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**Disposal of Fluidized Bed Combustion Ash in an
Underground Mine to Control Acid Mine Drainage and
Subsidence - Phase II - Small Scale Field Demonstration**

**Topical Report
December 1, 1996 - February 28, 1997**

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Phase II Small Scale Field Demonstration Fairfax Mine, Preston County, West Virginia

Introduction

The test injection of the grout developed in Phase I was conducted at the Fairfax Mine in the Preston County, West Virginia on May 20, 1996. One thousand cubic yards of grout was injected over a period of 4 days. A recipe of 34% water content (this is the amount added at the site and does not include the moisture present in the ash that reached the site) and 5% bentonite was adopted for the injection. A 40 yd³/hr capacity concrete pump was used to pump the grout through a 4" diameter injection hole.

The results of the injection were very encouraging and the grout exhibited the required standards of flowability and stability. A spread of 600 ft of running length of the mine corridor 18 feet wide was achieved from a single injection hole. The height to which the grout build up was about 2.5 feet at the injection point to about 6" midway through the length. The onsite spread tests showed a spread of 14". The test also shows that the dip on the floor had a significant influence on the direction of flow.

Field Methods

The cFBC ash was delivered to the Fairfax site in bottom dump (clam shell) trailers. The ash was placed in wind rows and then piled by a front end loader. The ash was placed into a hopper with the front end loader. The hopper emptied onto a short beltline that dumped into a mixer truck (See Photo 1). Bentonite was added to the beltline by a small screwconveyor (See Photo 2). Water was added to the mixer trucks as the dry materials were delivered. Once the materials were thoroughly mixed, the mixer truck poured the grout into a piston style concrete pump which delivered the grout to the borehole (See Photo 3). The grout dropped 230 feet vertically into the mine and began free flowing throughout the mine void (See Photos 4, 5 and 6).

Before entering the field, a mix design was decided upon in the laboratory. This design was modified, given field conditions (namely % of water in fresh FBC ash). The final mix design used for the 1000 yd³ field test is as follows:

14,700	lbs. cFBC ash
800	lbs. Bentonite
1,150	gallons (9593 lbs.) Water

This mix was chosen due to its high flowability. The only variance from the laboratory design is 4% in water content. The water content of the field mix is approximately 38%. Note that water content for this project is defined as weight of water divided by total weight of the mix.

Photo 1 - Grout Injection at Fairfax Mine.

Photo 2 - Ash is loaded into a hopper and onto a belt conveyor. Bentonite is added to the belt via a screw conveyor.

Photo 3 - Grout is loaded into a piston style concrete pump and placed underground at a rate of 40 cubic yards per hour.

Photo 4 - Grout is pumped into the mine and free flows to fill the mine void.

Photo 5 - Grout is self leveling and free flows to fill the void.

Photo 6 - The grout flowed around pillars and achieved a distance of over 600 feet from the injection borehole.

Observations of Grout Flow from Underground while Injecting

The following observations were made by Dr. Paul F. Ziemkiewicz of the National Mine Land Reclamation Center at West Virginia University. Dr. Ziemkiewicz was underground while the first four truckloads of grout were being injected.

Injection began at 9:35 am, 21 May 1996. Johnnie Nichols, mine superintendent and Paul Ziemkiewicz were in the mine, 75 ft. 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 a further 75 feet. Upon the subsequent pours, the slurry front remobilized with a roughly 1 minute lag time, initiated by a roughly ½ 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 ft heading width). At the end of pour #3 the thickness at the downstream end was 2 inches. A zone of bleed water about ½ inches was observed at the downstream end of the slurry. Between pours, when the slurry advance stopped a thin (1-2 mm) 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 (like bathwater). 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 .

Day Two

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 Jell-O 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.

Witnessing the injection underground on day two were: Johnny Nichols, Fairfax Fuels; Jeff Kelley, and two engineers from Anker Energy, Inc; Dwayne Maust and Dave Bayles from Patriot Mining, Inc.; Mike Main and Paul Ziemkiewicz from WVU.

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 2-3 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.

One Week After Injection

On 31 May 1996 a party consisting of: Johnny Nichols, Fairfax Fuels; Jer-Yu Chang, Scott Renninger, U.S. Department of Energy; Milton Wu, Bruce Leavitt, CONSOL, Inc; Jeff Young, WV Public Radio; Ed Lyons, Maryland DER; Jeff Skousen, Courtney Black, Therapatti Reddy and Paul Ziemkiewicz, 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 it 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 ft 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.

Numerical Modelling of Grout Flow

Since the project began, a computer model of grout flow has been developed. The purpose of the model is to extend the capabilities of the project from the two mines in question to all underground coal mines. Given the geometry of the mine and characteristics of the grout, a mine void fill could be simulated. Early attempts to model the grouting operation were partially successful. The capability of the personal computer was not great enough to allow for a simulation of any length of time. However, a new approach was tried in Phase II and was successful. The results of this section can be found in Appendix A.

Subsidence Control and Contaminant Transport

The results of the Subsidence Control group were reported in the Phase I Topical Report. Those results were used to validate the strength requirements of the grout used in Phase II. The Contaminant Transport section is still generating data that will be used in verifying water flows around the grout, model current leaching of contaminants (acid mine drainage) and show the reduction of contaminant transport into groundwater due to the grouting of the mine void. These results will be reported in Phase III before grouting commences.

Water Quality Monitoring

Purpose

This purpose of this task is to monitor baseline water quality and quantity of the acid mine drainage (AMD) from the Longridge and Fairfax Mines prior to grouting. The baseline data will be essential to evaluate and document the benefit of the grouting activity over time.

Background

The Longridge Mine is an ideal site for sampling since all water exits the mine from a single opening. It was relatively easy to modify the area near the opening so as to capture all the flow and then to direct it into a pipe for measurement and sampling. Several flow and water quality measurements were made on AMD from the mine in 1982. At that time the flow varied between 10 to 74 gallons per minute (gpm). This information was helpful in choosing a flow measurement system to monitor the expected large variation in flow over the project period. It was decided to set up a continuous sampling station for baseline monitoring of flow and water quality from the Longridge Mine. All water in the active Fairfax Mine has historically been collected in a sump and pumped out of the mine as required. It was initially planned that baseline samples would be taken of the pumped flow on a bi-monthly basis. However, no water accumulated in the sump during Phase 1. In Phase 2, a well was drilled to allow sampling by bailing and sampling began in June of 1996.

Methodology

In order to measure flow from the Longridge Mine, a rock and concrete dam was built at the entrance to back up water leaving the entrance to a depth of about 2 feet. The minewater was directed to flow through a 6 inch diameter PVC pipe built into the bottom of the dam and a variable gate flowmeter was attached to the end of the pipe to continually monitor the flow. Calculations show that the system should be able to monitor flows of from about 0.25 to over 200 gpm which will cover the expected flow range both prior to and after the grouting.

The site was visited weekly to inspect the equipment and to collect the data and samples. Flow data from the meter is continuously recorded and a signal is sent to a sampler in order to allow collection of samples in proportion to flow. The flow data is both recorded on a stripchart and stored on flowlink software for weekly downloading to a portable computer. Samples of minewater are taken and sent to a weatherproof sampling station (heated and cooled) where they are stored in a polyethylene container at 4 ° C. The sampled AMD is picked up on a weekly basis and transported to the laboratory for analysis. The sampler is programmed to take as many as 100 aliquots of minewater per week based on a preset flow interval such as 1200 gallons. Thus when the flow is high,

samples are taken more frequently than when flow falls off. The flow interval between samples is adjusted from time to time depending on the flow at that period so as to spread sample collection over the entire week's period.

Seventeen constituents were analyzed in the weekly samples. The constituents were chosen based on contaminants known to be in AMD and their potential toxicity to the environment. Another factor in the choice were those pollutants which might be leached from the MEA FGD by-product sludge. The constituents chosen for analysis are as follows:

acidity	magnesium	specific conductance	arsenic
calcium	pH	acidity	lead
temperature	alkalinity	sulfate	cadmium
manganese	iron	aluminum	boron
			selenium

It may be seen that a variety of major AMD constituents were chosen such as acidity, sulfate and iron as well as 5 trace elements. All analyses were performed according to accepted standard methods and QA/QC procedures rigorously observed.

Since the amount of precipitation in a given time period will affect the volume of water moving through the mines and the strength of the AMD, a precipitation gauge was set up close to the mines. Precipitation is measured with a battery operated tipping bucket rain gauge located in a setting away from trees and wind currents. The data is continuously recorded on a data logger and downloaded weekly to a portable computer.

Results and Discussion

Longridge Mine

This report covers activity from 10/1/95 to 12/13/96. Basic data obtained for the Longridge Mine are presented in Tables 1 and 2. Table 1 presents the data obtained for each sample while Table 2 provides the average values and range for each parameter. Samples were taken weekly during the period for a total of 45 samples. However, during some weeks, flow data is unavailable due to flow meter malfunction. The rain gauge also malfunctioned at times and precipitation data for some weeks was obtained from the Morgantown Lock and Dam as indicated on the table.

Flow and Precipitation Monitoring

As may be seen in Table 2, average weekly flow during the period varied from a low of 8.3 to a high of 251 gpm and averaged 107.5 gpm. Figure 1 presents a plot of flow vs date of sample for the period. High flow periods correspond to periods of high precipitation (Table 1) as would be expected. An example of a daily chart showing flow data (week of 11/15/96 to 11/22/96-sample 98) is shown in Figure 2. It may be noted that the flow varied significantly during the week. Figures 3 and 4 present plots of rainfall intensity and the

cumulative total as a function of time for the same period. It may be noted that 0.36 inches of precipitation occurred during the week, most of which occurred on 11/18. The rainfall was sufficient to make a marked change in the AMD flow as may be seen from Figure 2.

As shown in Tables 1 and 2, rainfall rates varied from 0 to 3.28 inches per week. Unfortunately, the rain gauge at the site malfunctioned a few times with loss of local precipitation data. For weeks where precipitation at the site was unavailable, precipitation records for the Morgantown Lock and Dam (MLD) are provided as indicated by an asterisk on Table 1. The Morgantown Lock and Dam Station is about 20 air miles from the site. Since storms can be very localized, especially in the summer period, the data from the MLD will not always truly reflect the precipitation received at the site.

Water Quality Analysis and Parameter Interrelationships

Examination of Tables 1 and 2 shows that the AMD from the Longridge Mine has pH values ranging from 2.5 to 3.1 and an average acidity of 858 mg/L (range; 508-1300 mg/L). Other important parameters include iron, sulfate, and aluminum averaging respectively 126 (range; 60-230), 1503 mg/L (range; 763-2540), and 58.1 mg/L (range; 32.4-99). It is difficult to define an "average" quality AMD since quality varies with many factors. These include the particular coal seam and character of the surrounding strata, age of the mine and whether the mine is in an active or an inactive status, availability of oxygen, amount of water flowing through the mine and time of contact of the water with the exposed strata. Skousen and Ziemkiewicz (1995) reported the analysis of AMD samples from four different sites in West Virginia. They found that acidity, iron and sulfate values averaged respectively 1536 mg/L (range; 516-3152), 409 mg/L (range; 7-1129), and 2472 mg/L (range; 640-4300). James (1984) sampled 12 different sites for AMD from the Upper Freeport Seam. The average of the mean values from the 12 sites for acidity, aluminum and sulfate were as follows: acidity 808 mg/L (range; 62-1698), aluminum 77 mg/L (range 1 to 169) and sulfate 1509 mg/L (range 384-3426). The values from James may be readily compared to the Phase 2 values noted above since the Longridge Mine is also in the Upper Freeport coal. It may be noted that the Longridge Mine AMD strength falls in the middle to upper end of samples reported by James showing the Longridge AMD to be a typical, to relatively strong AMD for the Upper Freeport formation.

Figure 5 presents mg/L of acidity and iron as a function of flow. The influence of dilution at higher flows is clearly shown as both acidity and iron decrease significantly as flow increases. Over the flow range shown (8 to 251 gpm), the concentration of acidity and iron both fell about 55 % based on the trendline shown. While the concentration of the contaminants decreased as flow rose, the actual mass of contaminants released per day actually rose significantly as flow increased. Figure 6 compares acid concentration (mg/L) and acid mass discharged (lbs/d) vs flow. It may be seen that the acid mass entering the environment increased from about 170 lb/d at 8 gpm to about 2000 lbs/d at 251 gpm showing an over 10 fold increase. It is interesting to note that James (1984) did not find a consistent trend when AMD parameters were plotted against flow. However, the author reported a variety of problems in obtained in obtaining reliable flow measurements. In

addition, the Phase 1 samples are from a single mine while the samples that James collected were from 12 different sites.

As might be expected, most constituents rose and fell together from sample to sample. That is, a sample with a high concentration of acidity would also have a relatively high concentration of sulfate. Figure 7 compares the concentration of acidity, sulfate and iron as a function of sample #. It may be noted that there is a general tendency for the contaminants to rise and fall together. This trend is shown clearly in Figures 8 to 10. Figures 8 and 9 present the correlation between aluminum and sulfate and iron and acidity respectively. While there is a significant amount of scatter, the trends are unmistakable with the contaminants rising or falling together. A similar correlation is shown between calcium, iron and aluminum in Figure 10.

The AMD from the Longridge Mine also contains environmentally significant levels of trace elements. As shown in Table 2, the average arsenic, selenium and lead concentrations were found to be 0.60, 0.49 and 0.27 mg/L respectively. The trace elements also varied greatly with flow as shown in Figure 11 where arsenic, selenium and lead concentrations are presented as a function of flow. For example, it may be noted that lead fell from about 0.3 mg/L at 8 gpm to approximately 0.1 at 251 gpm. As flow increased arsenic and selenium also fell off dramatically. These reductions in trace element concentration with flow are similar to those noted for the major AMD constituents above. While concentration decreased with flow, the actual mass rate of trace elements release actually increased with flow as depicted in Figure 12. It may be noted that the lbs/d of lead leaving the mine increased over 10 fold as flow increased. Figure 13 presents the comparison of the concentration of three trace elements with acidity. It may be noted that all three trace metals (As, Se, & Pb) tend to increase in concentration as acidity increases.

