GROUT STABILITY AND STRENGTH REQUIREMENTS FOR FIELD SCALE INJECTION OF FLUIDIZED BED COMBUSTION ASH GROUT[1]

by

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Abstract. This paper presents the results of a study involving a field scale injection of a grout made of Fluidized Bed Combustion Ash to control acid mine drainage and subsidence at an abandoned room and pillar coal mine. The grout mix was developed from results obtained from several laboratory scale experiments conducted to investigate flow characteristics and strength of the grout. Based on the rheological properties of the candidate grout mixes it was determined that admixtures were needed to stabilize the grout for optimum flow characteristics. Strength requirements for the grout were determined from site specific geologic information and expected stress levels. One thousand cubic yards of the candidate grout were pumped into an inactive panel of an active room and pillar coal mine to investigate the field performance of the grout. The field study showed that a grout made of Fluidized Bed Combustion ash can be successfully pumped to backfill the mine void.

Introduction

The goal of the project is to fill an underground mine with FBC-ash grout using as few injection holes as possible, due to the cost involved in drilling the holes. As a consequence, the distance the grout may be made to flow or the 'flowability' of the grout is of utmost importance to the project feasibility. The settling that occurs in unstable grouts may reduce the maximum flow distance to such a degree as to render the project impractical. One purpose of this project was to study the subsidence potential at abandoned mines, which have been backfilled with a grout. The study also includes a discussion on the strength requirements of grout and grout backfill configurations to be used for mitigation of subsidence potential at an abandoned mine.

Grout Instability

Initially on the project, observations on mixes of the ash and water showed some settling. When experiments for the pressure drop across a tube were being set up, the ash and water mix got locked up and there was no flow. This was an indication that settling was occurring. An attempt to perform rheological testing with a parallel rotating plate rheometer failed as the mix was settling.

Other tests done on the rotational viscometer using the T-bar spindle gave proof that particles in the pure FBC ash - water grouts were settling. First a series of tests was done in which the spindle was rotated at a constant speed while being moved up and down through a grout containing only fly ash. Torque readings were taken at five second intervals for the length of the test. When these readings were plotted versus time, the pattern showed that the torque increased as the spindle neared the bottom of its path, and decreased as it neared the top of the path, as seen in Figure 1. This periodic behavior is due to the variation in the length of the submerged shaft, but the increase in amplitude is due to the settling of the particles causing the lower portion of the sample to become more concentrated than the upper portion.

The concentration of solid particles varies with time and space because of gravity settling, implying that the grout becomes inhomogeneous. As the concentration of particles increases at the bottom of the grout mixture, friction will develop between the solid particles. This Coulomb friction acts as an additional resistance to flow of the grout and must be included in the rheological constitutive law used to define the grout mixture. For

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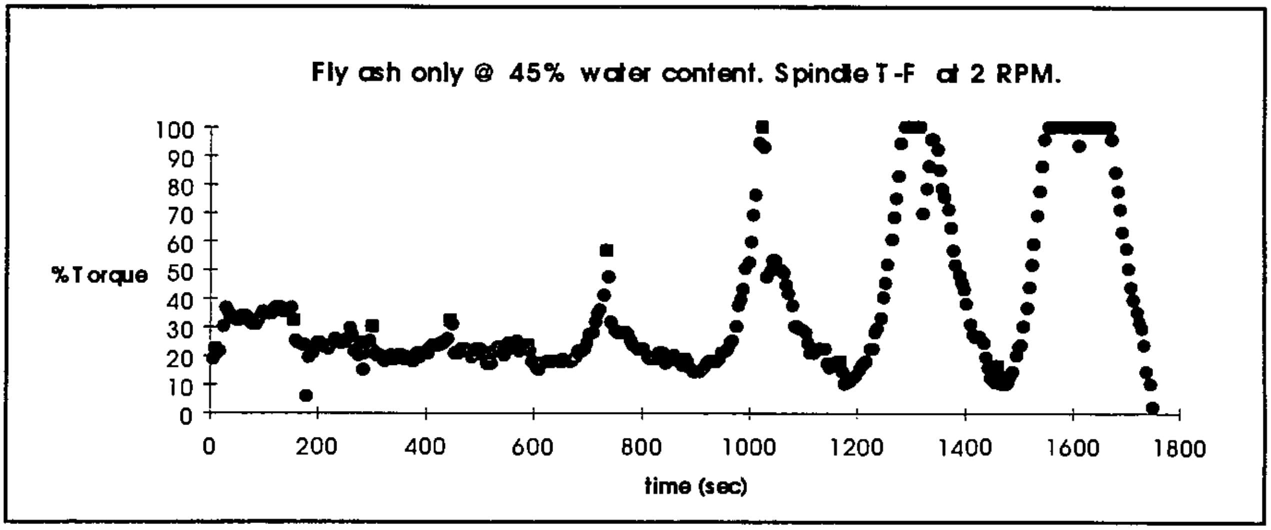

