessments are 24 surface water locations and 14 monitoring wells. Mine inundation is evaluated through water levels in the wells and subsequent water quality monitoring is utilized to assess mine flooding effects on water quality both inside and outside of the mine openings.

Introduction

The Broken Aro Mine site is located about seven miles west of Coshocton, Ohio on State Route 541 at the Woodbury Wildlife Preserve. An abandoned underground mine complex last mined in 1910, this site forms the headwaters of the Simmons Run Watershed. A No. 6 and a deeper No. 5 coal seam on the 40-acre site have been mined by means of underground mining in the 1910s. The mining operations produced acid mine drainage (AMD) that polluted receiving streams with acidity and heavy metals, killing aquatic and plant life. To prevent this pollution from continuing, a design for keeping the water inside the mine was developed with the cooperation of the Ohio Department of Natural Resources, R&F Coal Company, American Electric Power, and Ohio University. This paper will give a background of the Broken Aro Project, describe the FGD seal design, and demonstrate its effectiveness.

Re-mining was selected as the best option to economically extract remaining coal deposits and provide an opportunity to employ abatement technology. The groundwater was sealed inside the underground mine to inundate the mine voids with water, removing the air to minimize oxidation and reduce stream pollution. The seal was made from a chemical by-product produced in coal-fired power plants called fixated flue gas desulfurization (FGD) sludge. The FGD seal has a low hydraulic conductivity, which limits water from seeping out of the underground mine. It also has high alkalinity, which may neutralize the acidic waters of AMD when water does seep from the mine.

This document gives a brief background of AMD chemistry and its effects, and a discussion of the impact the fixated FGD seal has had on the water quality to date.

AMD Chemistry

Acid mine pollution is caused by the physical and chemical weathering of iron pyrite (FeS_2), also known as "fool's gold." Acidity, ferric iron (Fe^{3+}) precipitation, oxygen depletion, and the release of heavy metals, such as aluminum (Al^{3+}), zinc (Zn^{2+}), and manganese (Mn^{2+}) are pollutants, which may be associated with coal mining. The level of acidity and the concentration of the heavy metals is a function of the amount of pyrite in the area around the mine.

Physical weathering is essential to reduce the grain size of the pyrite. The early miners inadvertently accelerated this process by grinding up the ore and dumping the overburden in mine tailings. The next step in the geochemical process is the chemical oxidation of pyrite[1]:

$$2\ FeS_{2(s)} + 7\ O_{2(g)} + 2\ H_2O_{(l)} \rightarrow 2\ Fe^{2+}_{(aq)} + 4\ SO_4^{2-}{}_{(aq)} + 4\ H^+_{(aq)} \quad (1)$$

When the pyrite is exposed to oxygen and water, it reacts to form sulfuric acid (H_2SO_4), which causes a decrease in pH. The Fe^{2+} ions (ferrous) are released into the runoff waters from drainage tunnels or tailings piles. Next, the Fe^{2+} ions are oxidized to Fe^{3+} (ferric) ions, which hydrolyze in water to form iron (III) hydroxide [$Fe(OH)_3$] as shown in the following reactions:

$$4\ Fe^{2+}_{(aq)} + O_{2(g)} + 4\ H^+_{(aq)} \rightarrow 4\ Fe^{3+}_{(aq)} + 2\ H_2O_{(l)} \quad (2)$$

$$4\ Fe^{3+}_{(aq)} + 12\ H_2O_{(l)} \rightarrow 4\ Fe(OH)_{3\ (s)} + 12\ H^+_{(aq)} \quad (3)$$

This process releases more hydrogen ions into the environment, which continues to reduce the pH. The low pH of the water makes it difficult for aquatic life to survive. The iron (III) hydroxide formed in this reaction is referred to as "yellow boy," which is a yellowish-orange precipitate that turns the acidic runoff in the streams to an orange-red color and fouls the stream bed. The iron (III) hydroxide precipitate kills plants and fish by reducing the amount of light for photosynthesis and smothering aquatic life, their food resources, and spawning beds on the stream bottom.

