A FIELD DEMONSTRATION OF THE COAL COMBUSTION BY-PRODUCTS BASED PASTE BACKFILL FOR SUBSIDENCE CONTROL IN ILLINOIS[1]

by

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Abstract. In collaboration with the US Department of Energy, the Mining Engineering Department of Southern Illinois University at Carbondale has developed underground paste backfilling technology for controlling surface subsidence. In the Summer of 1996, approximately 8,000 tons of high density coal combustion by-products based pastes (>70% solids) were blind backfilled underground through a surface bore hole to fill a room-and-pillar panel at Peabody #10 mine. Observations through a borehole camera confirmed that the grout must have moved at least 200 ft from the injection point. Cores obtained from the placed materials indicated strength and stiffness in the range of 500-600 psi and 30,000-35,000 psi, respectively, after 60 days.

Additional Key Words: By-products management, flue gas desulfurization by-products, fluidized bed combustion ash, scrubber sludge

Introduction

In the USA, coal burning electric power plants produce approximately 90 million tons of coal combustion by-products (fly ash, bottom ash, and wet and dry scrubber sludge). The current utilization of fly ash and bottom ash in the USA is only 25% and 40%, respectively. The state of Illinois falls far behind the national average, utilizing only 10% of the fly ash produced in the state. The utilization of fluidized bed combustion (FBC) and flue gas desulfurization (FGD) by-products in the USA is only 2% to 3%. Large volume management of coal combustion by-products (CCBs) and FGD by-products in underground mines has significant potential to control subsidence, particularly in Illinois where high sulfur coals at shallow mining depths are exploited and the protection of prime agricultural lands and ground water resources are crucial. Furthermore, the hydrogeological characteristics surrounding the Illinois coal seams being actively mined are favorable for large volume management of CCBs and FGD by-products because the seams are well below potable water resources and in the underground brine water zone.

In 1993, the US Department of Energy (USDOE) entered into a cooperative research agreement (Program) with the Southern Illinois University at Carbondale (SIUC) to investigate the engineering, environmental, and economic feasibility of managing CCBs and FGD by-products in underground mines to control surface subsidence. The program has several components: 1. By-products and mix characterization for engineering and environmental properties, 2. materials handling and systems economics, 3. blind underground placement of CCBs using pneumatic and hydraulic technologies, 4. environmental monitoring and assessment, and 5. geotechnical monitoring and assessment. This paper only discusses the hydraulic placement technologies, emphasizing only the field demonstration aspects of the program.

Related Works

History of mining is replete with many instances of backfilling to make a safe underground mining environment, control subsidence and acid mine drainage. Table 1 summarizes some of these studies conducted in the USA and abroad. A few conclusions that can be derived from these studies are:

i) In the USA, mostly backfilling was done in abandoned mines to control surface subsidence.

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Table 1 Studies related to filling underground voids

Authors and Sources	Backfilling Reason	Comments
Carlson (1975)	Subsidence control	Model studies.
Maser et al. (1975)	Subsidence control	Fly ash-cement mine sealant.
Whaite and Allen (1975)	Subsidence control	Slurry backfill.
Galvin and Wagner (1982)	Enhance extraction	South African coal mines to increase extraction by 8%-12%. Fly ash only.
Petulanas (1988)	Subsidence control	High volume use of fly ash in underground void filling. Low solid density mixes.
Palarski (1993)	Enhance extraction	In Polish coal mines. Fly ash, tailings, rocks.
Hollinderbaumer and Kramer (1994)	Subsidence and ground control	Integrated approach in German longwall mines to dispose of incinerator ash.
Meiers, et al. (1995)	Subsidence control	Fly ash-scrubber sludge mix.
Gray et al. (1995)	AMD control	Disposal of FBC.
Chugh et al. (1996)	AMD control	Fly ash, scrubber sludge-based pastes pumped into an abandoned Maryland mine.

ii) Underground backfilling was done mostly using low solids content slurry. Paste backfilling is an emerging technology which offers higher economic and environmental advantages than the slurry backfill system (Brackebusch, 1994).