Figure 1 Plot showing how settling affects torque.

parallel shear flow of a Herschel-Bulkley fluid this relation is given as:

$$\tau = \tau_y + k(\gamma)_n + P\mu_f$$

where
τ = shear rate
τ_y = yield stress
k = consistency index
γ = strain rate
n = flow index
P = pressure
μ_f = friction coefficient

When there is no flow (i.e. γ=0) the residual shear stress may be as large as:

$$\tau = \tau_y + P\mu_f$$

Any yield stress fluid, stable or unstable, that is injected into a pipe or closed channel with a finite injection pressure, will eventually stop moving. Inevitably there will be a location downstream where the stress in the grout will fall below the yield stress at all points across the cross section, a solid plug will completely fill the pipe or channel, and flow will cease. Mixtures of pure FBC ash and water were unstable. To combat the settling of the solid particles, various percentages of WYO-BEN 250 mesh bentonite was added to the grout mix. Figure 2 shows that the percentage of bleed increases linearly with an increase in water fractions, while the amount of bleed is decreased by increasing the bentonite added. It was found that 5% bentonite was sufficient to render the grout stable for the water fractions of interest.

Tests were then done using different water fractions and different amounts of bentonite. At 7 % bentonite, there was very little settling. Another test where the spindle was rotated at a constant depth was performed with torque readings taken at a specified time interval. Figure 3 shows that with no bentonite used in

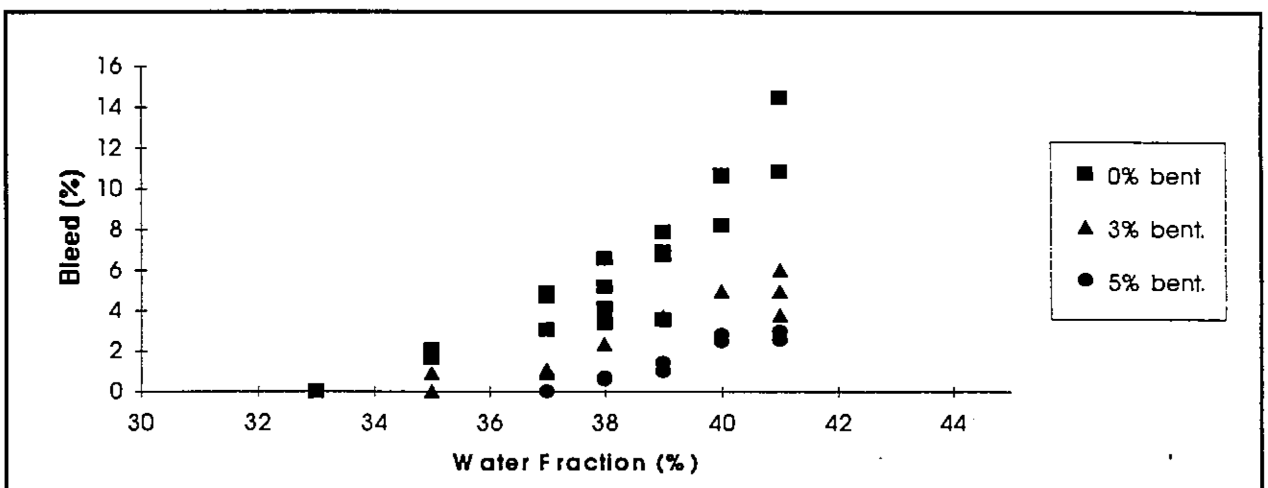

Figure 2 Results of bleed tests on mixes containing equal portions of fly ash and bottom ash.