Pyritic mine tailings leach AMD, in a large part due to the metabolic activity of *Thiobacillus ferrooxidans*[2]. These acid-tolerant bacteria serve to catalyze the oxidation of the pyrite in Equations 1, 2, and 3 above, thereby increasing the amounts of acidity and iron released to the environment.

Complex systems in nature such as mine tailings and mine drainage tunnels cannot be described by just a few equations. Other chemical reactions which may take place are[3]:

$$FeS_{2(aq)} + 14\ Fe^{2+}_{(aq)} + 8\ H_2O_{(l)} \rightarrow 15\ Fe^{3+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 16\ H^+_{(aq)} \quad (4)$$

In addition, sulfides of copper, zinc, cadmium, lead, and arsenic will undergo similar chemical reactions resulting in the contribution of toxic metal ions in polluted mine streams.

It is the oxygen requirement in Equations 1 and 2 that are exploited in mine sealing for AMD abatement. Notice that, if the iron pyrite is never oxidized or exposed to the atmosphere, the pollution caused by AMD could be eliminated. Therefore, if groundwater could be trapped inside an underground mine to the point of inundation, the air in the mine voids would be forced out. While traces of dissolved oxygen may still be present, the largest oxygen source would be removed. The FGD seal at Broken Aro was designed to retain the groundwater inside the mine to a level above the highest roof elevation, thus minimizing the availability of oxygen and inhibiting the oxidation reaction inside the mine.

Re-mining for the Purpose of FGD Seal Placement

Re-mining was the strategy used at Broken Aro to benefit the environment, industry, and the public. Re-mining operations ultimately accomplished three goals. First, it recovered remaining coal reserves left from previous mining operations. Second, re-mining allowed for the reclamation of the Broken Aro site and the placement of the FGD seal in order to achieve current environmental standards. Sites that are re-mined and reclaimed reduce environmental pollution, remove health and safety hazards, and considerably improve aesthetic properties[4]. Third, the State of Ohio, American Electric Power, and R&F Coal Company were able to share financial and regulatory

burdens so that the re-mining operation was possible. The normal barriers of an insufficient coal reserve; liabilities due to poor, pre-existing water quality; and seal material experimentation can be overcome with this kind of cooperative partnership.

Installation of the FGD seal began concurrent with the continued re-mining effort in June 1997. The seal design and construction has been described fully previously[5], but will be summarized here. A series of open pits were excavated to recover remaining coal in the re-mining operation. The construction of the seal started adjacent to the exposed highwall with the excavation of a keyway trench which was five feet wide and one foot deep in the pit floor. The FGD material was delivered to the site as needed with a moisture content of 40-45%. It was placed and compacted within ten days of production to achieve optimum performance. The FGD seal itself was constructed in two four-foot lifts at least 10 feet wide.

The first lift of the seal was constructed by placing the FGD material into the open pit and the keyway trench. The FGD material was forced into mine openings and compacted using a dozer. The compacted first lift was sufficient to cover the face of the exposed coal seam. After the first lift was installed, mine spoil from the adjacent pit was pushed into the current pit floor and used in the leveling of the first lift. This allowed trucks to transport the second lift of FGD without damaging the first.

The second lift was placed on top of the first lift, and the FGD material was pushed into the highwall with a dozer to fill and compact the lift. The now, compacted FGD seal was a minimum of eight feet above the pit floor. The top surface of the second lift was sloped gradually away from the highwall. This was to ensure that infiltration waters flowing through the reclaim would be diverted away from the highwall and off the seal.

All deep mine openings that were encountered during seal placement were handled accordingly. Openings were sealed from floor to roof by pushing FGD material as far back into the entrance as possible using a backhoe. Also, care was taken to ensure that there were no gaps between mining pits. This guaranteed that the mine seal was constructed continuously along the length of the highwall. Additional compaction was produced from the placement of overburden above the mine seal from the next pit.