Comparison of Phase 1 and Phase 2 Longridge Mine Data

Table 3 presents summary data from both Phase 1 and Phase 2 for comparison. It may be noted that the average flow in Phase 2 (107.5 gpm) was almost 3 times higher than the average flow in Phase 1 (36.2 gpm). As would be expected the average precipitation in Phase 2 (0.96 inches per sample week) was higher than in Phase 1 (0.62 inches per sample week). As a result of the higher average flows in Phase 2, the water quality parameter concentrations are lower. For example, the average acidity, iron, and arsenic concentrations for Phase 2 and Phase 1 respectively were 858/1002, 126/171, and 0.60/0.71 mg/L. However, the actual lbs of acid discharged per day was much higher in Phase 2 (952) as compared to Phase 1 (360). This trend was noted earlier and shows that more pollutant mass is discharged at higher flows even though the actual concentration values are lower.

Fairfax Mine

As noted earlier, sampling at the Fairfax Mine began in June of 1996. Water is

collected from the surface by bailing a well drilled below the mine depth using a long rope and a plastic pipe. Samples are taken approximately once per month to once every two months. Table 4 shows results of the water quality sampling. It may be seen that the water is actually alkaline and typical of a groundwater not contaminated with acid mine drainage. Water will continue to be monitored to check for any metals from the Phase II grouting operations.

Conclusions

Sampling during the Phase 1 and 2 periods has provided a good database of background water quality and quantity. Weekly average flow over the Phase 2 period varied from 8 to 251 gpm while precipitation ranged from 0 to 3.28 inches. Analyses of AMD from the Longridge Mine shows it to be typical in quality with respect to published data for AMD from the Upper Freeport Coal Seam. It is a relatively strong AMD with acidity, sulfate and iron averaging 858, 1503, and 126 mg/L respectively during Phase 2. Environmentally significant trace elements are present including lead, selenium and arsenic levels averaging 0.27, 0.49, and 0.60 mg/L respectively. It was found that the concentration of the water quality parameters decreased significantly as flow increased. While the concentration of the contaminants fell with increased flow, the actual mass of contaminants released per day actual increased with flow. For example, there was an over 10 fold increase in the lbs/d of lead leaving the mine as the flow increased from 8 to 251 gpm. As may be expected, there was a general trend for the different contaminant concentrations to rise and fall together with changes in flow.

The average flow during Phase 2 (107.5 gpm) was significantly higher than noted for Phase 1 (36.2 gpm) and hence the concentration of contaminants leaving the mine was lower during Phase 2. However, the mass of pollutants was higher during Phase 2 due to the higher flows experienced.

Analyses of water sampled from the Fairfax Mine shows it to be a typical groundwater and not polluted with acid mine drainage.

References

James, T. J. (1984) "Characterization of Water Quality for Deep Mine Effluents of Upper Freeport and Bakersfield Coal Mines in Central Preston County, WV," MS Thesis, West Virginia University, Morgantown, WV.

Skousen, J.G., and P.F. Ziemkiewicz (1995) "Acid Mine Drainage Control and Treatment," West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV.

Appendix A

Table 1. Sampling Data for Longridge Mine-10/1/95 to 12/13/96																	
Date		10/8	10/13	10/22	10/29	11/7	11/19	11/25	12/2	12/6	12/16	12/21	12/28	1/15	1/20		
Sample #		57	58	59	60	61	62	63	64 (1)	65	66	67	68 (1)	69	70		
Flow (gpm)		8.9	8.9	8.8	8.4	8.3	11.7	41.2	74.7	64.7	38.9	148.1	95.0	64.5	245.8		
Temp (C)		10	10	9	9	10	9	8	10	9	10	10	10	11	10		
Precip (in)		0.79	0	1.56	0.45	0.74	1.22	0.32	0.35	*0.08	*0.86	*2.03	*0.24	*1.30	*1.52		
pH		2.6	2.6	2.7	2.7	2.9	2.8	2.6	2.5	2.5	2.5	2.5	2.5	2.7	2.7		
Con. (umo/cm)		3140	3090	2790	3020	3120	3060	3060	3020	2520	2450	2050	2410	2130	1920		
Acid. (mg/L)		1200	1200	1260	1300	1250	1250	1240	1370	1230	1260	975	1140	1160	918		
Acid. (lbs/d)		129	129	133	131	124	176	613	1229	956	589	1734	1301	899	2710		
Fe (mg/L)		160	160	219	164	217	203	211	230	195	193	156	182	186	139		
Mn (mg/L)		22.9	24	23.8	24.8	25	22.8	27.5	45.1	29.7	27.6	21.2	23.8	21.4	60.9		
Al (mg/L)		84.1	88.1	88.4	99.3	99	101	86.2	93.2	80.6	81.8	60.7	71.7	74	51.8		
Ca (mg/L)		204	215	214	248	236	235	199	187	156	165	123	136	150	107		
Mg (mg/L)		107	110	106	108	104	107	98.4	106	92.6	95.1	70.4	83	78.2	60.9		
SO4 (mg/L)		2240	2310	2390	2260	2390	2540	1640	2400	2050	2220	1570	1840	2240	1680		
As (mg/L)		0.75	0.81	1	0.82	0.93	0.85	0.81	0.85	0.87	0.92	0.65	0.81	0.79	0.60		
Se (mg/L)		0.8	0.67	0.73	0.53	0.64	0.65	0.88	0.67	0.68	0.57	0.64	0.65	0.61	0.55		
Pb (mg/L)		0.29	0.29	0.33	0.35	0.42	0.31	0.32	0.33	0.29	0.29	0.22	0.26	0.27	0.21		
Ba (mg/L)		0.08	<.05	<.05	<.05	<.05	<.05	<.05	0.0583	0.483(2)	<0.010	<0.010	0.0599	0.0642	0.0605		
Cd (mg/L)		<0.05	<.05	<.05	<.05	<.05	<.05	<.05	0.0163	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007		
B (mg/L)		0.17	0.16	0.24	0.19	0.2	0.19	0.13	0.17	0.16	0.13	<0.030	0.13	0.16	0.06		
	(1) Data not utilized in obtaining average values					NA-Not available or applicable			(2) Data appears anomalous-not used in calculations								
	*Data taken from Morgantown Lock & Dam																

Table 1. Sampling Data for Longridge Mine-10/1/95 to 12/13/96**:Page 2**

1/26	2/2	2/9	2/17	2/23	3/10	3/16	3/23	3/31	4/7	4/13	4/19	4/27	5/3	5/10	5/18
71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
234.2	155.6	59.0	136.0	124.0	188.8	139	160	185	143	90.4	141	87.3	92.3	223	251
10	10	10	9	10	10	10	10	10	10	10	11	11	10	11	12
*1.14	*0.70	*0.67	*0.01	*0.0	3.28	0.38	1.83	0.39	1.22	0.14	0.18	0.93	1.52	1.50	1.60
2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.5	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
1800	1980	2140	1940	1840	1890	1890	1760	1660	1720	2070	1560	1710	2030	1810	1740
840	850	937	804	890	604	650	643	636	649	682	606	666	657	531	508
2363	1588	664	1313	1326	1370	1085	1236	1413	1115	740	1026	698	728	1422	1531
125	114	132	135	119	101	94	88	78	92	90	81	96	94	68	60
14.6	15.6	17.5	18.8	17.3	15.5	15.6	14.1	12.6	15.1	15.5	12.5	15.6	14.3	10.9	11.2
45	47.2	54.8	57.5	55	48.2	45.0	43.4	42.8	41.9	46.2	38.9	47.5	45.0	34.7	32.4
78	82	106	110	95	86	87	80	81	84	90	76	91	85	62	57
50.7	56.5	65.7	69.9	68	62.1	58.9	56.9	57.0	55.7	62.3	49.9	61.8	53.7	41.0	40.4
1440	1220	1600	1460	1340	931	983	1130	879	971	1170	1020	1270	1120	897	763
0.51	0.46	0.51	0.57	0.53	0.54	0.47	0.39	0.37	0.40	0.55	0.44	0.46	0.57	0.51	0.43
0.44	0.41	0.49	0.50	0.44	0.41	0.38	0.36	0.30	0.31	0.47	0.31	0.40	0.47	0.32	0.34
0.18	0.16	0.19	0.18	0.17	0.15	0.15	0.14	0.14	0.16	0.20	0.13	0.15	0.14	0.10	0.10
<0.010	<0.010	0.0968	0.205	1.13(2)	0.960(1)	<0.1	0.492(2)	0.053	0.010	0.026	0.008	0.119	0.030	0.050	0.014
<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	0.003	0.011	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<0.030	0.11	0.10	0.05	0.09	0.110	0.078	0.105	0.082	0.040	0.064	0.067	0.090	<0.030	<0.030	<0.030
(1) Data not utilized in obtaining average values					NA-Not available or applicable					(2) Data appears anomalous-not used in calculations					
*Data taken from Morgantown Lock & Dam															

Table 1. Sampling Data for Longridge Mine-10/1/95 to 12/13/96														:Page 3		
5/29	6/7	6/13	6/20	6/27	8/29	9/5	9/12	9/20	11/8	11/15	11/22	12/3	12/6	12/13		
87	88(1)	89(1)	90(1)	91(1)	92(1)	93(1)	94(1)	95(1)	96	97	98	99	100	101		
91.3	NA	NA	NA	NA	NA	NA	NA	NA	45.5	145	54.3	128	152	80		
12	12	12	12	12	12	12	12	12	12	12	10	9	11	11	11	
1.08	0.64	0.48	0.57	0.58	*0	*0	*0	*1.84	1.71	0.33	0.39	2.74	0.22	0.89		
2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.8	2.8	2.7	2.7	2.7	2.7	2.7	3.1		
1970	1970	2100	2120	1940	2330	2320	2430	2300	2410	1940	2210	2120	2020	1970		
623	637	690	573	691	1080	973	1000	1030	792	587	728	678	597	644		
683	NA	NA	NA	NA	NA	NA	NA	NA	433	1022	475	1042	1090	619		
80	94	100	115	135	160	160	170	160	120	77	97	93	84	93		
14.2	14.4	14.8	14.3	17.5	20	22	20	23	20	13	16	15	14	16		
42.4	40.7	43.5	44.8	48.8	63	76	72	75	55	35	46	43	43	50		
82	88	96	107	124.0	150	170	170	160	120	75	100	99	76	92		
52.1	59.2	57.1	57.4	72.9	78	95	92	93	72	45	60	56	47	55		
995	1120	1170	1230	1320	1400	1600	1800	1800	1400	1400	1200	1400	970	NA		
0.41	0.53	0.58	0.57	0.71	0.85	0.94	0.92	0.71	0.63	0.44	0.63	0.56	0.38	0.46		
0.40	0.38	0.42	0.41	0.57	0.63	0.86	0.88	0.74	0.62	0.37	0.5	0.45	0.33	0.31		
0.14	0.17	0.16	0.18	0.24	0.25	0.3	0.29	0.22	0.22	0.13	0.17	0.2	<.04(2)	<.04(2)		
0.009	0.014	0.008	0.019	0.008	0.0095	0.007	0.0089	0.01	0.0086	0.0082	0.01	0.062(2)	<.001	<.001		
<.001	<.001	<.001	<.001	0.002	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001		
<.030	<.030	<.030	0.270	0.103	<.03	<.03	<.03	<.03	0.053	<.03	<.03	<.03	0.07	<.03		
(1) Data not utilized in obtaining average values					NA-Not available or applicable					(2) Data appears anomalous-not used in calculations						
*Data taken from Morgantown Lock & Dam																

**Table 2. Summary Data-Longridge Mine
10/1/95 to 12/13/96**

<u>Parameter</u>	<u>Average</u>	<u>Range</u>
Flow (gpm)	107.5	8.3-251
Temp (C)	10.2	9-12
Precip (in)	0.96	0-3.28
pH	2.7	2.5-3.1
Con. (umo/cm)	2187	1740-3140
Acid. (mg/L)	858	508-1300
Acid. (lbs/d)	952	124-2710
Fe (mg/L)	126	60-230
Mn (mg/L)	19.3	11.2-45
Al (mg/L)	58.1	32.4-99
Ca (mg/L)	121	57.4-248
Mg (mg/L)	69.6	40.4-110
SO4 (mg/L)	1503	763-2540
As (mg/L)	0.60	0.36-1.0
Se (mg/L)	0.49	0.31-0.88
Pb (mg/L)	0.27	0.10-0.42
Ba (mg/L)	NA	<.01-.205
Cd (mg/L)	NA	<.001-.016
B (mg/L)	NA	<.03-.27

Table 3. Comparison of Data: Phases 1 and 2

	<u>Phase 1</u>		<u>Phase 2</u>	
	Average	Range	Average	Range
Flow (gpm)	36.2	8.8-121.4	107.5	8.3-251
Temp (C)	9.8	8-11	10.2	9-12
Precip (in)	0.62	0-4.52	0.96	0-3.28
pH	2.7	2.4-3.0	2.7	2.5-3.1
Con. (umo/cm)	2457	1830-3310	2187	1740-3140
Acid. (mg/L)	1002	693-1264	858	508-1300
Acid. (lbs/d)	360	110-1098	952	124-2710
Fe (mg/L)	171	100-238	126	60-230
Mn (mg/L)	21.8	14.9-29.9	19.3	11.2-45
Al (mg/L)	71.8	46.6-98.3	58.1	32.4-99
Ca (mg/L)	165.7	92-238	121	57.4-248
Mg (mg/L)	85.5	51.4-124.0	69.6	40.4-110
SO4 (mg/L)	1649	1070-2372	1503	763-2540
As (mg/L)	0.71	0.33-0.92	0.6	0.36-1.0
Se (mg/L)	0.58	0.30-0.75	0.49	0.31-0.88
Pb (mg/L)	0.25	0.12-.37	0.27	0.10-0.42
Ba (mg/L)	NA	<.05	NA	<.01-.205
Cd (mg/L)	NA	<.05	NA	<.001-.016
B (mg/L)	0.17	0.07-.26	NA	<.03-.27