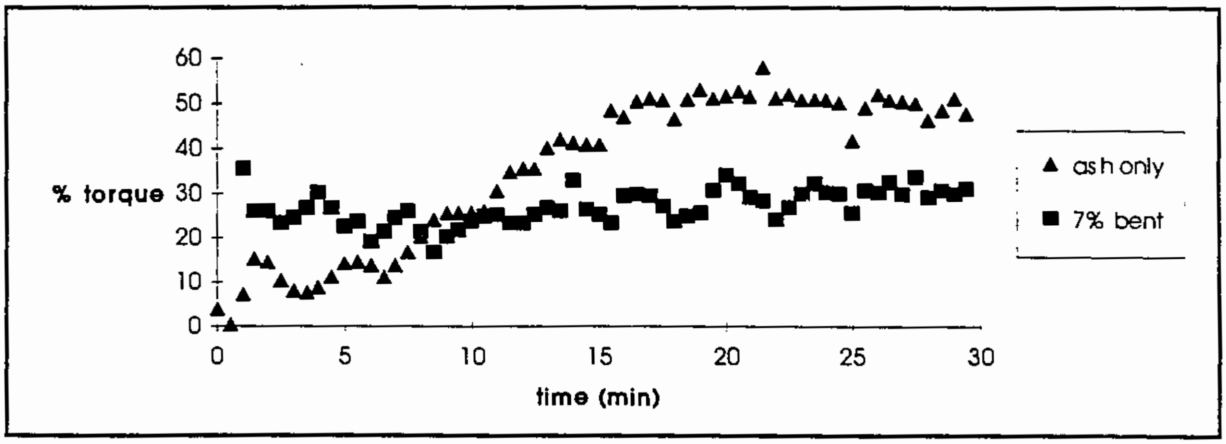

Figure 3: Plot showing increase in stability due to the addition of bentonite.

a fly ash only grout, the torque increased with time, but with 7 % bentonite, the torque at the constant depth showed much less increase. The increase in torque for the no bentonite grout is due to the settling of the ash particles. As the particles contact one, another there is an additional frictional mechanism that increases the torque. Eventually, the T-bar formed a slip surface in the sample that effectively caused the torque to become constant. The sample containing bentonite, on the other hand, has less torque increase, showing that particle settling is not a problem. All these tests have shown that bentonite is an effective additive in the reduction of particle settling and in increasing the stability of the grout.

Ash Variability

Different samples of ash taken from the Beechurst Avenue power plant not only contain varying percentages of fly and bottom ash, but also vary considerably in flow characteristics. This difference in behavior is likely due to the variability of material that the plant is burning and to the plant's method of collecting the ash. The power plant burns a mixture of pure coal, limestone, and "gob," which is refuse coal found in the overburden. Limestone is added to decrease the sulfur emissions from the exhaust stack. The percentage of gob burned is changed according to the output power requirements. Another cause of variability is due to the ash handling at the power plant. Every truck is filled from one of three ash holding hoppers. At any time these hoppers can contain any combination of fly and bottom ash.