The Goal of the FGD Seal

The ultimate goal of the seal was to displace the air voids inside the underground mine with groundwater. By retaining the water inside the mine to the point of inundation, the FGD seal limits the amount of oxygen present in the mine. This inhibits the oxidation reaction and subsequently minimizes the acidic drainage. It would be impractical to expect that all of the water would be restricted only to the mine, especially with the increasing head pressure due to the rising water level. It is expected that some water will continue to seep from the mine complex. The expectation is that the amount of AMD that is produced can be treated by means of natural attenuation, and therefore it will not be a threat to water quality further downstream.

Environmental Monitoring

Sampling Locations and Methods

A map of the Broken Aro Mine site is presented in Figure 1. On site there are 15 surface water locations that are sampled and tested that are comprised of underground seeps, ponds, streams, and stormwater runoff from the mined areas. Originally, there were 8 monitoring wells situated in four pairs that were drilled into and below the mine. Six additional wells were installed in the reclaim area outside of the seal in August of 1998. The groundwater from each of these wells is also sampled and tested. Sampling began in April of 1997, prior to the re-mining effort to establish background contaminant profiles. Sampling continued during mining operations and, to date, for over two years after the completion of the FGD seal.

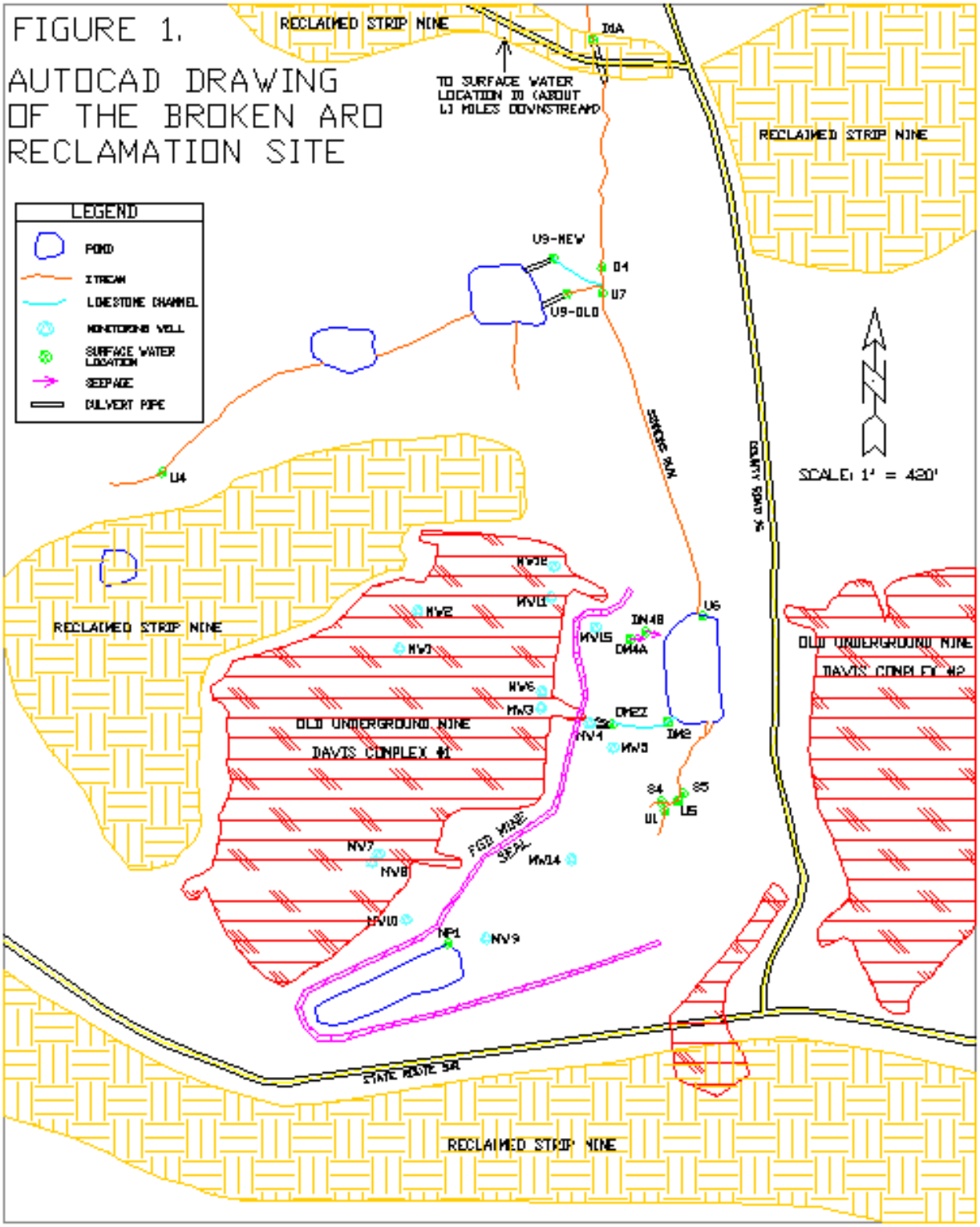

Figure 1. Site map for Broken Aro Mine identifying the locations of the mine complex, the FGD seal, monitoring wells, and surface sampling sites.

For each stream location, three tasks are performed in the field. First, preserved and unpreserved samples are obtained. Second, field evaluations for water quality indicators are performed. Finally, the flowrate is measured for each stream location.