Table 4. Data for Fairfax Mine-10/1/95 to 12/13/96**

								Average	
Date		6/13	6/20	6/27	8/29	11/8	11/15	NA	
Sample #		89F	90F	91F	92F	96F	97F	NA	
Flow (gpm)		NA	NA	NA	NA	NA	NA	NA	
Temp (C)		NA	NA	NA	NA	NA	NA	NA	
Precip. (in)		0.48	0.57	0.58	*0	1.71	0.33	0.6	
pH		6.5	7.0	7.5	6.9	7	7.0	7.0	
Cond. (umo/cm)		760	730	578	700	600	580	658.0	
Acid. (mg/L)		<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	NA	
Alkalinity (mg/L)		150	153	160	338	145	146	182.0	
Fe (mg/L)		1.24	1.11	0.497	0.068	0.11	0.18	0.5	
Mn (mg/L)		0.329	0.281	0.158	0.052	0.12	0.11	0.2	
Al (mg/L)		0.816	0.741	0.571	0.17	1.4	1.5	0.9	
Ca (mg/L)		81.3	76.5	78.9	68	56	55	69.3	
Mg (mg/L)		18.8	17.9	18	15	12	12	15.6	
SO4 (mg/L)		225	219	225	190	160	170	198.2	
As (mg/L)		<.175	<.175	<.175	<.175	<.175	<.175	NA	
Se (mg/L)		<.139	<.139	<.139	<.139	<.139	<.139	NA	
Pb (mg/L)		<.040	<.040	<.040	<.040	>.040	<.040	NA	
Ba (mg/L)		0.094	0.091	0.095	0.091	0.096	0.11	0.1	
Cd (mg/L)		<.001	<.001	<.001	<.001	<.001	<.001	NA	
B (mg/L)		<.030	<.030	<.030	<.030	<.030	<.030	NA	
*precip. data taken from Morgantown Lock & Dam due to malfunc. of site rain gauge									
NA = not available				**samples were taken only on the dates shown					

Figure 1. Flow vs Date of Sample

Figure 2, Flow Data; Sample 98
Set # 98

SET98

Site 98

Figure 3. Rainfall Plot; Week 98

Type: 674L-8K

inches

Recorder ID: 0001

Figure 4. Running Rainfall Total; Week 98

Saved Recorder Status

Type: 674L-8K Range:-0.00 - 2.55 inches Recorder ID: 0001
 Time at Recorder: 11/22/96 18:54:35 Accum Reset @:11/15/96 16:17:41
 Signal process: Not Applicable Accum: 0.39 inches
 Values being saved: Totals

Totalizing period: 00:01:30 Amount of data recorded: 7 days 02:37:30

Storage Capacity: 8140 values records: 8 days 11:30:00 Prescaler: 1
 Output compressed by a factor of 100

Date	Time	Avg inches	Period Total	Running Total	
11/15/96	16:16:11	-0.00	-0.00	-0.00	*
11/15/96	18:46:11	-0.00	-0.00	-0.00	*
11/15/96	21:16:11	-0.00	-0.00	-0.00	*
11/15/96	23:46:11	-0.00	-0.00	-0.00	*
11/16/96	02:16:11	-0.00	-0.00	-0.00	*
11/16/96	04:46:11	-0.00	-0.00	-0.00	*
11/16/96	07:16:11	-0.00	-0.00	-0.00	*
11/16/96	09:46:11	0.00	0.01	0.01	*
11/16/96	12:16:11	-0.00	-0.00	0.01	*
11/16/96	14:46:11	-0.00	-0.00	0.01	*
11/16/96	17:16:11	-0.00	-0.00	0.01	*
11/16/96	19:46:11	-0.00	-0.00	0.01	*
11/16/96	22:16:11	-0.00	-0.00	0.01	*
11/17/96	00:46:11	-0.00	-0.00	0.01	*
11/17/96	03:16:11	-0.00	-0.00	0.01	*
11/17/96	05:46:11	-0.00	-0.00	0.01	*
11/17/96	08:16:11	-0.00	-0.00	0.01	*
11/17/96	10:46:11	-0.00	-0.00	0.01	*
11/17/96	13:16:11	-0.00	-0.00	0.01	*
11/17/96	15:46:11	-0.00	-0.00	0.01	*
11/17/96	18:16:11	-0.00	-0.00	0.01	*
11/17/96	20:46:11	-0.00	-0.00	0.01	*
11/17/96	23:16:11	-0.00	-0.00	0.01	*
11/18/96	01:46:11	0.00	0.03	0.04	*
11/18/96	04:16:11	0.00	0.02	0.06	*
11/18/96	06:46:11	0.00	0.11	0.17	*
11/18/96	09:16:11	0.00	0.07	0.24	*
11/18/96	11:46:11	0.00	0.04	0.28	*
11/18/96	14:16:11	0.00	0.07	0.35	*
11/18/96	16:46:11	0.00	0.01	0.36	*
11/18/96	19:16:11	-0.00	-0.00	0.36	*
11/18/96	21:46:11	-0.00	-0.00	0.36	*
11/19/96	00:16:11	-0.00	-0.00	0.36	*
11/19/96	02:46:11	-0.00	-0.00	0.36	*
11/19/96	05:16:11	-0.00	-0.00	0.36	*
11/19/96	07:46:11	-0.00	-0.00	0.36	*
11/19/96	10:16:11	-0.00	-0.00	0.36	*
11/19/96	12:46:11	-0.00	-0.00	0.36	*
11/19/96	15:16:11	-0.00	-0.00	0.36	*
11/19/96	17:46:11	-0.00	-0.00	0.36	*
11/19/96	20:16:11	-0.00	-0.00	0.36	*
11/19/96	22:46:11	-0.00	-0.00	0.36	*
11/20/96	01:16:11	-0.00	-0.00	0.36	*
11/20/96	03:46:11	-0.00	-0.00	0.36	*
11/20/96	06:16:11	-0.00	-0.00	0.36	*

Figure 5. Flow vs Acidity & Fe

Figure 6. Flow vs Acid Concentration & Acid Mass

Figure 7. Acidity, Sulfate & Iron vs Sample #

Figure 8. Al vs Sulfate

Figure 9. Fe vs Acidity

Figure 10. Ca, Al, & Fe vs Sample #

Figure 11. As, Se, & Pb vs Flow

Figure 12. Flow vs Pb Concentration and Pb Mass

Figure 13. As, Se, & Pb vs Acidity

STABILITY, RHEOLOGY AND NUMERICAL SIMULATION OF FBC ASH GROUT FOR FILLING ABANDONED COAL MINES

THESIS

Submitted to the
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by
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1. INTRODUCTION

The United States currently has over 480 billion tons of mineable reserve base of coal (*Head et al., 1996*). Two-thirds of this reserve is mineable by underground methods. Room and pillar type of underground mines are common in Appalachian region. The coal is excavated by special equipment which leave behind a series of interconnecting passageways with pillars of unremoved coal. In addition to carbon, coal contains a number of components such as sulfur, nitrogen and incombustible mineral matter called the 'gob'. The sulfur and nitrogen form undesirable oxides during combustion. The incombustible mineral matter is converted into ash and leads to suspended particles in air. Several technologies designed to prevent the release of these undesired oxides have been developed. One such technology is the Fluidized Bed Combustion (FBC) technique. The FBC technique combusts coal along with limestone in a special combustion chamber at low temperatures. The limestone captures sulfides and the relatively low temperatures prevent the formation of the harmful oxides. The demerit of this method is the highly basic nature of the ash arising from the presence of free lime or slaked lime in it. The disposal of such ashes in open landfills is very expensive.

The other problems attached with the mining practice are those of ground collapse (subsidence) and acid mine drainage (formation of sulfuric acid from the reaction of the pyrite of the mine with underground water pools formed from the draining groundwater in abandoned mines). The environmental damage caused by these phenomena and the problems of ash disposal drew a lot of attention, recently.

The hydraulic backfilling of the FBC ash can be looked at as a cure-all for the above problems. A grout made from the FBC ash, water and possibly other additives, when injected into

the abandoned underground mines from the surface, can fill the mine and thus solve the problems of subsidence (if the hardened grout meets the strength requirements), acid mine drainage (by preventing the formation of underground water pools and neutralizing the acid formation) and ash disposal. This solution carries the multiple benefit of creating a market for the FBC byproducts and providing mine closure engineers and abandoned mine authorities a new tool to combat abandoned mine problems.

The injection from the surface requires boreholes to pump the grout through. If the grout flows only a small distance from the injection hole in the mine, a large number of boreholes will be needed to fill the mine. Drilling boreholes is the most expensive part of any such project and a high number of boreholes required can render such projects uneconomical and nonviable. Hence the distance the grout will flow from the point of injection in the mine is of utmost importance. Investigation of the flow properties of the grout is addressed in this report.

In the present work, various grout compositions were investigated for properties like stability of the suspension, fluid flow parameters like viscosity, yield value, etc., and the spread distances. Several test procedures have been adapted and developed for this purpose. Certain additives have been added and a suitable grout composition was arrived at. The appropriate fluid model that describes the flow properties of the grout was formulated. Use was made of a numerical code to predict the flow behavior of these grouts on a computer. Bench-scale injection tests were conducted as a preliminary test for a full-scale injection test, which was performed by injecting the grout mix into an abandoned mine. Vital conclusions that are critical for hydraulic backfilling practice to take the position of a tested and effective solution have been made.

Head et al. (1996), Gray et al. (1997), Gray and Putnam (1996), and Gray and Atkinson (1995) are the papers that were presented during the course of the work on the project.

2. STABILITY OF THE GROUT MIX

2.1 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 tried, 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 also failed due to settling.

Another test done on a commercially available rotational viscometer (details of this viscometer are discussed in section 3.2.1 of the next chapter) gave proof that particles in the ash-water mix were settling. The viscometer used a T-bar spindle with the cross-bar length equal to 10.9 mm, mounted such that its axis of rotation was vertical. The spindle is driven by a synchronous motor through a calibrated spring; the deflection of the spring is a measure of the torque required to rotate the spindle. A beaker filled with the ash-water mix was placed such that the cross-bar on the T-bar was just submerged. The viscometer was mounted on a helical-path device which translates the spindle vertically up and down along its axis, while it rotates about its axis. The spindle was rotated at 2 RPM speed while it translated vertically downwards to a certain depth at a speed 22.2 mm per minute. After the cross-bar reached a certain depth in the beaker, it automatically started to rise to the initial position. Readings of the torque were recorded every 5 seconds. The spindle was allowed to move up and down for about 30 minutes. When the readings of torque 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 its path, as seen in Figure 2.1. The periodic behavior is due to the variation in the length of the submerged shaft, but the increase in amplitude over time is due to the

particles in the suspension causing the lower layers of the sample to become more concentrated than the upper layers. The 'flat' part on the curve at the last two 'peaks' was a result of exceeding the full-scale reading of the spring. The concentration of the solid particles varied with time and depth because of gravity settling. As the concentration of particles increases at the bottom of the grout mixture, friction develops between the solid particles, which acts as an additional resistance to its flow.

2.1.1 Maximum Spread Distances

The project goal is to fill an underground mine with FBC ash grout from the surface using as few injection holes as possible, since drilling holes will be a major expenditure in the project. Hence, the distance the grout may be made to flow is of direct importance to the project viability. It is anticipated that grout injected into the mine cavity through the mine roof, will spread under gravity, radially in a horizontal mine or down the dip in an inclined mine. Eventually the pile may contact the roof. At this point the flow will be driven in part by the pumping pressure. In either case, settling may reduce the maximum spread distance to such a degree as to render the project impractical.

Any fluid that has a yield stress (value of shear stress for less than which there is no movement of the fluid), with or without settling (unstable or stable respectively), when injected into a pipe or a closed channel with a finite pumping pressure, will eventually stop moving. Inevitably there will be a location downstream where the stress in the grout will fall below the yield stress. A plug will completely fill the pipe or channel and the flow will cease. For a grout with settling, Coulomb friction will further limit the extent of flow. The hardening of the grout has been neglected in this discussion because the time required for hardening is much longer than the time scale of the flow.

Lombardi (1985) used a balance of forces on a pressure driven grout which contacts the roof, and which has come to rest, to determine the maximum distance of spread for both stable and unstable grouts. These results have been corrected by Atkinson (1995) to describe the pressure gradient along a channel and the maximum flow distances.

Based on the pumping pressures and discharge rates of commercially available concrete pumps, maximum flow distances were calculated using the above mentioned solutions. A comparison of the cases when the grout is stable and unstable (with different friction coefficients) is presented in Table 2.1. The injection borehole is assumed to be 4 inches in diameter and 200 ft in depth. The yield stress of the grout is assumed to be 63 Pa, based on preliminary rheological testing of certain grout mixes. The results presented for unstable grouts show the cases when the coefficient of Coulomb friction (μ) is 0.1, 0.3 and 0.4.

Gage Pressure at Pump (atm)	Discharge Rates (Cu.m/min)	Pressure lost in Injection hole (.atm)	Maximum flow distance (m)			
			Stable Grout	Unstable grout		
				$\mu=0.1$	$\mu=0.3$	$\mu=0.4$
63.8	0.648	20.1	105	46	23	19
75.8	0.384	12.6	127	50	24	20
65.5	0.535	16.9	111	47	23	19
59.2	0.875	26.5	91	43	22	18
59.3	0.888	26.8	91	43	22	18
100.0	0.446	14.4	148	53	26	21
115.0	1.044	31.1	146	53	26	21
83.9	1.080	32.2	115	47	24	19
164.5	1.355	39.3	179	57	27	22

Table 2.1: Comparison of the maximum flow distances for stable and unstable grout mixes.

From the table it can be seen that the maximum flow distance can fall as much as 4-6 times in case of unstable grouts. An analytical model has been developed for gravity spread of the grouts by Gray et al. (1997). This work describes the maximum distance the grout will spread in case where the grout does not contact the roof.

2.1.2 Bleed Tests

A suspension can be classified as unstable when it shows either (1) settling as discussed earlier, or (2) bleed water, the supernatant water developed from a slurry after standing quiescent for two hours. In the case of grouts both these phenomena occur simultaneously.

Tests to measure the bleed of grout were done using methods similar to ASTM standard C232-87 (Test Methods for Bleed of Concrete). The weight of water being added to prepare grout mix was noted. Care was taken while mixing and transferring that no water spilled. These samples were placed in cylinders and were covered to prevent evaporation. After two hours of standing, any clear supernatant water that had bled to the surface was carefully pipetted out. Suspended ash also comes out with the water. This water was placed in a container and weighed. The container was then placed in an oven to evaporate all the water. Then the dry container with some ash is weighed. The difference of the two weights was the weight of the bleed water. This weight, expressed as a percentage of the weight of the water that went into the mix, gave the bleed percentage. Mixes with bleed percentage more than 5 were considered to be unstable (or, in other words, they do not meet the bleed criteria for stability).

Mixtures of ash and water only were unstable for the water fractions needed to make the mix

flow. To combat settling and bleed, various percentages of WYO-BEN 250 mesh bentonite were added to the grout mixes. The amount of bentonite added is expressed as a percent of the bentonite weight to the weight of ash in the mix and the amount of water as the percentage of the weight of water to the weight of the total mix. Hence, a 1000 gm grout mix with 7% bentonite and 48% water fraction contained 480 gm of water, 7% of 520 gm ($= 36.4$ gm) of bentonite and the remaining weight ($= 483.6$ gm) of ash. Bleed for 0%, 3% and 5% bentonite for various water-fractions is shown in Figure 2.2. This plot shows that the percentage of bleed increases almost linearly with an increase in water-fraction, while it decreases with an increase in the amount of bentonite. It was found that 5% bentonite mixes satisfied the bleed criteria for stability.