iii) Instances of systematic mix development to engineer a paste of appropriate structural and environmental characteristics are few and far between. Most systematic mix development procedures were directed towards developing flowable fills except a paste development study by Chugh et al. (1996a).

iv) Instances of integrated environmental studies in conjunction with backfilling are very few.

v) Economic analyses of backfilling operations have not been discussed in the literature.

vi) Required engineering properties of cured backfill materials to control surface subsidence are not available.

vii) Studies related to mechanisms of subsidence control due to backfilling have not been done extensively. This also includes studying the effects of backfilling heights and spatial extent of backfilling for effective subsidence control.

The USDOE program is a comprehensive study of all these issues related to underground backfilling using CCBs based mixes. The program has addressed these issues and provided solutions to various problems associated with the implementation of underground backfilling techniques.

Backfilling Considerations

Engineering considerations for designing a CCBs-based paste backfill material and selection of equipment for pumping the developed paste underground can be broadly classified in two phases. In the first phase, individual components of a paste mix are identified and the *workability* and *in-service* properties of the mix are established. In the second phase, materials flow schematic are developed and proper selection of equipment is made to produce required paste tonnage per hour.

Selection of Mix Components

The individual components of a CCBs-based paste are F-type pulverized coal combustion (PCC) fly ash, bottom ash, sulfate-rich scrubber sludge, fluidized bed combustion fly ash and spent bed ash. The availability of these materials and their production ratios play an important role in designing an appropriate paste. A power plant utilizing scrubber technology will produce fly ash, bottom ash, and scrubber sludge. If it is possible to develop a paste using the same proportions of individual components as their production ratios (or ratios of by-products available after sale of fly ash, bottom ash, and scrubber sludge), then effective utilization of these materials is possible by consuming all the materials destined for surface disposal. But the ratio of available individual materials may not produce a stable paste in terms of bleed off and flowability (or the stability of paste). Brackebusch (1994) has recommended at least 15% by weight of particles in the mix to be less than 20 μm diameter (or 625 mesh) for a stable paste. If F-type fly ash and scrubber sludge are selected as mix components, then a lime-based material is required to activate the pozzolanic reactions in the F-type fly ash. This lime based material can be hydrated lime, FBC fly ash, lime waste, or other materials where free lime is available. Also, sufficient quantity of F type fly ash is required for proper mixing with scrubber sludge.

Properties of Mixes

The fresh grout should have required *workability* properties, namely flowability and bleed off water. The flowability of the paste can be readily tested using an ASTM slump cone. However, a half size slump cone (six inches high, three-inch top diameter and six-inch bottom diameter) is more convenient for se in the field. Figure 1 shows that the values obtained from a half-size slump cone are approximately half of that obtained from an ASTM slump cone. The bleed water is measured using the procedure outlined in ASTM C 940. Bleed of a fresh grout should be limited to less than 5%. Besides, visual observations of particle size segregation and rapid settling of larger particles help decide the stability of a fresh grout.

The *in service* properties of grouts are decided by the intended application. For subsidence control, a cured grout should have adequate strength and stiffness (elastic modulus) properties. The required strength and stiffness properties can be determined by finite element modeling (Chugh et al., 1996). Proper modeling will require an understanding of the subsidence mechanisms. In the Illinois coal basin, subsidence is mainly caused by the weakening of the floor strata resulting in floor heaves and pillar punching into the soft floors. For this reason, low solids content slurry was not considered suitable for subsidence control.

Equipment Selection Consideration

Mixing of individual components is one of the most important considerations for producing a stable paste. A high speed shear mixer, such as a pug mill of adequate capacity is required for paste production. A continuous system should have a proper material flow mechanism to feed the pug mill with mix components and water at the same time and continuously. Unstable pastes with excessive bleeding and segregation may result if materials and water are not mixed properly. The size of water pipes should be capable of discharging required amounts of water to the plug mill. If it is not selected properly, the production rate of pastes cannot be increased because enough water will not be available in the pug mill for producing required slump. Materials handling can become a bottleneck in