At the well locations, the water level elevation, and the depth of the well is measured first. Then, unfiltered, unpreserved and filtered, preserved groundwater samples are obtained. Finally, field evaluations for water quality indicators are performed. Once samples have been collected from each location, they are transported to an environmental testing laboratory for analysis. This is done at the end of the same day of the sampling event.

Field Water Quality Assessments

The field tests must be conducted and recorded for each stream and/or well location. The pH, temperature, specific conductivity or total dissolved solids (TDS), and the oxidation-reduction potential (ORP) are measured directly in the field using specific probes. Then, 3% peroxide (H_2O_2) is added to the sample cup. Next, the pH and ORP are tested for the oxidized sample to see if it has changed[6]. Most groundwater samples are in a reduced state. For mine water samples that contain a substantial mineral fraction, the peroxide addition causes the release of hydrogen ions (H^+) in the oxidation process and thus lowers the pH. This provides the researcher with the ability to predict the potential acidification of a receiving stream once the source has an opportunity to oxidize.

In the streams, volumetric flowrates are determined using different devices such as weirs, flumes, current meters, or culverts. The choice of a flowrate measuring technique depends on the nature (e.g., quantity, site topography, etc.) of the sample location. This enables the calculations of mass loadings from concentration data obtained in the laboratory.

Laboratory Water Quality Assessments

Each water sample is tested in the laboratory for the following constituents: pH, total acidity, total alkalinity, bicarbonate alkalinity, carbonate alkalinity, specific conductance at 25°C, total non-filterable residue, total dissolved solids, sulfate, chloride, total calcium, total magnesium, total sodium, total potassium, total iron, total manganese, total aluminum, and hardness. The trace compounds analyzed are: total zinc, phosphate, copper, chromium, arsenic, barium, cadmium, lead, mercury, selenium, silver, cobalt, boron, total nickel, bromide, and total molybdenum. All constituents were analyzed during the first year. Subsequently, the trace compound series were only analyzed on a quarterly basis.