2.2 GROUT STABILIZATION

Though 5% bentonite mixes were behaving well with respect to the bleed water, settling was still a problem. Further rotational viscometer tests were carried out with ash-water-bentonite grouts with various bentonite fractions. The T-bar spindle in the rotational viscometer was moved vertically downwards at a constant rate from the top of the grout sample while rotating at a constant angular velocity. This was done twice for each sample, once immediately after stirring the mix to uniformity and again after allowing settling for a certain time (about 20 minutes). The torque increased as the spindle moved downwards in both cases, but the increase was greater in the second case. Assuming that no settling has occurred in the freshly stirred mix, the increase in the torque in this case can be attributed solely to the increase in the submerged length of the spindle. Subtracting the torques in the freshly stirred grout profile from the torques at the corresponding points in the second profile, gives residuals which show the presence of settling. The rate of increase of these residuals with depth

is a indicative of the degree of settling. Figure 2.3 shows a straight line fit for the torque difference versus a measure of depth for 48% water fraction grouts with 0% and 7% bentonite. The slopes of these lines are a direct representation of the degree of settling. As can be seen from the plot, the slope of the 7% bentonite mix is almost zero, indicating that the torques were not very different from the two readings. During the testing it was found that 7% bentonite mixes had the same consistency for long periods; until about the time (about one hour) when hardening started to set in. Hence this mix of 7% bentonite and 48% water fraction was selected for rheological testing.

A possible explanation for how bentonite reduces settling (*Driscoll, 1986*) is presented now. Bentonite is a clay whose particles are tiny in size (less than about 4 microns) and have large surface areas. The particles have a platelike structure; groups of these platelets are common. The edges of clay platelets are positively charged, whereas the flat surfaces are negatively charged. Because clay particles are so small, electrostatic charges govern their activity and they are strongly attracted or repulsed by each other and various other substances. Settling-preventing action of bentonite can arise from either such an action between the ash particles and the bentonite particles or from the situation where the electric forces between the bentonite particles overcome the gravity of the ash particles. It was also observed that the addition of bentonite to the grout reduced its flowability. The reason for this could be that clay particles generally swell when exposed to water because the electrically unbalanced water molecules are strongly attracted to the plate surfaces and thereby force the plates apart. This results in the clay particles occupying a larger space, which leads to a more viscous grout mix.

3. GROUT RHEOLOGY

3.1 LITERATURE REVIEW

3.1.1 Non-Newtonian Fluids

All those fluids for which the shear stress versus shear rate (flow) curve is not a straight line through the origin at a given temperature and pressure are said to be non-Newtonian. These materials are commonly divided into three broad groups, although in reality these classifications are often by no means distinct or sharply defined.

1. Time-independent fluids are those for which the shear rate at a given point is solely dependent upon the instantaneous shear stress at that point .

2. Time-dependent fluids are those for which the shear rate is a function of both the magnitude and the duration of the shear and possibly of the time lapse between consecutive applications of shear stress.

3. Viscoelastic fluids are those that show partial elastic recovery upon the removal of a deforming shear stress. Such materials possess properties of both fluids and elastic solids.

Time-independent non-Newtonian fluids are of interest here and are discussed at length. Typical flow curves are sketched in Figure 3.1. A logarithmic plot of the shear stress and shear rate for many non-Newtonian fluids is often found to be linear over a wide range of shear rate and this accounts for the widespread use of the following empirical equation :

$$\tau = k \gamma^m \quad (3.1)$$

where τ is the shear stress, γ is the shear rate, k is a constant called "consistency index" and m is another constant called "flow behavior index". m is the slope of the logarithmic plot. k is calculated

from the y-intercept (i.e., where $\ln(x)=0$) on the logarithmic plot. In general k is more sensitive than m to changes in temperature (Skelland, 1967). The examples of power-law fluids include rubber solutions, adhesives, soap and detergent slurries, paints, napalm, etc..

Several empirical and theoretical models have been proposed and used for time-independent non-Newtonian fluids with yield stress. The general form of the constitutive equation may be expressed as follows for simple parallel shear flow:

$$\begin{aligned} \gamma &= 0, & \tau &< \tau_y \\ \tau &= \tau_y + \eta_a \gamma & \tau &\geq \tau_y, \end{aligned} \quad (3.2)$$

where τ_y is the yield stress that must be exceeded to start the flow, and η_a is a characteristic viscosity describing the non-Newtonian flow. η_a may generally vary with shear rate, and as such, may be termed as the “ apparent plastic viscosity ”.

If η_a is constant ($= \eta_b$), the fluid is called a Bingham plastic (Bingham, 1922):

$$\tau = \tau_y + \eta_b \gamma \quad \tau \geq \tau_y. \quad (3.3)$$

This model predicts that when the yield stress τ_y is exceeded, the fluid flows with a viscosity η_b . A shear stress-shear rate (flow) curve for a Bingham plastic is linear, as can be seen in Figure 3.1. τ_y is the intercept of the line at zero shear rate and η_b is its slope. The Bingham model represents the ideal case in which the micro-structure that helps the material to resist irreversible deformation breaks down completely as soon as the applied shear stress exceeds the yield value.

Non-Newtonian fluids with yield stress that are not Bingham plastics may exhibit nonlinear flow behavior. Nonlinear flow behavior with a yield stress may be described by an empirical equation proposed by Herschel and Bulkley (1926). The apparent plastic viscosity for these fluids changes with the increase in shear rate. The empirical equation is a modified form of the equation 3.3:

$$\tau = \tau_y + k \dot{\gamma}^m, \quad \tau \geq \tau_y. \quad (3.4)$$

Here, k and m are constants, equivalent to the power-law parameters. For, $m = 1$ the equation reduces to the Bingham equation (3.2), and if $\tau_y = 0$, power-law behavior is obtained. The three-parameter Herschel and Bulkley model has been found applicable to a variety of non-Newtonian fluids with yield stress (*Bird et al., 1983*). Certain plastic melts, oil well drilling muds, ores, sand in water, coal, cement, aqueous thorium oxide slurries, grain water suspensions, chocolate mixtures, toothpaste and paper pulps are some examples of fluids with yield stress.

3.2 RHEOLOGICAL TESTING ON GROUT

3.2.1 Preliminary Testing

Initially on the project, experiments for the pressure drop across a tube were conducted using a capillary tube rheometer. The essential feature of this method is the measurement of the pressure drop associated with the laminar flow of fluid at a given rate through a long smooth, cylindrical tube of known dimensions. It can be shown (*Skelland, 1967*) that the flow curve for a fluid can be deduced from a series of such measurements.

Several capillary tubes with a range of lengths and diameters are needed. The ratio of tube length to diameter should be as large as conveniently possible (100-1000). The capillary tube is fastened to the base of a reservoir. Gas pressure is supplied to the reservoir which contains the non-Newtonian fluid and forces it through the capillary. A gage measures the pressure in the reservoir. A certain volume (about 25 cc) of the fluid is collected in a weighed receiver during a timed interval. Hence the volumetric flow rate is determined. Volumetric flowrates are measured for various gas pressures and dimensions of capillary tubes. This data can be reduced (*Skelland, 1967*) to determine

the flow parameters. In case of slurries and suspension where rapid settling is observed, this method is not very successful. In this project, the ash and water mix got locked up and there was no flow. Since setting was occurring, it was decided that capillary tube rheometry was not suitable for the testing on the grout.

Similar was the case with a parallel plate rotating rheometer. This instrument consists of two flat, horizontal plates nearly in contact with each other. The fluid sample is located in the small gap between the two plates. The flow curve can be constructed from measurements of the torque required to rotate one of the plates at various speeds. This method was not suitable for grout suspension since it was settling.

A concentric cylinder rotary viscometer was also tried. These instruments are designed to shear a fluid located in the annulus between two concentric cylinders, one of which is rotating while the other is held stationary. It can be shown (*Skelland, 1967*) that a series of measurements of the angular speed of the rotating cylinder and of the torque applied to the rotating cylinder can be interpreted to provide the flow curve for the material under shear. A variety of these instruments is commercially available.

A commercially available rotational viscometer, the *Brookfield Digital Viscometer LVDV-III*, was used to perform the rheological testing on grout. The principle of operation of this programmable viscometer is to drive a spindle (which is immersed in the test fluid) at a constant angular speed through a calibrated spring. The drag of the fluid against the spindle is measured by the spring deflection. The spring deflection is measured with a rotary transducer. The measuring range of this viscometer with a certain stiffness of spring is determined by the rotational speed of the spindle, the size and the shape of spindle, and the container the spindle is rotating in.

The torques on the inner cylinder were much higher than the maximum limit (674 dyne-cm) on the available rotational viscometer. The range of speeds at which the motor can be rotated is 0-250 RPM, in steps of 1 RPM, but usually the upper limit is that value for which the maximum torque reading is reached. Only one data point could be gathered at 1 RPM speed, as at higher speeds the torque limit on the viscometer was exceeded. Other rheometric methods were tried rather than procuring a rotational viscometer with a wider range of torque values.

The rotating cylinder in an "infinite" medium method was tried next. This is one of the simplest viscometers to use, being really a modification of the concentric cylinder viscometer in which the outer cylinder radius is extended effectively to infinity. The flow curve can be deduced from measurements of the torque required to rotate a cylindrical rod at various known speeds, when immersed in an "infinite" fluid. The fluid is contained in a beaker whose radius is much larger than the rod so the walls of the beaker exert no influence on the shearing movement of the fluid. The grout mix sample was placed in a beaker with an inner diameter about 10 cm. A cylindrical spindle serving as the inner cylinder of diameter 5 mm was attached to the rotational viscometer described above.

Some tests were conducted with this set up. It was observed that torque values fell sharply very soon after the spindle was started to rotate. On close observation it was found that slip developed between the rotating cylinder and the grout close to it. The slip was more obvious at higher speeds. A thin film of water seemed to separate the grout mix from the spindle. One option to counter the slip, though not completely, was to roughen the surface of the spindle by subjecting it to knurling. This idea was dropped in favor of using spindles other than the cylindrical ones.

3.2.2 Theory of the Mixer Viscometer Method Adapted For the Grout Rheology

A mixer viscometer method in which a rotating element is immersed in a sample of power law fluid was introduced by Metzner and Otto (1957). This method was adapted to testing fresh concrete by Tattersall and Bloomer (1979) who assumed a Bingham fluid law. This adaptation was extended to testing the grout assuming that it is a Hershel-Bulkley (HB) fluid (based on the work by Gupta, (1993)). The other two models - Bingham and power-law - are the special cases of the HB model, and, depending on the results for the various parameters and their values, an appropriate model can be assigned. The mixer viscometer method uses the slope and intercept of torque versus angular speed plot.

The basic principle of this method is that the torque T needed to maintain a constant rotational speed N is equal to N multiplied by the apparent viscosity (η_a) of the substance at the corresponding rate of strain and an instrument constant, say G :

$$T = G \eta_a N \quad (3.5)$$

For an HB fluid, the constitutive equation is given by equation 3.4:

$$\tau = \tau_y + k \gamma^m, \quad \tau \geq \tau_y. \quad (3.4)$$

and the apparent viscosity is defined by

$$\tau = \eta_a \gamma \quad (3.6)$$

Solving equations 3.4 and 3.6, for the apparent viscosity gives

$$\eta_a = \frac{\tau_y}{\gamma} + k\gamma^{m-1} \quad (3.7)$$

Further simplification requires that the rate of strain be related to the rotational speed. Skelland (1983) verified a simple assumption for numerous non-Newtonian fluids

$$\dot{\gamma} = KN \quad (3.8)$$

where K is another instrument constant. Substituting this relationship and equation 3.7 into equation 3.5, we obtain,

$$T = \frac{G\tau_y}{K} + GkK^{m-1}N^m \quad (3.9)$$

Taking natural logarithms on both sides, we get:

$$\ln \left(T - \frac{G\tau_y}{K} \right) = \ln (GkK^{m-1}) + m \ln (N) \quad (3.10)$$

A plot of the left hand side with $\ln(N)$ is a straight line which when extrapolated gives the value of torque axis intercept at $\ln(N)=0$. The line has

$$\text{slope} = m$$

$$\text{intercept} = \ln(GkK^{m-1})$$

here, G and K are computed from independent tests with fluids of known flow parameters. To calculate the left hand side of equation 3.10, we need to know the τ_y of the fluid. This can be obtained using the vane method of Nguyen and Boger (1992), using a Stormer viscometer. Thus the flow parameters m and k can be determined.

After a few tests were conducted by this method it was found that for a grout mix with 48% water fraction and 7% bentonite, the flow curve was very close to being a straight line with a non-zero intercept on the shear-stress axis. HB calculations gave a very small (almost zero) value for ' $m-1$ '. Hence it was decided that the said mix was behaving like a Bingham model fluid. In a

Bingham model fluid there are only two flow parameters, the yield stress τ_y and the apparent viscosity k , which is a constant (called plastic viscosity). The constitutive equation for a Bingham fluid is given by equation 3.3,

$$\tau = \tau_y + \eta_b \dot{\gamma} \quad \tau \geq \tau_y \quad (3.3)$$

Here, η_b refers to the same variable as k , so replace it with k . Following the steps of derivation for HB fluid, the equivalent of equation 3.9 for Bingham model will be

$$T = \frac{G\tau_y}{K} + GkN \quad (3.12)$$

The plot of torque versus angular speed is a straight line with

$$\text{Slope} = G.k$$

$$\text{Intercept} = (G\tau_y)/K$$

As the value of G and K are known, the values of k and τ_y can be determined. In this case the independent measurement of τ_y will serve as a verification for their method.

3.2.3 Mixer Viscometer Test Procedure

A variety of spindles were supplied along with the *Brookfield Digital Viscometer LVDV-III* viscometer. A T-bar spindle was selected for the rheological testing on the grout. The T-bar consisted of a shaft rod of 2 mm diameter filled with a cross-bar near one end of it, as shown in Figure 3.2. The other end has a threading to enable fastening this spindle to the viscometer. The cross-bar is a rod of 1 mm diameter and 10.9 mm length, welded symmetrically perpendicular to the shaft rod.