The variability of the ash will require that the grout recipe be varied to maintain consistent flowability. The spread test was developed as a simple infield test to determine grout flowability. The spread test uses a cylinder 3 inches in diameter by 6 inches in height open at both ends. The cylinder is placed vertically on a horizontal surface and filled with grout. The cylinder is then slowly lifted and the grout is allowed to spread in a radial fashion. The distance of spread is then measured in two perpendicular directions and an average is taken. Spread tests were done using varying amounts of bentonite and water. Figure 4 shows how the addition of bentonite reduces the spread of the grout. This reduction in spread may call for a super-plasticizer or air entraining agents to counteract the effect of the bentonite. Work is currently planned to see how these additives will affect the flow of the grout, and to obtain a correlation between the spread and the appropriate rheological parameters. These values are being used to simulate the injection process on a computer using the commercially available flow code PHOENICS with some modifications for non-Newtonian fluids.

During the test injection at the Fairfax mine, this problem of ash variability was handled by choosing that amount of bentonite that gave the spread considered adequately flowable. Owing to the variability in the ash, a 5% bentonite recipe at the site gave the same spread as the 7% mix in the laboratory. Hence for the test injection a 5% bentonite recipe was adopted.

Grout Strength Requirements

Subsidence prediction, proper usages of damage

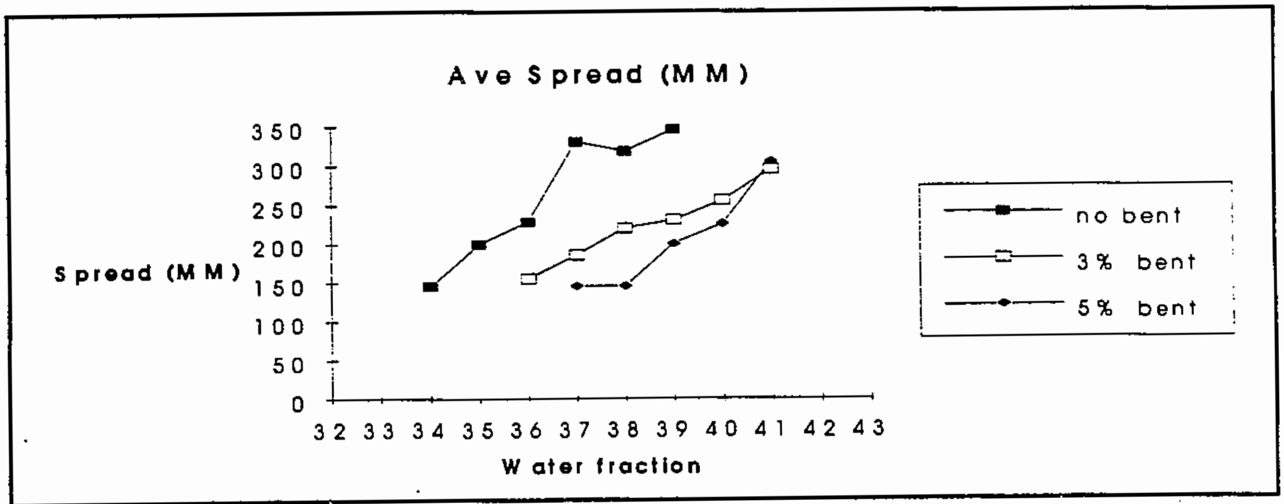

Figure 4 Spread versus water fraction for fly ash only samples at varying amounts of bentonite.

mititigation techniques, and methods for mine backfill are essential prerequisites to control or reduce potential subsidence in abandoned room-and-pillar mines. Inadequate pillar support due to deterioration of pillars causes the overlying strata to cave into the mine voids. This process propagates upward and finally reaches the surface. In room-and pillar mining, it takes several years for surface subsidence to occur. Pumped slurry backfilling has been used in the past for controlling subsidence (Colaizzi, et. al). Subsidence is a function of the type of overlying strata, the depth of excavation and the method of mining.

Site Description

Fairfax mine is an active coal mine in Preston County, West Virginia. The coal seam is found at an approximate depth of 225 feet below the ground surface. The thickness of the coal seam is about 5 feet. Figure 5 shows the soil and rock stratigraphy at core hole location SQ41 at the Fairfax Mine. Information pertinent to these core holes was extracted from the bore hole logs obtained from the mining company. The geologic columns at the mine show that the thickness of soft clay layer overlying the rock layers ranges from 19 to 28 feet. The rocks at the bedrock surface appear to be weathered. As shown in Figure 5, there is about 80 feet of weathered shale, which can be fairly massive and uninterrupted. Immediately below the top soil is a layer of sandy shale of about 15 to 20 feet in thickness. The Fairfax mine site is located in hilly terrain.