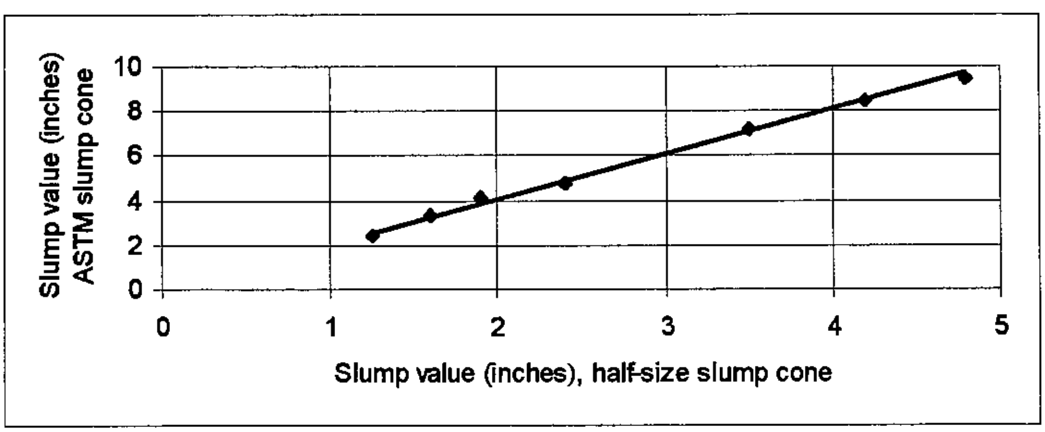

Figure 1 Relationship between ASTM slump and half-size slump

the continuous system if proper equipment is not used. Constant rates of various material flow to the pug mill are required for producing a consistent grout continuously.

Mine Characteristics

The backfilling area is a small panel of Peabody No. 10 mine near Pawnee, Illinois. The Herrin (No. 6) coal seam was mined at depths ranging from 325-375 ft. The entries of the panel were 20 ft wide and the pillars were 40 ft by 60 ft. In most of the underground works, the immediate roof rock was the Anna Shale which was overlain by the Brereton Limestone. The floor was weak clay stone. The study area included portions of the Horse Creek and Clear Creek drainage basins, both tributaries to the South Fork of the Sangamon River. No community public groundwater supplies exist within a one mile radius of the backfilling site. The areas targeted for backfilling were well below potable groundwater resources.

Mix Component Selection and Mix Design

The required *in service* properties of cured grouts were determined using 2-diemsional, time dependent finite element models. The absence of the effect of cross-cuts in the 2-dimensional model was simulated by augmenting the overburden weight by a facter k, where $k = (1 + W_e/W_p)$ and W_e and W_p are the entry and pillar widths, respectively. The immediate floor of the model was assumed to have time dependent behaviors. The detail of the modeling procedure and results can be found in Chugh et al. (1996b). The finite element analyses indicated that the strength and stiffness (elastic modulus) of the backfill materials should be approximately 200 psi and 12,000-18,000 psi, respectively, for effective surface subsidence control.

We used F-type fly ash and scrubber sludge with mean particle sizes of 0.05 and 0.06 mm diameter, respectively, to design the backfill material. Hydrated lime and lime waste in the range from 2%-5% and 5% to 10%, respectively, were tried for activating the pozzolanic characteristics of F-type fly ash. A paste with less than 40% fly ash showed signs of instability because hard or denser layers were observed after 15 minutes of quiescence. Pastes with at least 40% fly ash were found to be stable.

Mix development was done in three phases. In the first phase, no pozzolanic accelerators (like lime or lime waste) were used. The second phase used lime and the third phase used lime waste as pozzolanic activators. Maximum compressive strength and stiffness of the mix without any pozzolanic activator and 50% F type fly ash were 55 psi and 6,700 psi, respectively. This mix, however, completely disintegrated in water because there was no pozzolanic reaction in F-type fly ash. With 5% lime and 40% F-type fly ash, a 28-day compressive strength equal to 324 psi and a stiffness equal to 11,200 psi were obtained. When 5% lime was replaced by 5% lime waste, the strength dropped to 185 psi but the stiffness remained the same. For each mix, slump at different solids content of the paste were also determined. The final mix containing 40% F-type fly ash, 55% scrubber sludge and 2%-3% lime were selected based on the 28-day compressive strength and stiffness of the mix. It was found that a slump of 8 to 9 inches could be obtained from grouts with 74%-77% solids. Leaching characteristics of the mixes showed that they were environmentally acceptable.