Effectiveness of the FGD Seal

The effectiveness of the seal to date can be seen via examination of the data collected as a function of time. Sampling events began on a regular basis two months prior to the start of the installation of the FGD seal. Therefore, one can see the effects of re-mining and dewatering activities and any immediate effect the FGD seal had on the AMD pollution. Water level elevations in the monitoring wells will be used to demonstrate how the FGD seal developed and maintained flooding of the underground mines. Chemical concentration profiles in one pair of the monitoring wells will be utilized to demonstrate water quality improvements inside the mine. Contaminant loads at surface water location D1A will be used as an indicator of the FGD seal's effectiveness due to its critical location at the boundary of the mining areas.

Figure 2 presents the water levels in the monitoring wells as a function of time. The water inside the mine is monitored by wells MW3, MW7, and MW11. Monitoring wells MW6, MW8, and MW12 are screened in a geologic interval under the deep mine, and they describe the water level and water quality below the mine. Monitoring well MW2 is located in a perched aquifer, where the water level is much higher than in the other wells. It should be noted that some vertical connectivity exists between the mine and MW8 as demonstrated by the fact that the water elevation in that well (below the mine) is the same as the water levels inside the mine.

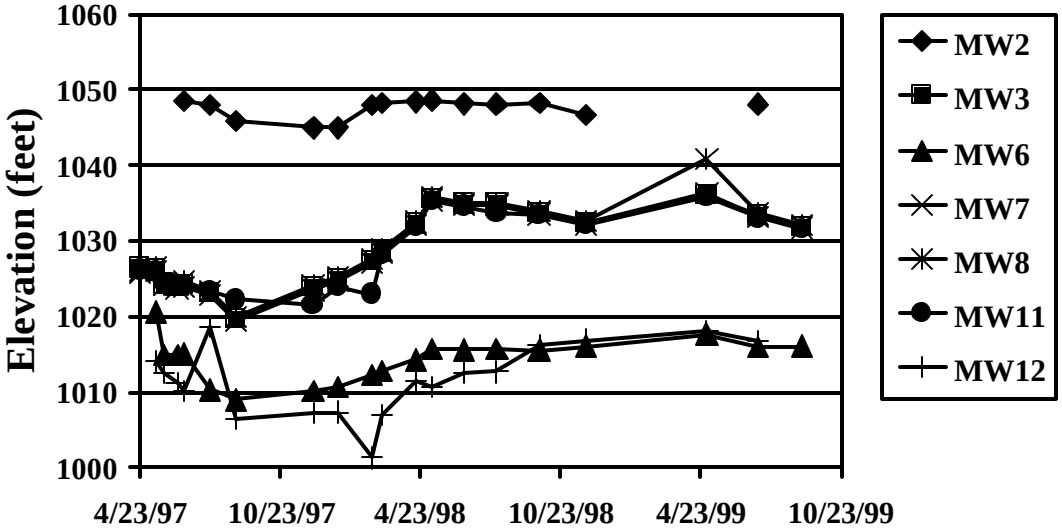

Figure 2. Water levels in monitoring wells as a function of time.

Prior to dewatering the water levels inside the underground mine were at an elevation of 1026 ft. During mining operations the water level dropped to 1020 ft due to the fact that the mining activity and the FGD seal construction disturbed some of the mine openings and allowed for dewatering of the underground mine complex. After the completion of the mine seal in August of 1997, the water levels inside the mine complex rose at a rate of approximately 1.5 feet per month to a maximum of 1036 ft in May of 1996. During the drier summer and fall months, the water levels slowly dropped to an elevation of 1032 ft. This decrease of 4 feet was recharged during the winter/spring of 1999. The mine appears to have established a cycle of recharge and loss, which correlates well with the seasonal precipitation. In general, the wells screened within the mine consistently show water levels 6-10 feet above pre-mining levels and 12-16 feet above the dewatered mine levels.