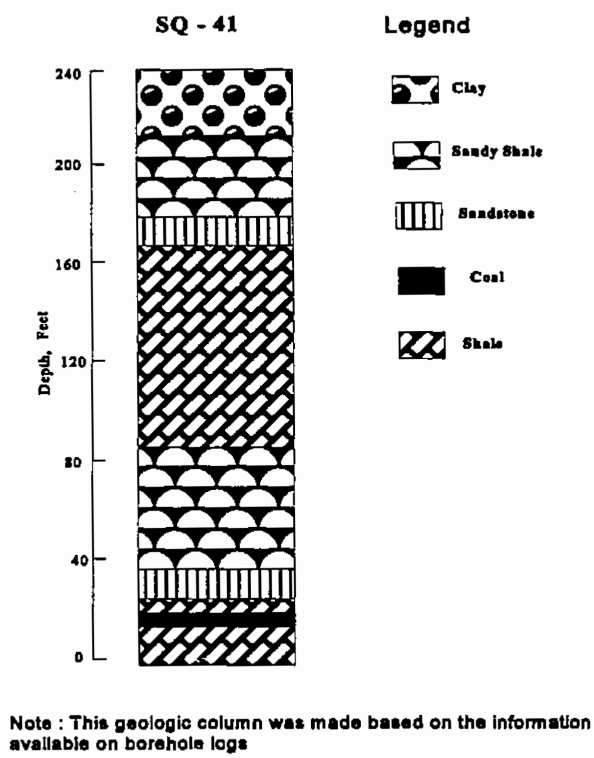

Figure 5 Geologic column at core hole location SQ-41of Fairfax Mine.

Methodology for Analysis

Subsidence predictions and an estimate of the strength requirements of the grout to be used for backfilling the mine voids at the Fairfax and the Longridge mines are two of the major objectives of this study. Finite element analysis was performed to study the influence of varying backfill configurations on subsidence (Siriwardane, 1978, 1991). The effect of bulking of the fallen overburden rock into the mine cavity in reducing the subsidence potential was also considered in the analysis by using a bulking factor.

Strength calculations were based on the fact that the grout after being injected into the mine void should develop sufficient compressive strength to withstand the stresses caused by the overburden, along with the pillars. In effect, it should play the role of the excavated coal with its full strength. Traditionally, the vertical stress at the level of coal seam is calculated by multiplying the unit weight of the materials comprising the overburden with the respective thicknesses. However, the theoretical strength obtained by following the steps outlined above is not a true representation of the in situ strength requirement as some factors that affect grout strength, such as stress concentrations (Boresi, et.al, 1978), have to be accounted for in the model. Moreover, pillar failures can affect the in situ stresses in pillars (Siriwardane, 1983) and possibly surrounding areas. The state of stress around discontinuities such as mine cavities is three dimensional in nature, and hence it is difficult to obtain analytical solutions. A separate Finite Element Analysis (Horino) was performed to obtain information on stress concentrations around mine cavities.

Computed Grout Strength Requirements

Reasonably accurate prediction of subsidence potential is possible with growing usage of numerical methods like the Finite Element Method. Strength requirements of grout may vary with the method used for backfilling mine voids. In situ strength requirements of grout backfill materials are affected by various uncertainties such as;

1) Local geology
2) Stress concentrations around mine cavities
3) Segregation during placement of the grout
4) Presence of water in mine cavities and the result of reactions between water and the various minerals present in the mine cavities on grout strength to name a few.

Strength requirements found in the analysis may have to be multiplied by a factor of safety to account for these uncertainties. Also, the differences in laboratory and field conditions and strengths need to be considered.