Equipment Setup For Field Demonstration

Figure 2 shows the schematic of the mixing plant as set up at the demonstration site. A 10 ft long, six cubic yard capacity pug mill was fed with fly ash/bottom ash mixture, scrubber sludge, and lime to make grouts of eight- to ten-inches slump containing 70-78% solids. Water to the pug mill was added at the front-end of the pug mill as shown in Figure 2. A blend of scrubber sludge and fly ash/bottom ash mixture was crushed through a hammer mill and fed to a 15-ton storage hopper that fed the blend to the main belt at a constant rate. A 30 ft tall lime silo of 35-ton capacity released lime on the main belt through a screw feeder at a predefined rate controlled by a variable speed motor. The main and the storage hopper belts had weighing scales to measure the feed rate of these two belts driven by two fixed speed motors. Openings of the hopper doors controlled the feed rate into the hopper belts. Water flow rate was measured using a flow meter attached to the outlet of a water pump that pumped water into the pug mill. The water pump drew water from a storage tank that was periodically filled with water from a water reservoir.

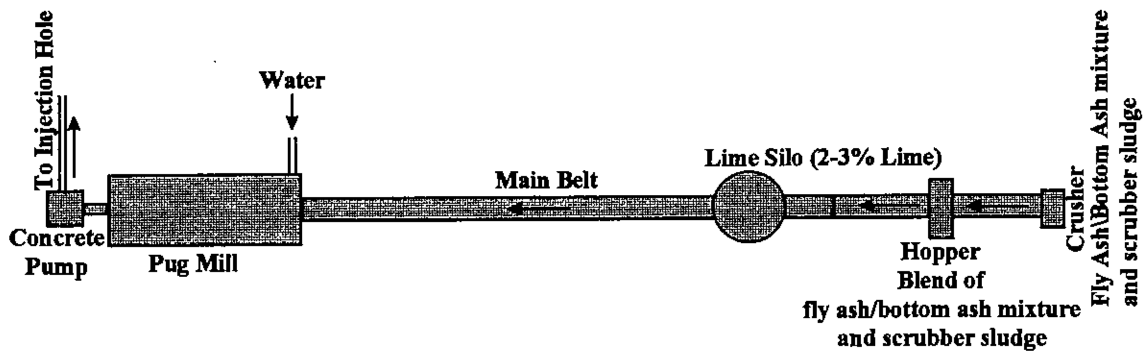

Figure 2 Schematic of mixing plant for hydraulic placement

The grout from the pug mill came to a Schwing 750 concrete pump through a chute. The 70-cubic yard (or 140 tons of concrete) per hour capacity concrete pump was capable of exerting 750 psi pressure at its delivery end. The grout was pumped to the borehole using 6-inch diameter and 10 ft long steel pipes joined with victaulic couplings. Except the concrete pump, the complete mixing plant was operated from a computer control center housed in a trailer. The location of the mixing plant with respect to the injection areas is shown in Figure 3.

The as-received fly ash/bottom ash mixture and scrubber sludge were blended in equal proportions by volume on the surface using a front-end loader. Equal volumes of fly ash mixture and scrubber sludge in the paste approximated 52% fly ash mixture and 48% scrubber sludge by dry weights.

Large-scale Demonstration

Large variation of moisture in the as-received materials and approximately 10% variation of feed rate to the pug mill necessitated continuous adjustment of water and material flow rates to the pug mill to produce a grout of approximately 9-inch slump. After observing the grouts of different slump for a couple of hours, the pug mill operator was able to adjust the slump within one inch by adjusting the material and water flow rates.