The viscometer is mounted on a helipath device. This mounting slowly raises and lowers the viscometer vertically at a rate of 22.2 mm/minute, while the T-bar spindle rotates in the sample material. The cross-bar of the spindle thus continuously cuts into fresh material, describing a helical path through the sample as it rotates. The "channeling" effect (i.e., the fall in the values of the torque required for rotation due to the spindle rotating in the previously cut path) of spindles rotating at same height within the sample is completely eliminated. The pitch of the helical path has to at least be greater than twice the diameter of the cross-bar to ensure that neither half-length of the cross-bar passes through previously cut layers. Since the vertical speed of the helipath mount is constant, the limit on the pitch is a limit on the angular speed of the spindle. Safely a maximum angular speed producing a pitch twice the minimum was used. A schematic of the viscometer set-up is shown in Figure 3.2.

A freshly prepared, well stirred, mix of grout was placed in a beaker with an inner diameter of about 10 cm and a height of 16 cm. The level of grout in the beaker was kept a few centimeters short of the brim of the beaker for all readings. The cross-bar of the T-bar spindle was immersed about 1 cm below the free surface of the grout. The helipath mount and the motor rotating the spindle were started at the same time. The spindle lowered into the grout and simultaneously rotated about its axis. The time measured on a stop watch was also a measure of the depth of the cross-bar in the grout, as the vertical speed of the mount was constant. The time reading was noted when the cross-bar reached about half the depth of the beaker. This time was used as a measure of length where readings were always taken. At the press of a key on the viscometer, the torque reading at that instant was stored in its memory. A fresh mix of grout was used for every set of data and the mix was stirred between every two readings to counter the effects of settling (if any). Torques could be

measured only for 1, 2, 3 and 4 RPM, for the reasons mentioned earlier in this section. The torque reading for these RPMs for various samples of the 48% water fraction and 7% bentonite grout were collected. A plot of the torque vs speed data is presented in Figure 3.3. The slope (B) and the intercept (A) of the torque versus the speed plot from the T-bar spindle test for 48% water fraction and 7% bentonite mix were found to be

$$\text{Slope (B)} = 32.921 \text{ dyne.cm/RPM}$$

$$\text{Intercept (A)} = 231.53 \text{ dyne.cm}$$

Using the methods described earlier, these data were used to determine τ_y and k .

3.2.4 Determination of the Instrument Constants G & K

The instrument constants G and K were determined by tests on standard fluids. The method of testing is similar to the one described in the last section. A Newtonian fluid was used to determine the value of the constant G, and another test was performed with a 10% bentonite slurry (a Bingham model fluid) to determine K.

The equivalent of equation 3.5 for a Newtonian fluid is:

$$T = G k N \quad (3.13)$$

here viscosity ' k ' for the standard fluid F500 supplied by *Brookfield* is 0.485 Ns/m^2 at 20°C .

The T-bar mixer viscometer experiment was conducted on the fluid and the slope of the T vs N plot was equated to ' $G.k$ '. As the value of ' k ' is known, the value of G can be found. The torque versus speed data for the standard fluid is presented in Figure 3.4.

The method adopted for determining 'K' is very similar, except that a Bingham fluid of known yield stress value was used here. Equation 3.12 is

$$T = \frac{G\tau_y}{K} + GkN \quad (3.12)$$

The torque intercept in a plot of torque versus speed (Figure 3.5) for a 10% bentonite slurry was equated to $G\tau_y/K$. The value of yield stress for a 10% bentonite slurry is 12.5 Pa at 20°C. Then, as G is known from the previous experiment, the value of K can be computed.

The values of G and K from independent measurements are as follows:

$$G = 0.0718 \text{ cm}^3$$

$$K = 0.168 \text{ (no units)}$$

3.2.5 Independent Yield Stress Measurement

The vane method of Nguyen and Boger (1992) was used to determine the yield stress of the grout mix. A Stormer viscometer with the rotating cylinder replaced by a four-bladed vane was used for this purpose. A vane method is a direct method of determining the yield stress of fluids. A vane comprises of an even number of blades located symmetrically around a shaft rod. The number of vanes typically ranges from four to eight. A known torque is applied to the shaft. This torque is increased gradually in small steps until the shaft in the grout overcomes the yield stress of the grout and the shaft just starts to rotate. When the shaft rotates the surface of the grout subject to shear is approximately equal to the total surface area of a cylinder having the length and diameter dimension of the vane. A balance of forces yields the following relationship between torque applied and yield stress τ_y ,

$$T = \frac{\pi}{2} d^3 \left(\frac{H}{d} + \frac{1}{3} \right) \tau_y \quad (3.14)$$

where H and d are the dimensions of the vane as shown in Figure 3.6.

The vane was submerged in a grout mix of 48% water fraction and 7% bentonite and the torque increased by small steps by increasing the weights suspended on a string that went around a drum connected to the spindle. As soon as the first movement of the spindle was observed, the loading was stopped. The weights suspended were weighed and torque on the spindle calculated. Using the relationship in equation 3.14, the yield stress was calculated. This was repeated for 5-6 times and an average of these readings was taken as the value of yield stress for the said grout mix. The yield stress (τ_y) from independent measurement using the vane method has been found to be equal to 54.8 Pa

3.2.6 Results and Uncertainties

The various results are summarized here. The slope (B) and the intercept (A) of the torque versus the speed plot from the T-bar spindle test for 48% water fraction and 7% bentonite mix were found to be

$$\text{Slope (B)} = 32.921 \text{ dyne.cm/RPM}$$

$$\text{Intercept (A)} = 231.53 \text{ dyne.cm}$$

The values of G and K from independent measurements are as follows:

$$G = 0.0718 \text{ cm}^3$$

$$K = 0.168 \text{ (no units)}$$

Using these values, the computed values of the flow parameters for the Bingham model are

$$\text{Plastic Viscosity (k)} = 0.0128 \text{ Ns/m}^2$$

$$\text{Yield stress } (\tau_y) = 55.38 \text{ Pa}$$

To calculate the uncertainty on these values, the methods described by Taylor (1982) were applied and the following uncertainties were obtained.

UNCERTAINTIES	
PARAMETER	UNCERTAINTY
A	1.1%
B	2.9%
k	4.6%
G	3.6%
K	5.2%
τ_y (intercept-method)	6.4%
τ_y (independent measurement)	0.5%

Table 3.1: Uncertainties for various parameters determined from the tests.

Hence, the results for a 48% water fraction and 7% bentonite mix can be reported as:

The plastic viscosity (k) $= 0.0128 \pm 0.0006 \text{ N.s/m}^2$

The yield stress (τ_y) (from extrapolation) $= 55.38 \pm 3.54 \text{ Pa}$

The yield stress (τ_y) (from ind. meas.) $= 54.8 \pm 0.3 \text{ Pa}$

The uncertainty range of the results from the mixer viscometer method are shown in the Figure 3.7.

The lower straight line shows the lower limit of the shear stress for the strain rates on the x-axis and the upper line shows the upper limit of the shear stress for those strain rates. Also shown in the figure is the uncertainty range of the yield stress from the independent vane test measurement. As can be seen this from figure, the range of values of yield stress from both the tests overlap and so are in agreement.

3.2.7 The Flow Curve

The torque versus angular speed data for the 48% water fraction and 7% bentonite grout mix was used to get its flow curve using the relationships, $\gamma = K.N$ and $\tau = \tau_y + k \gamma$. The flow curves for a few observed data from the T-bar mixer viscometer test have been plotted (Figure 3.8). The yield stress from the vane test also was measured for the same samples that were used for the T-bar test. The results from this test also are indicated in the flow curves in Figure 3.8. In all these plots, it can be observed that the independent measurement for yield stress serves as a good verification of the T-bar viscometer test. For all the plots, yield stress from the independent measurement fell within the uncertainty range of the yield stress from extrapolation.

An average of a few observations that were very close was calculated and a flow curve for these data were plotted (Figure 3.9). As can be seen here, the results from the two tests are consistent. Thus, the proposition that the 48% water fraction and 7% bentonite grout mix is a Bingham fluid for the strain rates on the tests, with flow parameters as presented, has been convincingly established for the range of shear rates tested.

The values of the strain rates in the lab were about 50 times lower than the highest strain rates that could be encountered at the site of actual injection in the field. As can be seen from the results of numerical simulations performed for parametric study of the plastic viscosity and yield stress, described in the next chapter, the grout flow is critically dependent on the value of its yield stress than its plastic viscosity. This comes a relief as it means that the slope and the apparent viscosity for the fluid are not as important as the yield stress for predicting its flow. Hence, the values of apparent viscosities at higher strain rates than those produced in the lab are not critical for the project.

4. NUMERICAL SIMULATIONS

Full-scale field injections were proposed to be performed towards the end of second phase of the project. These field injection tests are expensive and predictions of the mine-filling during such injections and in fact any future injections, were thus necessary. Bench-scale tests cannot simulate all the features (like the particle-size to the length dimension ratios) of the full-scale case. Also during the bench-scale tests problems were encountered due to the clogging of the pipeline at the similitude value of the flow rates. Computational predictions can be fairly accurate and are advantageous for their low cost and remarkable speeds. Configurations and parameters can be changed very easily and ideal situations can also be simulated.

Numerical simulations are very useful in performing parametric studies to study the effects of one or a set of parameters on the flow of grout. They have also been employed in studying the effects of the slopes of the floor on the mine-filling. Numerical simulations could provide a validation of the rheological properties used to describe the grout. This is done by comparing the results from the simulations with those from the field tests and bench-scale tests.

4.1 PHOENICS AND FINITE-VOLUME DISCRETIZATION

The present numerical simulations were performed on a PC version of the commercially available CFD software PHOENICS - version 2.0. The computer used had an Intel Pentium CPU operating at 90 MHZ, with a 500 MB hard disk, 16 MB RAM, and the MS-DOS operating system. PHOENICS is a general purpose Computational Fluid Dynamics (CFD) code that was developed at Imperial College in the U.K. by Ludwig, Qin, and Spalding (1989). PHOENICS solves fluid-flow

problems that can be described by differential equations of the form (for single-phase flows):

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho\phi \bar{V}) - \nabla \cdot (\Gamma_\phi \nabla \phi) = S_\phi \quad (4.1)$$

transient
convection
diffusion
source

- ϕ is the dependent variable to be computed
- ρ is the density of the medium
- $\bar{V}$ is the velocity vector (same as $\mathbf{V}$ in the text)
- Γ_ϕ is the diffusion coefficient
- S_ϕ is a source term

Equation 4.1, for $\phi = 1$ and $S_\phi = 0$ yields the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{V}) = 0 \quad (4.2)$$

similarly, $\phi = V$ yields the momentum equation and $\phi = T$ yields the energy equation, where $\mathbf{V}$ is the velocity vector and T the temperature.

These differential equations must be supplemented with boundary conditions and laws for the physical properties (constitutive laws). PHOENICS supplies a range of built-in options for both; but users can also append their own laws.

CFD methods transform differential equations such as the above into algebraic equations which are suitable for being solved through a computer program. PHOENICS uses the *finite-volume method* largely developed at Los Alamos National Lab (USA) and the Imperial College (London,

UK), in the late 60's and early 70's (*Patankar, 1980*).

Finite-volume methods can be thought of having three well-defined stages: discretization of the domain, integration of each differential equation for each cell to yield an algebraic equation, and solution of the resulting set of algebraic equations. The computational domain is discretized into a number of cells, which fill entirely the domain in which the fluid flows. PHOENICS can handle Cartesian, cylindrical-polar or Body Fitted Coordinate grids; and these can be one-dimensional, two-dimensional or three-dimensional. In transient problems, time must be also discretized into time intervals. The values of the flow variables at each cell and at each time-step are the outcome of the computation. PHOENICS uses a staggered grid arrangement, in which the velocity nodes are on the faces of the cell, and the scalar variables are calculated at the centroid.

The differential equation for each variable is transformed into an algebraic one at each cell by integration over the control volume. The results of the integration can be grouped in an algebraic equation involving values of flow parameters from the cell neighbors and from the previous time step. Such equations can be written for all the cells. The CFD problem is therefore, reduced to the solution of this system of interlinked algebraic equations. To solve these several levels of interlinkage, the CFD codes resort to iteration.

PHOENICS consists of two essential computer codes and two auxiliary ones. The essential ones are a pre-processor called SATELLITE and a processor called EARTH. The auxiliary ones are post-processors called PHOTON and AUTOPLOT.

SATELLITE is an interpreter. From instructions provided by the user it creates a data file containing instructions which EARTH can understand and obey. SATELLITE may receive its instructions from the user in the following ways:

- reading an instruction file called Q1, which the user has provided;
- receiving keyboard input during an interactive session with the user; and
- loading an instruction file from the PHOENICS input library.

SATELLITE also possesses two FORTRAN subroutines called SATLIT and GROUND. The former allows data-setting statements to be inserted by the user and the latter, an otherwise empty subroutine, came with a code called GREX3.FOR as the buyer requested it. By modifying GREX3.FOR, the solution method implementing various fluid models can be replaced by user-defined models.

EARTH contains the main flow-simulating software; it thus incorporates coding sequences which represent the relevant laws of physics applied to elements of material distributed in space and time. EARTH reads the data file provided by SATELLITE and executes the corresponding computations; it then produces an output file called RESULT, which the user can read, and also (when so instructed) a file of results called PHIDA, which can be read by the post-processors PHOTON or AUTO PLOT, or by EARTH itself when a new run is started with a part of these results as the initial conditions. While AUTO PLOT simply plots the values of one variable versus the other, PHOTON is a more advanced graphics package, where perspective views of the flows can be depicted.

PHOENICS has two built-in methods for tracking a moving interface between two fluid phases during a transient flow simulation. The two methods are the Scalar Equation Method (SEM), and the Height of Liquid method (HOL). Both are coded within the GREX3.FOR subroutine, and may be activated by making the appropriate setting within the Q1 file. Both SEM and HOL methods treat the flow as one phase. The methods permit fluid properties such as density and viscosity to vary

throughout the domain to represent the spatial distribution of the two phases.

Height of Liquid Method : In a rectangular mesh of cells of width δx and height δy one might define the vertical height, h , of the free boundary above the bottom of the mesh in each column of cells. This would approximate a curve $h=f(x,t)$ by assigning values of h to discrete values of x (Hirt and Nichols, 1979). This method does not work well when the boundary slope, dh/dx , exceeds the mesh cell aspect ratio $\delta y/\delta x$, and does not work at all for multiple-valued surfaces having more than one y value for a given x value. This is a severe limitation because many simple shapes, such as bubbles or drops, cannot be treated. However, when it can be used, this representation is extremely efficient, requiring only a one-dimensional storage array to record the surface height values. Likewise the evolution of the surface only requires the updating of the one dimensional array.