The water quality in the paired wells MW3 and MW6 will be used as typical of groundwater conditions since MW6 is located under the mine and MW3 is located within the underground mine complex. As can be seen in Figures 3, 4, and 5, the water quality of MW6 has remained relatively unchanged throughout the testing period with respect to acidity, total iron, and sulfate concentrations. This is a good indicator that the mine waters have remained inside the complex and have not descended into a lower geologic formation. Water quality within the mine after the completion of the seal demonstrated immediate signs of improvement. In MW3, the acidity, sulfate, and iron concentrations have slowly decreased since re-mining and dewatering activities. The improvement in acidity was so dramatic that there are portions of the year in which the mine complex water possesses a net alkalinity.

It is interesting to note that the cycling of the water levels has an impact on the water quality inside the mine. It is believed that the small increases in the contaminant concentrations in each of the late spring months since the completion of the seal can be attributed to a “roof effect”. This provides confirmation that the mine is inundated after the winter recharge, however, it is also apparent that portions of the mine roof become exposed during the fall decline in water elevation. This exposed mineral fraction then releases contaminants into the mine water when the complex recharges and re-inundates.

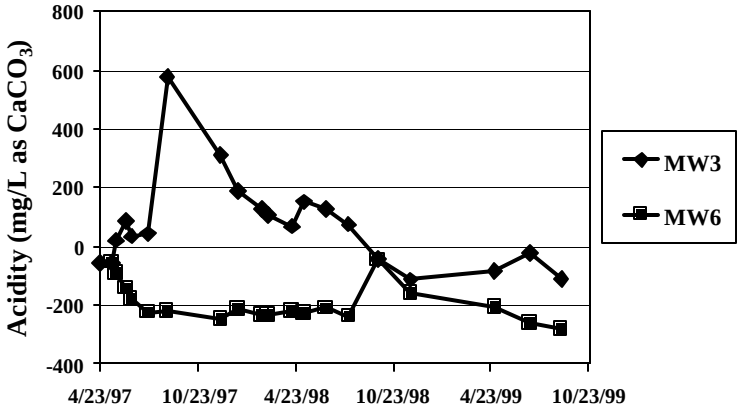

Figure 3. Total acidity in monitoring wells 3 and 6 as a function of time.

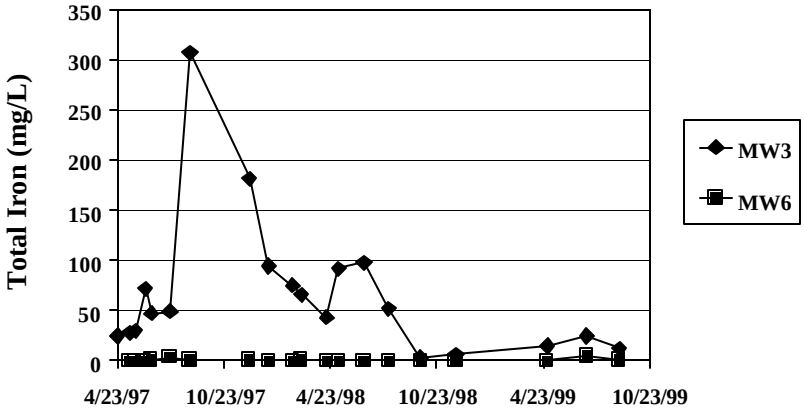

Figure 4. Total iron concentrations in monitoring well 3 and 6 as a function of time.