Effect of Stress Concentrations Around Mine Cavities

In situ strength requirement varies from place to place and is a function of various factors such as segregation and stress orientations and stress concentrations. The variation of stress concentration factors was determined by varying elastic moduli and Poisson's ratio of the grout for two different overburden materials. This variation shows that the overburden stiffness has a marked effect on the stress concentration factors. For areas overlain by a stiff overburden the stress concentration factor around mine cavities appears to be close to 3.1. The values of the stress concentration factors comes down with increase in the elastic modulus of the grout and reaches a value close to 1.0 for values of elastic modulus equal to that of the overburden. In the case of a weak overburden the stress concentration factor remains almost constant with a value close to 1.0 for different values of the elastic modulus of the grout after reaching a peak value of 3.16 for the cavity without any grout. For a grout that has a typical elastic modulus equal to 0.5 million psi, the value of the stress concentration factor appears to fall in the range of 2.5 to 2.75.

For a real situation, the overburden is likely to have a stiffness value in between the two scenarios considered in the previous section. In this study a value of 2.5 was assumed as a factor of safety to be used on the theoretical strength requirement of the grout to account for potential stress concentrations at the Fairfax and Longridge mines. Table I shows the computed strength requirements of the grout to be used as backfill material at the Fairfax mine. It should be noted that there are many other uncertainties such as those listed earlier, which were not considered in this study (for example, the effect of segregation during placement on grout strength, water content of the grout mix etc.). Therefore, it would be prudent to investigate the effect of these uncertainties on the strength requirement of the grout and then obtain a factor of safety that accounts for all the factors affecting the grout strength. A fair measure of the strength requirement can be obtained from field observations of the grout performance at the Fairfax mine, where grout injections have been completed.

Table 1: Strength Requirements for the Grout at the Fairfax Mine

Core Holes	Computed Stress (psf)	Stress (psi)	Factor of Safety	Grout Strength Require-ment (psi)
SQ-41	34,495	239.0	2.5	600
SQ-42	358,035	243.0	2.5	608
SQ-43	32,815	227.0	2.5	570

Field Injection

Grout injection at the Fairfax mine has been completed. The locations of the wells were established so that a comparison can be made between wells located at interceptions and mid-sections of hallways. Two of the injection wells are located at interceptions of hallways. Two additional wells are located at the center of hallway sections. The field experiment may provide information on the strength requirements of the grout and a measure of performance of the grout injection in terms of flow of grout and the extent of fill. The results on the performance of the grouting operation may provide valuable input to the location of injection and monitoring wells at the Longridge mine (Phase III site).

Observations on First Day

Injection began at 9:35 am, 21 May 1996. Johnnie Nichols, mine superintendent and Paul Ziemkiewicz were in the mine, 75 feet From the injection borehole when injection began. FBC ash slurry was injected in batch mode from two alternating cement trucks on the surface. Each pour comprised about 9-10 cu yds of slurry. Each pour lasted about 20 minutes and the interval between pours was 5-10 minutes.

Pour #1 flowed 75 feet from the borehole. At the downstream end of the ash lobe its depth was about 1 inch. At the borehole the depth was about 2 inches. The ash front continued to advance until injection stopped. The slurry was very fluid, finding and progressively filling low spots. It formed a leveled channel between 1 to 2 foot wide with the narrower widths associated with higher flow rates over constrictions and overfalls. In incompletely filled headings, slurry flowed down the center line of a channel which was semicircular in cross section, ~4 foot wide and 3 inches high at the center line. These channels eventually became occluded, at which side channels would break out and initiate a new lobe.

Pour # 2 advanced an additional 75 feet. In subsequent pours, the slurry front remobilized with a 1 minute lag time, initiated by a 1/2 inch wave which propagated in line with the axis of advance. The wave was parabolic with its apex at the downstream end. The second pour did not ride over the first pour, rather it displaced it from the upstream end pushing the entire mass forward. Shale rocks (4-6 inches long, 2 inches square) were observed carried along with the slurry. Slurry velocity was 12 inches/sec at overfalls and more typically 6 inches/sec on the level floor.