In the case of a free fluid boundary, the time evolution of the height function is governed by a kinematic equation expressing the fact that the surface must move with the fluid,

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} = v \quad (4.3)$$

where, (u,v) are fluid velocity components in the (x,y) coordinate directions. It should be noted that the above equation is Eulerian in the horizontal direction, but Lagrangian-like in the vertical direction, which is more or less normal to the surface. Finite difference approximations to this equation are easily made. The height function method is directly extendable to three-dimensional situations for single-valued surfaces describable by, e.g. $h=f(x,y,t)$.

Scalar Equation Method : The SEM simulates the transient convection of a scalar variable throughout the simulation domain. Markers are spread all over the fluid-occupied regions with markers in each cell specified to move with the fluid velocity at that cell location. If ' ϕ ' represents

the value (between 0 and 1) of this massless marker variable, then it would be transported according to the following convection equation,

$$\frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} + v \frac{\partial \phi}{\partial y} + w \frac{\partial \phi}{\partial z} = 0 \quad (4.4)$$

where,

ϕ is the marker scalar variable

u, v, w are the velocity components in the x, y, z directions

Clearly, storage requirements increase significantly with this method because of the large increase in the point coordinates that must be stored. Surfaces are defined as lying at the boundary between regions with marker variable values zero and one. The actual location of the free surface is determined by interpolation of the variable values in these cells. SEM method offers the advantage of eliminating all logic problems associated with intersecting and overturning surfaces.

4.2 TWO-DIMENSIONAL SIMULATIONS

Two-dimensional simulations were performed as the preliminary work for more realistic three-dimensional simulations. Two-dimensional simulations were particularly useful to determine the domain size and computational information like the grid time steps and convergence criteria. Two-dimensional simulations were very useful in performing sensitivity analysis for the flow parameters and to study the effects of the slopes in the mine floor on the mine-filling.

4.2.1 Two-dimensional Numerical Model

A transient 2D axi-symmetric model was prepared to simulate the mine filling in a lengthwise vertical section of the mine passage way. Though the height of the passageway in the mine was about 1.5 m and the distance between intersections was varying from 10 m to 15 m, the numerical domain was made only 0.5 m in height and 1 m in length as the preliminary simulations showed the grout did not fill up to the roof, but was filling to about one-thirds of the height during its horizontal spread of one passageway length. The grout inlet at the site is from the roof top. An attempt to simulate this failed as there was flow segmentation at the inlet, due to slower flow velocities in the pipe than the velocities of free fall. Hence the grout inlet had to be placed just above the flow, simulating a case where the inlet pipe extended all the way down to a height above the floor equal to one-fourth of the diameter of the pipe.

The domain, inlet and boundary conditions are as shown in figure 4.1. The flow rates at the field injection site were about 30.5 m³/hr. Dividing this by the area of the injection pipe, with a 4 inch diameter, will give an inlet velocity of 0.0254 m/s. Referring to Figure 4.1, the inlet velocity was set to 0.0254 m/s in the -z direction. The left boundary had the axisymmetric line-of-symmetry condition, the right boundary and the roof had the open-outlet condition, the floor had the no-slip wall conditions. A non-uniform grid with 5 cells in the z direction and 10 cells in the y direction was fit to the domain. The cell sizes increased in a geometric progression of common ratio 1.5 in both z and y directions. This was used to get greater resolution at the inlet and near the floor. A time step of 0.01 s was used for numerical convergence. All these settings are made in the Q1 file. The physical and flow properties of the grout used in the model were derived from the results of rheological testing in the previous chapters. The fluid model was set to the Bingham model. The density of the grout was set to 1680 kg/m³, the plastic viscosity to 0.0128 Pa.s and the yield stress to 54.8 Pa.

The value of acceleration due to gravity was set to 9.81 m/s in the -z direction in all the simulations except in the simulations done to study the effect of slopes in the mine floor on the flow, where the gravity vector was at a angle with the -z direction. The components of gravity in the latter case were calculated according to the direction of the slope. Preliminary runs showed that about 10 iterations per time step were sufficient for convergence of the numerical scheme. The results were saved at equal intervals of time, typically every one second. The Q1 file with all the settings is shown below. The CPU time for a simulation of 50 s of the flow time was about 25 min.

The Q1 input file for 2D simulations

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
GROUP 1. Run title and other preliminaries
TEXT(Real Grout Props. Bingham model.)
TITLE
REAL(vin,vmax,length,delz,dely,height)
REAL(time,delt,dtpnt,steps,flsfact)
```

Define an inlet velocity that gives a flowrate within range of available concrete pumps. Goal is (0.0127) m³/s (60 cu.yds/hr). Patch the inlet bc to the first z-column of cells. This simulates an inlet pipe radius = the y-dimension of the first y-cell. If the number of y-cells changes, the inlet velocity must be updated.

```
length=1.0 ; ny=10 ; dely=length/ny ; nx=1
height=0.2 ; nz=5 ; delz=height/nz
vin= 0.0127 / (3.1415927*dely*dely*16)
time=10
```

```
An "estimate" for the time step is:  delt = delz/vin
delt=0.01
steps = time/delt
```

```
dtprnt=1./delt  
time  
steps  
delt  
dtprnt
```

GROUP 2-5. Grid specification

```
steady=f  
lstep=steps  
grdpwr(t,lstep,time,1.0)
```

```
cartes=f  
xulast=0.0872664  
grdpwr(y,ny,length,1.5)  
grdpwr(z,nz,height,1.5)
```

GROUP 7. Variables stored, solved & named

```
store(den1,prps,enul)  
solve(vfol,surn,genk)  
solutn(pl,y,y,y,n,n,n)  
solutn(vl,y,y,n,n,n,n)  
solutn(wl,y,y,n,n,n,n)
```

GROUP 8. Terms (in differential equations) & devices

```
gala=t  
terms(vfol,n,n,n,n,p,p)  
terms(surn,n,n,n,n,p,p)  
difcut=t  
surf=t  
genk=t
```

GROUP 9. Properties of the medium (or media)

```
** Properties may be read from PROPS file if grnd10 is  
** Fluid #68= non-newt fluid
```

** Fluid #0 = air @ STP

```
rho1=grnd10 ; enul=grnd5
enula=7.6e-6 ; enulb=0.0329
iprpsa=68 ; iprpsb=0
```

GROUP 11. Initialization of variable or porosity fields

```
fiinit( p1 )=0.0 ; fiinit( w1 )=0.0
fiinit( v1 )=0.0 ; fiinit(surn)=0.0
fiinit(den1)=1.2
iniadd=f
```

GROUP 13. Boundary conditions and special sources

```
patch(iflo,high,1,nx,1,1,2,2,1,lstep)
coval(iflo,p1,fixflu,vin*1683)
coval(iflo,v1,onlyms,0.0)
coval(iflo,w1,onlyms,-vin)
coval(iflo,surn,fixflu,vin)
coval(iflo,vfol,onlyms,1.0/1683)
patch(gravity,phasem,1,nx,1,ny,1,nz,1,lstep)
coval(gravity,w1,fixflu,-9.76)
coval(gravity,v1,fixflu,0.98)
```

```
outlet(outr,north,1,nx,ny,ny,1,nz,1,lstep)
value(outr, p1 ,0.0)
wall(bottom,low,1,nx,1,ny,1,1,1,lstep)
wall(roof,high,1,nx,1,ny,nz,nz,1,lstep)
wall(bloc,low,1,nx,1,3,3,3,1,lstep)
wall(bloc2,north,1,nx,3,3,3,nz,1,lstep)
```

```
patch(tcon,cell,1,nx,1,ny,1,nz,1,lstep)
coval(tcon,surn,grnd,grnd)
```

GROUP 15. Termination of sweeps

```
lsweep=10 ; liter(surn)=1
```

GROUP 16. Termination of iterations

```
resref(p1)=1.e-6 ; resref(v1)=1.e-4 ; resref(w1)=1.e-4  
resref(surn)=1.e-4
```

GROUP 17. Under-relaxation devices

```
varmin(surn)=0.0 ; varmax(surn)=1.0  
relax(p1,linrlx,0.25)
```

HINT: proper false time step should be within .01 to 1000 times
the variable "flsfact"

```
flsfact=delz/vin  
relax(v1,falsdt,0.1*flsfact); relax(w1,falsdt,0.1*flsfact)
```

GROUP 19. Data communicated by satellite to GROUND

```
idispa=dtprnt ; csg1=z ; inifld=f ; SURF=T  
rlolim=0.40 ; ruplim=0.60  
idispa
```

GROUP 22. Spot-value print-out

```
echo=f;ntprin=1step/2  
nprmon=1sweep;iymon=ny/2;ixmon=1 ;izmon=1  
tstswp=10
```

GROUP 23. Field print-out and plot control

```
output( p1 ,y,n,n,n,y,y); output( v1 ,y,n,n,n,y,y)  
output( w1 ,y,n,n,n,y,y); output(vfol,y,n,n,n,n,n)  
output(den1,y,n,n,n,n,n); output(surn,y,n,n,n,n,n)  
output(genk,y,n,n,n,n,n)  
STOP
```

4.2.2. Sensitivity Study for Flow Parameters

An interesting result from the rheological point of view was the sensitivity of the grout flow to plastic viscosity and yield stress. The numerical simulation on the computer was an ideal option

to conduct this analysis. The values of plastic viscosities and yield stresses could be changed as wished just by changing the settings in the Q1 file.

The same physical and numerical model described in the previous section was used to conduct the sensitivity analysis. Five sets of simulations were conducted with real inlet speeds (0.0254 m/s) and the simulations were continued till 50 s of injection was simulated.

SET I : Real (experimentally calculated) values were assigned for the flow parameters

Simulation 1: Real plastic viscosity value ($= 0.0128 \text{ Pa.S}$) ; real yield stress value ($= 54.8 \text{ Pa}$)

SET II : The plastic viscosity values were increased by powers of 10 and yield stress held constant.

Simulation 2: Plastic viscosity $= 10 * (\text{real value})$; real yield stress value

Simulation 3: Plastic viscosity $= 100 * (\text{real value})$; real yield stress value

Simulation 4: Plastic viscosity $= 1,000 * (\text{real value})$; real yield stress value

Simulation 5: Plastic viscosity $= 10,000 * (\text{real value})$; real yield stress value

SET III : The plastic viscosity values were decreased by powers of 10 and yield stress held constant.

Simulation 6: Plastic viscosity $= 0.1 * (\text{real value})$; real yield stress value

Simulation 7: Plastic viscosity $= 0.01 * (\text{real value})$; real yield stress value

Simulation 8: Plastic viscosity $= 0.001 * (\text{real value})$; real yield stress value

Simulation 9: Plastic viscosity $= 0.0001 * (\text{real value})$; real yield stress value

SET IV: The plastic viscosity values were held constant and yield stress values were increased by multiples of 10.

Simulation 10: Real plastic viscosity value ; yield stress $= 10 * (\text{real value})$

Simulation 11: Real plastic viscosity value ; yield stress $= 20 * (\text{real value})$

SET V : The plastic viscosity values were set to zero and the yield stress values were increased by

multiples of 10.

Simulation 12: Plastic viscosity = zero ; yield stress = 10 * (real value)

Simulation 13: Plastic viscosity = zero ; yield stress = 20 * (real value)

Simulation SET I was the simulation of the real case with the values of flow parameters set to the values calculated from the rheological testing. The top most plot on figure 4.2 is the position of the free surface of the grout after an injection for 50 s.

In simulation SET II, plastic viscosities were incremented by the powers of 10 until 10,000 times the real value, holding the yield stress constant at the real value. Figures 4.2 and 4.3 have the plot of results. In SET III the plastic viscosities were decreased by powers of 10 till 0.0001 times the real value. Figures 4.4 and 4.5 show the plot of the corresponding results. The spread decreased and height increased as the plastic viscosity increased and vice-versa. The spread distance versus the plastic viscosity plot of Figure 4.8 shows the above trend.

In SET IV, the yield stress values were increased by 10 and 20 times, holding the plastic viscosity constant. From the result in Figure 4.6, it could be observed that an increase of 20 times in yield stress at real plastic viscosity had a similar effect on the flow as was when the plastic viscosity was increased 10,000 times at constant yield stress. This observation shows that the flow of grout is more critically sensitive to its yield stress than to its plastic viscosity.

SET V was encouraged by the previous results. Now the plastic viscosity was set to zero and the yield stress values were incremented 10 and 20 times. The results (Figure 4.7) here were not much different from the results of SET IV, which strengthens the conclusion made above.

Two graphs (Figures 4.8 and 4.9) summarize the results from above observations of the

sensitivity of the spread distance to the fluid flow parameters.

4.2.3 Studying the Effects of Slope in the Mine Floor

A qualitative study of the effect of slopes in the mine floor on the mine filling was very easily achieved using the 2D numerical simulation on the computer. The same numerical and physical model described in section 4.2.1 was used for these simulations, except for the following changes:

- The axi-symmetric setting was changed to Cartesian setting,
- The acceleration due to gravity vector was no longer in the $-z$ direction, but was at an angle to it. This angle was calculated based on the slope on the floor. The acceleration due to gravity vector was resolved into two components along the z and y axes.

These above settings are also made in the Q1 file. Simulations were conducted for upslope and downslope flow of grout in 4%, 6%, 8% and 10% dip cases.

The results (figures 4.10, 4.11, 4.12, 4.13) show an expected behavior. The spread increases with increase in slopes downslope and decreases with increase in slopes upslope. The arrows in these figures are the velocity vectors of the two fluids (air and grout) at the cell centers. A graph (Figure 4.14) summarizing the effects of slope on the flow distance both upslope and downslope has been plotted. Clearly, the slope on the mine floor causes the flow to be predominant in the direction of the dip. The effect could be that the grout will never stop flowing as shown by Gray et al. (1997).

4.3 THREE-DIMENSIONAL SIMULATIONS

The ultimate purpose of using numerical simulations was to get a complete three dimensional mine filling simulation. Though this problem turned out to be too ambitious for the PC that was being

used, partial three dimensional simulations were achieved.

4.3.1 The BFC Grid

A body fitted coordinate (BFC) or curvilinear grid was fitted to a domain that represented one-eighth of a mine intersection and passageways (Figure 4.15). A curvilinear grid is best imagined by supposing that a regular Cartesian grid is embedded in a jelly-like medium, which is then squeezed, stretched, bent and twisted in an arbitrary way. All the cells which were originally in contact with one another remain so; but their shapes may have changed considerably.

Curvilinear grids are most often used for flow simulations where the grid must conform to the curved surface of some solid body; hence they are referred to as body-fitted-coordinate grids. In GridMenu, the process of specifying a BFC grid follows this general procedure:

1. Some points, defining the key features of the computational domain (such as the outer boundaries), are specified in terms of their Cartesian coordinates.
2. Points are joined by lines, which are divided into segments corresponding to the number of cells which lie along the line.
3. Lines are linked to make 2D frames which have a point (defined above) at each corner (frames are topologically 2D, but corner points need not be co-planar).
4. A 2D grid plane is then matched to the frame.
5. 2D grid planes are linked to form a 3D grid.

4.3.2 The 3D Numerical Model

Figure 4.16 shows the BFC grid that was fit to the domain using the PHOENICS GRIDMENU preprocessor. The grid has 8x10x25 cells in the x, y and z directions (in the curvilinear

coordinate system) respectively, shown in the figure. The length of the domain runs from very close to the injection point to about half the length of the passageway. The outline in the figure marks one-eighth of the actual mine geometry. The numerical domain is of the height 1.0 m in contrast to 1.7 m height of the domain. This was done to reduce unnecessary computational space as it was known from the 2D simulations that grout does not build up to those heights for a spread about the length of the domain. The flow rates at the field injection site were about 30.5 m³/hr. This translated to a inlet velocity of 0.01 m/s through the inlet cells marked in Figure 4.12, in the -z direction.

Open outlet boundary conditions were applied to the wall marking the end of domain in the -z direction and to the roof, and no-slip boundary conditions to the parallel section of the wall normal to +x axis and to the floor. All other walls are no-slip boundary conditions. By trial it was found that for a time step of 0.01 s the simulation converged.

A Bingham fluid model was used with values of plastic viscosity equal to 0.0128 Pa.s and yield stress equal to 54.8 Pa. The density of the grout was set as 1680 kg/m³. The acceleration due to gravity was set to 9.81 m/s in the -y direction. The Scalar Equation Method (SEM) scheme was used for free surface tracking. For this model, the PC spent about 1000 seconds to simulate one second of injection.

The Q1 input file for 3D simulations is as follows

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
GROUP 1. Run title and other preliminaries
TEXT(Bingham Model fit; 3D BFC Simulation)
TITLE
```

```

REAL(vin,vmax)
REAL(time,delt,dtprnt,steps,flsfact)
      * for injection rates of 40 yd**3/hr, the 'vin' in this
      file
      * will be 0.01 m/s.
vin= 0.01
time=10
      An "estimate" for the time step is:  delt = delz/vin
delt=0.01
steps = time/delt
dtprnt=1./delt
time
steps
delt
dtprnt