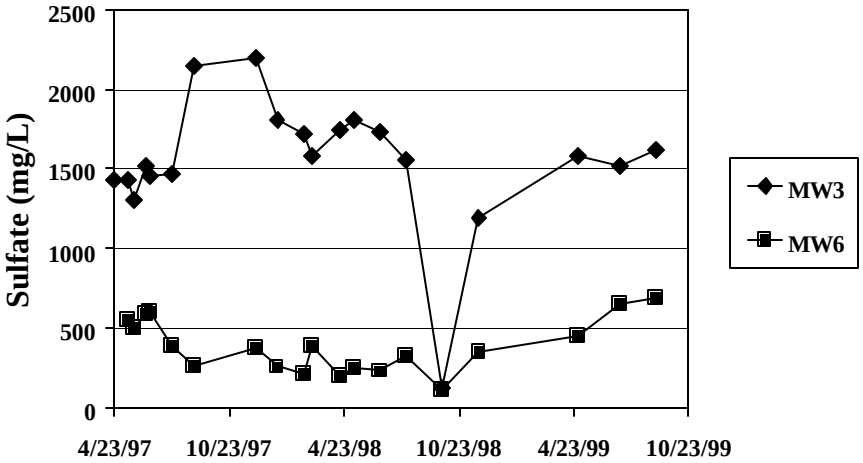

Figure 5. Sulfate concentrations in monitoring wells 3 and 6 as a function of time.

Figure 6 presents sulfate and total iron loadings at location D1A (site boundary). Sulfate loadings reached a high of 1120 kg/day during the re-mining in May of 1997, but decreased to 370 kg/day by September of 1999. This constitutes a reduction in sulfate load to the watershed of 67%. The iron loadings have decreased in even a more drastic manner, from over 43 kg/day during re-mining operations to about 1.1 kg/day in September of 1999. This is equal to 97.5% reduction in total iron load off-site. Again, the recharge roof effect can be seen in the loading profiles as small increases in contaminant loads appear during the spring months.

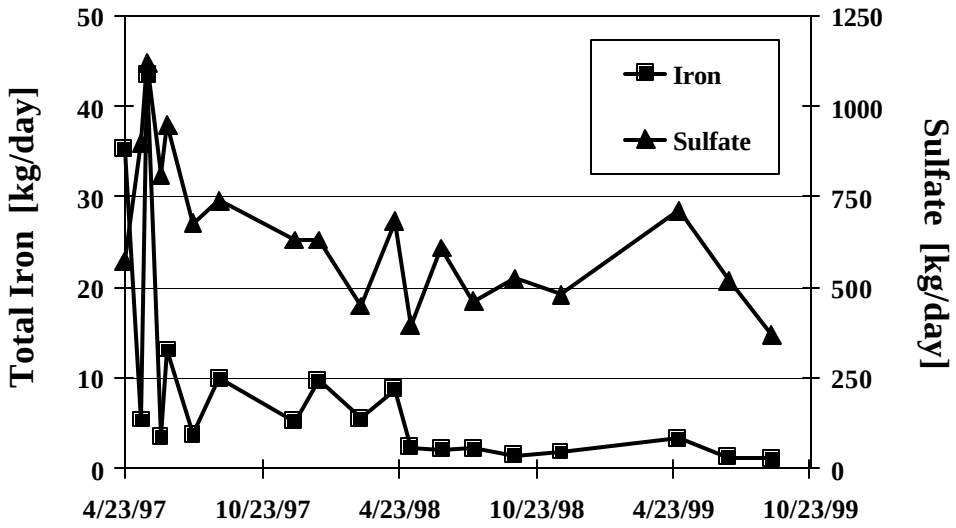

Figure 6. Iron and sulfate loads at sampling location D1A, the project boundary.

Conclusion

The Broken Aro Project will continue to be monitored in years to come to determine the level of success of the fixated FGD seal. The cooperative re-mining effort shared the benefits and liabilities, as well as the costs, of coal recovery and implementation of novel environmental control strategies. To date, the FGD seal has shown that it has improved water quality inside the mine, reduced the quantity of water seeping from the mine, and reduced contaminant loads to Simmons Run by up to 97.5%. The site still needs to reach its hydrogeologic equilibrium to completely determine the seal's effectiveness. The seasonal cycling of the mine water elevations has had a small, but noticeable, effect on contaminant profiles. It is important to either lower the concentration of the contaminants or the flowrate so that ultimately the total loading decreases. In this project, both the concentrations and flowrates have consistently decreased due to the mine seal, which is optimal for contaminant load reduction.

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