Pour #3 advanced only another foot or so, but it spread out to fill two headings from pillar to pillar (18 feet heading width). At the end of pour #3 the thickness at the downstream end was 2 inches. A zone of bleed water about 1/2 inches was observed at the downstream end of the slurry. Between pours, when the slurry advance stopped a thin (1/8 inch) layer of bleed water could be seen moving slowly along the top of the slurry. At the end of Pour #3 slurry depths were 2 inches at the downstream end, 6 inches in a low spot at the first spad (center of intersection) and 4 inches at the borehole. There appeared to be some particle size segregation with higher sand contents at the borehole and in the main channels with more fines at the downstream end and in the side channels and bays.

Slurry flowed down the 1-2% slope of the mine floor. It would dam behind roof falls and floor irregularities then flow over or around. Pouring continued until 5:30 pm on the first day. About 125 cubic yards of slurry were injected on the first day. The slurry was warm to the touch but not uncomfortable (approx. 80^0F). It generated a good deal of vapor. Also, since AMD treatment water was used to make up the slurry, and the AMD was treated with NH_3, contact with the lime caused deprotonation of the ammonium ion and release of more than perceptible amounts of NH_3.

Observations on Second Day

Results of the previous day's injection: About 5,400 sq. ft. of mine floor were covered by the end of the first day to an average depth of about 8 inches. While floor elevation varied in the order of 1-2 ft from roof fall, the slurry had the effect of leveling to an almost planar surface. From an almost watery consistency the first day the slurry had set up slightly to a gelatin consistency. At the end of the day one the injection crew ran about 800 gallons of water down the line to clean out the pump. This flushed out the slurry channels leaving them free for the next day's slurry.

Injection began at 7:30 am and while deforming the day one slurry in the immediate vicinity of the injection borehole, the new slurry flowed on top of the old slurry. It did not remobilize the old slurry to any significant extent. Since the FBC ash had been allowed to sit out overnight in a thunderstorm, it had developed a crust. This was broken up into 23 in diameter chunks which were transmitted with the slurry. These could be seen floating by in the slurry channel.

With well developed channels, flow proceeded in surges particularly at constrictions and overfalls. Velocity would decelerate over a period of minutes, stop for a second or so, then release in a surge. The flow would then spread out evenly behind a small (1 in) wave below the overfall. Injection proceeded to 24 May 1996 until 1,000 cu yds were placed in the mine. The next in-mine visit occurred one week after injection on 31 May 1996.

Observations One Week After Injection

On 31 May 1996 a party consisting of representatives from Fairfax Fuels, U.S. Department of Energy, CONSOL, Inc, WV Public Radio, Maryland DER and WVU inspected the mine. By this time the slurry had solidified to the extent that samples had to be chopped out with an entrenching tool. In spots of > 6 inches of slurry was still moist 3 inches from the top. The slurry had developed cracks which penetrated about 4 inches. These tended to run normal to the direction of ash flow. The ash had flowed about 550 feet from the injection borehole and surrounded four pillars. Headings were filled pillar to pillar and some rooms were filled with 2 ft of slurry (the roof was 4 ft high). At the injection borehole the slurry had coned but was still about 10 inches from the roof.

Conclusions

A grout made from FBC ash can be successfully pumped into an underground mine to backfill a mine void. The grout will however require the addition of admixtures in order to stabilize the grout. In this project bentonite was added at a rate of 5% by total weight of the grout for the field trial. The availability of FBC ash is suspect for the Phase III demonstration (grouting of the 11 acre Longridge mine). The rheological tests and overburden analysis methods described within this paper have proven to be beneficial in analyzing candidate grout mixtures and mine sites. The Phase III grout mixture will consist of a high loss on ignition ash, cement kiln dust as a binder and water. The demonstration will take place in Spring of 1998. Information regarding additional testing and preparations for Phase IIwill be presented at the conference.

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