```

GROUP 2-5. Grid specification

```

steady=f
lstep=steps
grdpwr(t,lstep,time,1)
      * Overall number of cells, RSET(M,NX,NY,NZ,tolerance)
RSET(M,8,10,25)
      * Overall domain extent, RSET(D,name,XULAST,YVLAST,ZWLAST)
RSET(D,CHAM,2.743E+00,1.000E+00,1.000E+00)

```

Group 6. Body-Fitted coordinates

```

BFC=T
      * Set points
GSET(P,P1,0.0000E+00,0.0000E+00,2.2430E+00)
GSET(P,P2,3.5400E-01,0.0000E+00,2.3890E+00)
GSET(P,P3,2.7430E+00,0.0000E+00,0.0000E+00)
GSET(P,P6,0.0000E+00,0.0000E+00,0.0000E+00)
GSET(P,P7,0.0000E+00,1.0000E+00,2.2430E+00)
GSET(P,P8,3.5400E-01,1.0000E+00,2.3890E+00)

```

```

GSET(P,P9,2.7430E+00,1.0000E+00,0.0000E+00)
GSET(P,P12,0.0000E+00,1.0000E+00,0.0000E+00)
GSET(P,P14,2.0061E-01,-1.1613E-03,2.2303E+00)
GSET(P,P15,2.0061E-01,9.8550E-01,2.2303E+00)
    * Set lines/arcs
GSET(L,L1,P1,P7,1,1.0)
GSET(L,L2,P8,P2,1,1.0)
GSET(L,L3,P2,P3,10,1.0)
GSET(L,L4,P8,P9,10,1.0)
GSET(L,L11,P12,P7,10,1.0)
GSET(L,L12,P6,P1,10,1.0)
GSET(L,L13,P9,P3,1,1.0)
GSET(L,L14,P12,P6,1,1.0)
GSET(L,A18,P7,P8,8,1.0,ARC,P15)
GSET(L,A19,P1,P2,8,1.0,ARC,P14)
GSET(L,L20,P9,P12,8,1.0)
GSET(L,L21,P6,P3,8,1.0)
    * Set frames
GSET(F,F3,P7,-,P8,-,P9,-,P12,-)
GSET(F,F4,P1,-,P2,-,P3,-,P6,-)
    * Match a grid mesh
GSET(M,F3,+I+K,1,11,1,TRANS)
GSET(M,F4,+I+K,1,1,1,TRANS)
    * Copy/Transfer/Block grid planes
GSET(C,J11,F,J1,1,8,1,10,+,0,1,0,INC,1)
GSET(C,K26,F,K11,1,8,1,10,+,0,0,-5.2570E+00,INC,1)
NONORT =      T
    GROUP 7. Variables stored, solved & named
store(den1,prps,enul)
solve(vfol,surn,genk)
solutn(pl,y,y,y,n,n,n)
solutn(v1,y,y,n,n,n,n)
solutn(w1,y,y,n,n,n,n)
solutn(u1,y,y,n,n,n,n)

```

GROUP 8. Terms (in differential equations) & devices

```
gala=t
terms(vfol,n,n,n,n,p,p)
terms(surn,n,n,n,n,p,p)
difcut=t
surf=t
genk=t
```

GROUP 9. Properties of the medium (or media)

** Properties may be read from PROPS file if grnd10 is

** Fluid #68= non-newt fluid

** Fluid #0 = air @ STP

```
rho1=grnd10 ; enul=grnd5
enula=7.6E-06 ; enulb=0.0329
iprpsa=68 ; iprpsb=0
```

GROUP 11. Initialization of variable or porosity fields

```
fiinit( p1 )=0.0 ; fiinit( w1 )=0.0
fiinit( v1 )=0.0 ; fiinit(surn)=0.0
fiinit(den1)=1.2 ; fiinit(prps)=0.0
fiinit( u1 )=0.0
iniadd=f
```

GROUP 13. Boundary conditions and special sources

```
patch(iflo,south,1,8,2,2,2,2,1,1step)
coval(iflo,p1,fixflu,vin*1683)
coval(iflo,v1,onlyms,-vin)
coval(iflo,u1,onlyms,0.0)
coval(iflo,w1,onlyms,0.0)
coval(iflo,surn,fixflu,vin)
coval(iflo,vfol,onlyms,1.0/1683)

patch(grav,phasem,1,nx,1,ny,1,nz,1,1step)
```

coval(grav,v1,fixflu,-9.81)

outlet(outr,low,1,8,1,10,25,25,1,1step)
value(outr,p1,0.0)

wall(roof,north,1,8,10,10,1,25,1,1step)
wall(floor,south,1,8,1,1,1,25,1,1step)
wall(wall1,west,1,1,1,10,1,25,1,1step)
wall(wall2,high,1,8,1,10,1,1,1,1step)
wall(wall3,east,8,8,1,10,1,25,1,1step)

patch(tcon,cell,1,nx,1,ny,1,nz,1,1step)
coval(tcon,surn,grnd,grnd)

GROUP 15. Termination of sweeps

lsweep=10 ; liter(surn)=1

GROUP 16. Termination of iterations

resref(p1)=1.e-4 ; resref(v1)=1.e-4; resref(w1)=1.e-4
resref(surn)=1.e-4

GROUP 17. Under-relaxation devices

varmin(surn)=0.0 ; varmax(surn)=1.0
relax(p1,linrlx,0.001)

HINT: proper false time step should be within .01 to 1000 times
the variable "flsfact"

flsfact=0.2
relax(v1,falsdt,0.01); relax(w1,falsdt,0.01)
relax(u1,falsdt,0.01)

GROUP 19. Data communicated by satellite to GROUND

idispa=250 ; csg1=1 ; inifld=f ; SURF=T
rlolim=0.40 ; ruplim=0.60
idispa

GROUP 22. Spot-value print-out

```
echo=f;ntprin=1step/2
nprmon=1sweep;iymon=1;ixmon=4 ;izmon=2
tstswp=10
```

```
GROUP 23. Field print-out and plot control
output( p1 ,y,n,n,n,y,y); output( v1 ,y,n,n,n,y,y)
output( w1 ,y,n,n,n,y,y); output(vf01,y,n,n,n,n,n)
output(den1,y,n,n,n,n,n); output(surn,y,n,n,n,n,n)
output(genk,y,n,n,n,n,n); output( u1 ,y,n,n,n,y,y)
STOP
```

4.3.3 The 3D Simulation Results

The inlet velocities were initially set to values that matched those at the field injection tests. However these proved very slow for the computer. As stated earlier the CPU time to the simulated time ratio was 1000:1, which implied that the computer would spend about 9,000,000 seconds (or 2,500 hrs or about 104 days) to simulate the injection for 2.5 hr, which is approximately the time the grout will take to flow considerably into the passageway from the point of injection. Besides, such slow rates of flow resulted in convergence problems. Such an impracticality meant that the injection rates had to be increased in the numerical model. A five times higher inlet velocity was adopted to get near-reality simulations of the mine-filling. Now the grout would take about 0.5 hr to reach the position mentioned above. This simulation was conducted in 20 batches of 90s simulation for each of which the computer spent approximately one day. On the whole about 25 days (not continuously) were spent, including the time spent on restarts to obtain this 3D simulation.

It was feared that if the grout built up to the roof before it would move out radially, the flow would become a pressure-driven flow and as the pumping pressures are finite and small compared

to the resistance, total spread would be dramatically reduced. This would mean that more pumping holes would have to be drilled, leaving the project uneconomic. Figures 4.17, 4.18, 4.19, 4.20 and 4.21 show the position of the grout after 530 s, 835 s, 1350 s, 1575 s and 1850 s respectively, after the start the injection. After, about 20 minutes from the start of the injection the grout reached the passageway. The change in the direction of the velocity of the grout when it hit the pillar was a smooth one as the speeds were very low. The major observation in these simulations is that the grout does not build up to the roof of the mine for the distances of the flow seen here.

In contrast to the simulations performed earlier in the project by Atkinson (1995), the simulations performed here used more realistic values for flow properties of the grout and flow rates. Slower speed of flows meant that the time steps of simulations must be kept low to capture the movement of the grout in the huge domain. But the number iterations for the numerical convergence decreased.

5. BENCH-SCALE AND SPREAD TESTS

5.1 BENCH-SCALE INJECTION TESTS

After the rheological parameters were determined for the grout mix that was adequately stable and flowable, the next step in the project was to predict how the grout of this recipe would fill the mine cavity. Two methods were selected to make this prediction. The first was to model the mine geometry and simulate the injection process on a computer using a CFD code, as discussed in chapter 4. The other method was to perform a bench-scale injection into a model that approximately represented the mine geometry. Results from the bench-scale model injection could be used to validate the computer simulations. Geometries in both these methods were based on a section of the Fairfax mine in Preston County, West Virginia.

5.1.1 Experimental Setup

A typical section of the Fairfax mine site was modeled using wood and plexiglas. The geometry of the underground mine is known. It is of high irregularities, so simplifications and assumptions were needed to facilitate the construction of the model box. Figure 5.1 shows the actual mine plan view for the section and the idealization of this geometry according to which the box was constructed. The mine is a series of interconnecting passageways with pillars of unremoved coal. The pillars range in size from 10 m to 25 m per side at this site. The seam of the mine averages 152 cm (5 ft) in height and the passageway 5.49 m (18 ft) in width. The mine floor has a dip of 1-2%, sloping in the east-to-west direction. The location in the mine on which the box is based was a site proposed for a field injection test. However, at the time of the field injection test, the injection

borehole was moved by about 200 ft to a nearby location. The direction of dip is also indicated here. The model to prototype length ratio was 1 : 36, except for the model injection hole diameter. A 46"x 46"x 2" box was constructed with wood. A schematic of this box with dimensions is shown in the Figure 5.2. A plexiglas sheet was used as the roof to enable observation and video recording. Air pressure was used to pump the grout into this box. An acrylic cylinder 14" in height and 6" in diameter served as the grout reservoir, and an inlet valve for air and an outlet valve for the grout made up the pump. A transducer attached, showed the pressure inside the cylinder. The typical pressures used were around 1 atm gage pressure. The cylinder was connected to the top of the box by a ½" diameter polyethylene pipe with a globe valve in the line to regulate flow. This made the injection hole ½" in diameter (equivalent to 18" in the prototype that actually was 4"), which is out of the scale of similitude. The injection hole was at the intersection of two passageways. The portion of the lateral boundary of the box where the passageways intersected it were left open to let the grout flow out when it reached the boundary. The pneumatic cylinder was filled with grout and pressure increased till the required flow rates were achieved. The cylinder was refilled after the entire grout was pumped into the box. This was done for two injection tests, one when the box was horizontal and the other when box had a dip of 4% in a direction shown in the figure 5.2. The injection continued until grout first flowed out of the box.

5.1.2 Flow Parameters

A practical basis for similitude in models where gravitational and viscous forces dominate is equating of viscous/gravity forces ratios of prototype and model.

$$\frac{V_m v_m}{gL_m^2} = \frac{V_p v_p}{gL_p^2} \quad (5.1)$$

Where, L is the characteristic length; V is the characteristic velocity and v is the kinematic viscosity of the fluid, and the subscripts 'm' and 'p' mean indicate that parameter is for the model and prototype respectively. A match of this ratio results in velocity in model to velocity in prototype ratio of 1 : 1296, i.e., the velocities in the model need to be of the order of 10^{-3} m/s which is not practicable. And since the gravity forces are relatively more dominant than the viscous forces, the Froude numbers for the prototype and the model were matched and not the Reynolds numbers. When the Reynolds numbers are matched:

$$\frac{L_m V_m}{v_m} = \frac{L_p V_p}{v_p} \quad (5.2)$$

As $v_m = v_p$, equation 5.1 reduces to

$$\frac{V_p}{V_m} = 36, \text{ as } \frac{L_m}{L_p} = 36 \quad (5.3)$$

Velocities at the prototype were at the order of 1 cm/s, and this reduced by 36th, reduced the order two times to the order of 0.1 mm/s, which is very difficult to setup experimentally. While a match of Froude numbers:

gives,
$$Fr = \left(\frac{V}{\sqrt{gL}} \right)_{model} = \left(\frac{V}{\sqrt{gL}} \right)_{prototype} \quad (5.4)$$

$$\frac{V_p}{V_m} = 6 \quad (5.5)$$

Figure 5.3 is a depiction of the position of the grout with time for the horizontal case. Figure 5.4 is a similar one for the 4% dip case. The spread for the test with the box horizontal was uniform; i.e., approximately equal lengths with time in all the four directions, as can be seen in the Figure 5.3. As can be observed from the comparison, the dip of 4% has a significant effect on the predominant direction of flow. This, as can be seen in the next chapter, very well predicted the predominant direction of flow for the field injection test.

The box injection also predicts that the grout will fill to the roof after it flows for some distance in each direction. Then the situation is similar to a closed-pipe flow conditions where the flow would be pressure-driven. This predicts that the pumping pressures must be more than that required just to force the flow through the pipeline and the borehole. Analytically, there would be a maximum distance a pump of given pumping pressure can drive the grout. Nevertheless, the distance the grout flows before it builds up to the roof could be different from what is observed from the two figures. This would be due to the higher flows rates than calculated and the higher particle-size to length dimension ratios in the model. This can also explain why the grout built up to the roof in the box while it did not in the field tests which are discussed in the chapter 6. Also, it can be observed that in the 4% dip case grout builds up to the roof a little later than in the case without the dip. This shows that the dip on the floor at the mine site can be beneficial for the mine-filling.

5.2 ASH VARIABILITY AND SPREAD TESTS

Different samples of ash taken from the Beechurst Avenue power plant contained varying percentages of fly and bottom ash. Fly ash particles sizes varied from about 5 μm to 100 μm and bottom ash particle sizes from 75 μm to 10,000 μm . Simple tests performed on these samples

showed that the flow parameters of these samples also differed significantly. This difference in behavior is likely due to the variability of material that the plant is burning and also to the plant's method of collecting the ash. The power plant burns a mixture of pure coal, limestone, and "gob", which is a refuse coal. 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. This change in the fuel affects the properties of the ash collected at different times, significantly. Ash properties also showed variability from truck load to truck load collected at about the same point of time. The cause for such a 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 the amounts of fly and bottom ash.

The variability of the ash will require that the grout recipe be varied to maintain consistent flowability. A spread test was adopted (from *Bhat et al., 1995*) as a sample 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. Another option was to lift the cylinder up rapidly than slowly. Though initially the latter option was rejected as the rapid motion would impart a vertical velocity to the column of the grout, lately tests with rapid lifting are being performed. 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 on one lot of ash collected from the same load. Figure 5.5, which is a plot of spread versus percentage of bentonite for some water fractions, shows how the increase in the amount of bentonite reduces the spread of the grout. As will be discussed in the next chapter, for the field injection test these spread tests were

performed to match the spread of the mixes on the site with those in the lab. These spread tests are developed to be used as a measure of the flowability of the grout mixes. Also, research needs to be continued to counter the spread reducing effect of bentonite. The use of a super-plasticizer should be tried for this purpose.

6. FIELD INJECTION

Field tests were undertaken to observe the mine-filling by grout at a full scale. The Fairfax mine in Preston County, West Virginia., (Figure 6.1), was selected for the injection. A part of this mine is abandoned, while mining continues on some parts of it. It is a room and pillar mine with a coal seam of about 152 cm thickness and located about 65 m below the ground surface. The initially decided spot for injection was slightly moved as shown in the Figure 6.2, as there was some roof fall in the mine at the previous spot. About a 765 m³ of the grout was injected during a four day period.

On the first day (20th May 1996) mine safety training was imparted and safety equipment provided to everybody at the site. Points where the boreholes were to be drilled were decided four 4 inch diameter boreholes were drilled. Two of these were located vertically above two adjacent mine corridor intersections and the other two were located above midpoints of two mine corridors.

Injection actually began on 21st May 1996, at 10 AM. A borehole that was vertically above an intersection was chosen for injection; eventually this was the only hole from which injection was done. Spread tests were used to determine the composition of the grout mix. The ash that arrived at the site had moisture in it. Hence additional water and bentonite to the effect of 38%, 36%, and 34% water fraction and 5% bentonite mixes were tested for spread. A mix of 34% water fraction (not including the moisture already present in the ash that came to the site) and 5% bentonite at the site, seemed to spread equal to that of 52% water fraction and 7% bentonite mix in the lab. Hence this recipe was decided to be used for this injection test.

On the first day about 90 m³ of the grout was pumped into the mine. The grout flowed in the direction of the dip on the floor of the mine, from the point of injection. It formed a pile about 30

cm high right under the injection hole and spread to a length of about 50 m. A bleed water zone of about 1 cm was found at the leading front of the grout.

On the day II, the injection began at 7.30 AM. About 230 m³ of the grout was pumped that day. Pumping continued for another two days till about 765 m³ of the grout was pumped. The position of the grout in the plan view of the mine is shown in Figure 6.3 (after second day of injection) and Figure 6.4 (after complete injection). The grout spread to about a length of 170 m and had risen to a height of about 120 cm, at the injection hole, at the end of the injection. At the time of observations made after one week after the completion of the injection, the slurry had solidified to the extent that samples had to be chopped out with an entrenching tool. The slurry had developed cracks which penetrated about 10 cm. These tended to run normal to the direction of the ash flow.

The hydraulic back fill method promises to be a huge success in meeting the objectives of the project. Spread of 170 m and more in length from one injection hole means, that the cost of drilling holes in the project well be very low. The grout did not fill up to the roof as initially feared and the total spread thus became independent of the pumping pressures and thus the power of the pump used. As predicted by the bench-scale tests the flow was predominantly in the direction of the dip on mine floor. An injection test on a much larger scale is planned for the later phases of the project when a mine will be completely filled by continuous injection. It is very likely that this method will prove to be effective in filling the whole mine using FBC ash grout.

7. CONCLUSIONS

The injection of grout made from FBC ash and water with some additives promises to be very successful in filling the underground abandoned coal mines, thus providing direct solutions the problems of ash disposal and subsidence control for the mines. As the grout fills up the mine it also helps reduce acid mine drainage by preventing the pyrite of the mine coming in contact with the underground water pools and by the neutralization reaction between the pyrite and basic ash.

The stability problem of the grouts which threatened to be a major cause of failure for the project has been effectively remedied. Addition of certain amounts of bentonite largely reduced the bleed and settling in the grout mixes. The fluid flow properties of certain mixes of ash, water and bentonite have been established. Rheological testing methods have been developed to suit the behavior of the grouts. Measurements have been made by these methods and the results were used to simulate the flow of a fluid with those properties on a computer. A commercially available CFD code was used for this purpose. Various 2D and 3D simulations have been performed. The results have provided very useful information about the sensitivity of the flow to the fluid parameters, and the effect of mine slope on the spread of grout.

Bench-scale model injection tests brought forth some of the practical problems that could be encountered at the time of full-scale field injection tests. Spread tests have been developed as a measure of the flowability of the grout. Full-scale field injection tests were performed at an abandoned coal mine site. About 1000 cu.yd of the grout was injected into the mine over a period of 5 days. The tests turned out to be to be a huge success. All the grout could be injected from one hole and a single low capacity pump was sufficient. The grout flowed long distances without

contacting the roof of the mine.

7.1 Recommendations for Further Studies.

The following recommendations are being made for future study that will make the backfilling project more effective and successful.

- Other additives such as superplasticizers should be tried to counter the flow reducing effects of the bentonite.
- A generalized relationship between the grout composition and the fluid flow properties has to be worked on. This can address the problem of ash variability. A series of tests with varying amounts of the constituents; i.e., fly ash, bottom ash, water and bentonite, using the methods described in this work will be useful in this purpose.
- Tests should be performed on apparatus of higher ranges of maximum torques to match the strain rates produced by them and the ones in the field.
- As simulation of the filling of a large section of the mine is not possible with the available computers, a 2D vertically averaged simulation should be designed. Here, the model simulates the depth as a function of position and time. Thus the grid will depict the plan view of the mine.

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Figure 2.1: Plot of a measure of torque versus time ('time' is representative of the immersed spindle length), showing the settling effects of a ash-water mix (45% water-fraction).

Figure 2.2 : Results of bleed tests on mixes containing equal portions of fly ash and bottom ash.

Figure 2.3: Effect of addition of bentonite on settling.

Figure 3.1: Typical flow curves for some non-Newtonian fluid models.

Figure 3.2: Mixer viscometer schematic and important dimensions of the T-bar.

Figure 3.3: Torque versus angular speed plot for 48% water fraction and 7% bentonite mix.

Figure 3.4: Torque versus angular speed plot for F500, a Newtonian fluid, to determine the constant 'G'.

Figure 3.5: Torque versus angular speed plot for 10% bentonite slurry, for the calculation of 'K'.

Figure 3.6: Dimensions of the vane for Stormer viscometer.

Figure 3.7: Plot showing the ranges of shear stresses for corresponding strain rates from uncertainty analysis for 48% water fraction and 7% bentonite mix. The points on the lines are the maximum and minimum shear stresses for the corresponding strain rates.

Figure 3.8: Flow curves for some observations from tests on 48% WF and 7% bentonite.

Figure 3.9: The flow curve for 48% WF and 7% bentonite grout mix.

Fig. 4.1: Domain for all 2D simulations .

PHOTON

z
y

real plast.visc / real yield stress

real plastic visc. $\times 10$

[real plastic visc] $\times 100$

Fig. 4.2: Sensitivity study for the flow parameters.

PHOTON

real plast. visc. / real yield stress

[real plastic visc.] $\times 1000$

[real plastic visc.] $\times 10000$

Fig. 4.3: Sensitivity study for the flow parameters.

PHOTON

real plast. visc. / real yield stress

[real plastic visc.] X 0.1

[real plastic visc.] X 0.01

Fig. 4.4: Sensitivity study for the flow parameters.

PHOTON

real plast. visc. / real yield stress

(real plastic visc.) $\times 0.001$

(real plastic visc.) $\times 0.0001$

Fig. 4.5: Sensitivity study for the flow parameters.

PHOTON

real plastic visc / real yield stress

(real yield stress) X 10

(real yield stress) X 20

Fig. 4.6: Sensitivity study for the flow parameters.

PHOTON

Zero Plastic Visc. and real Yield Stress

Zero Plastic Visc. and (real Yield Stress) $\times 10$

Zero Plastic Visc. and (real Yield Stress) $\times 20$

Fig. 4.7: Sensitivity study for the flow parameters.

Figure 4.8: Plot of spread distances versus varying plastic viscosities for actual yield stress values.

Figure 4.9: Plot of spread distances versus varying yield stress values for zero and actual plastic viscosities

PHOTON

No slope case

Downslope spread in the 6% slope case

Upslope spread in the 6% slope case

Fig. 4.11: Effect of 6% slope in the floor of the mine; 2D cartesian simulation.

PHOTON

No slope case

Downslope spread in the 8% slope case

Upslope spread in the 8% slope case

Fig. 4.12: Effect of 8% slope in the floor of the mine; 2D cartesian simulation.

PHOTON

No slope case

Downslope spread in a 10% slope case

Upslope spread in the 10% slope case

Fig. 4.13: Effect of 10% slope in the floor of the mine; 2D cartesian simulation.

Figure 4.14: Plot showing the effect of slope on the spread distance

Figure 4.15: Typical mine intersection (not to scale) showing the symmetric 1/8th of the mine intersection used in numerical simulations.

PHOTON

Fig. 4.17: Position of grout after $t=530s$.
Bingham Model fit; 3D BFC Simulation.

PHOTON

Fig. 4.18: Position of the grout after $t=835s$.

Bingham Model fit; 3D BFC Simulation.

PHOTON

Fig. 4.19: Position of the grout after $t=1350s$.

Bingham Model fit; 3D BFC Simulation.

PHOTON

Fig. 4. 20: Position of the grout after $t=1575s$.

Bingham Model fit; 3D BFC Simulation.

PHOTON

Fig. 4.21: Position of the grout after $t=1850s$.

Bingham Model fit; 3D BFC Simulation.

Figure 5.1: Left - the actual mine plan view for the section according to which the box was constructed. Right - idealization of the actual geometry. (discontinuous lines mark the box)

Fig 5.2 . Bench-Scale model of the chosen section of the mine
(above figure not to scale)

Scale of Model is 1" = 3 ft

Time= 4 min

Time= 8 min

Time= 12 min

Time= 16 min

Time= 20 min

Time= 24 min

Fig. 5.3 : Injection I (horizontal case) : Position of the grout in the box with time. Outer line indicates leading edge of grout. Hatched region indicates contact with the roof

Figure 5.5: Spread versus bentonite percentage for grout samples at varying values of water fraction

Figure 6.2: Mine plan showing the sites chosen for field injection.

Figure 6.3: Plan view of the Fairfax mine showing the grout position after the second day of injection.

Figure 6.4: Plan view of the Fairfax mine map and the position of the grout after five days of injection.

ABSTRACT

It has been proposed that a mix made from fly and bottom ash from atmospheric pressure fluidized bed coal combusters (FBC ash), water, and stabilizers be injected from the surface into abandoned room and pillar coal mines through boreholes. Besides ash disposal, this process would prevent subsidence and acid mine drainage. Such a mix (called 'grout') needs to be an adequately stable and flowable suspension for it to spread and cover large areas in the mine. This is necessary as the drilling of the boreholes will be an expensive operation and the number such holes should be minimized. Addition of bentonite was found to be needed for this purpose.

A suitable grout mix was tested rheologically to determine its fluid flow properties. Finding little published information on such materials, tests were performed using a commercial rotational viscometer with a T-bar rotor and a stand which produced a helical rotor path. Existing mixer viscometer test methods were modified and adapted to convert the measurements of torque vs. angular speed to the material properties appearing in several non-Newtonian constitutive equations. Yield stress was measured by an independent test called the vane method. The rheological behavior was a close fit to the Bingham fluid model. Bleed tests were conducted to ascertain the stability of the mixtures. Spread tests were conducted to compare the flowability of various mixes.

Using the flow parameters determined in the laboratory, numerical simulations of grout flow were performed and compared with the results of scale model and field tests. A field injection of this grout was performed at the Fairfax mines in Preston county, W.V.. The observations there proved that this FBC ash grout flows as desired, is a very economical way of disposing the environmentally menacing ash, while also preventing the subsidence and acid mine drainage of the mines.