Though the quality control (grout consistency) of the entire operation rested on the pug mill operator's ability in predicting the slump from visual observations of grout and adjusting the material and water flow rates, samples of grout were periodically taken for slump, moisture, and bleed measurements. Three-inch by six-inch and six-inch by 12-inch cylindrical samples were also molded for strength and stiffness testing. Cured samples were also subjected to leachate analysis to determine elemental concentrations. Video transmissions of underground openings were recorded periodically using a borehole camera lowered through the vent hole.

Borehole camera was first lowered in the vent hole after pumping 3,912 tons of grout through the injection hole. The entry opening measured through the vent hole was 5.3 ft, indicating that most of the grout was flowing in the south direction as was expected because of the south-east dipping seam. The grout shore-line, 50 ft away from the vent hole in the north direction, could be seen through the borehole camera. This confirmed that the grout had moved at least 200 ft from the injection point. Pumping was stopped during the July 4th week end (for four days) and resumed thereafter. The injection hole was plugged after pumping an additional 549 tons of grout. An entry opening of 4.3 ft at the vent hole indicated that the additional 549 tons of grout almost completely traveled in the north direction.

Pumping of a thinner grout (10-inch slump) was resumed through the vent hole and 2,275 tons of grout was injected through the vent hole before lowering the camera again through the vent hole. An entry opening of 9.5 inches was observed. An additional 1,324 tons of grout through the vent hole completely filled the open area around the vent hole. A total of 8,062 tons of grout was placed in the panel.

Table 2 shows a summary of 15 days of pumping. With the system developed, a high rate of pumping is possible to increase the productivity. Figure 4 shows pumping rate along with the average solids content of grouts pumped. Average solids content of grouts pumped was higher than 70% and a pumping rate as high as 140 tons was achieved with 72% solids content.

Table 2 Summary of 15 days of pumping

Total pumping hours	76.6
Total as-received solids (blend of fly ash/bottom ash mixture, scrubber sludge, and lime) pumped	6906 tons
Total water added	1156 tons
Total grout pumped	8062 tons
% Water of as-received solids	16.7
% solids pumped	71-76
Average pumping rate	105 tons/hr

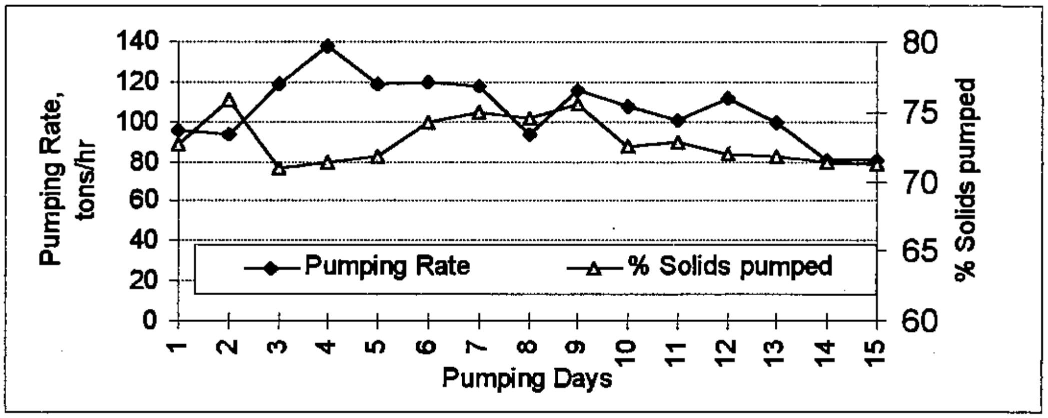

Figure 4 Pumping rate and percentage solids pumped

Figure 5 shows a typical pumping day. In a seven-hour period, a total of 580 tons of grouts were pumped. This shows that a typical 8-hour production shift is able to pump 600-700 tons of grout. Samples taken during the same day indicated solids content in the range of 72-76%.

Table 3 summarizes fresh and cured grout properties. Though the intention was to pump a nine-inch slump grout, it was difficult to produce a grout of a particular slump value because of wide variations in as-received moisture content of the materials and flow rate.

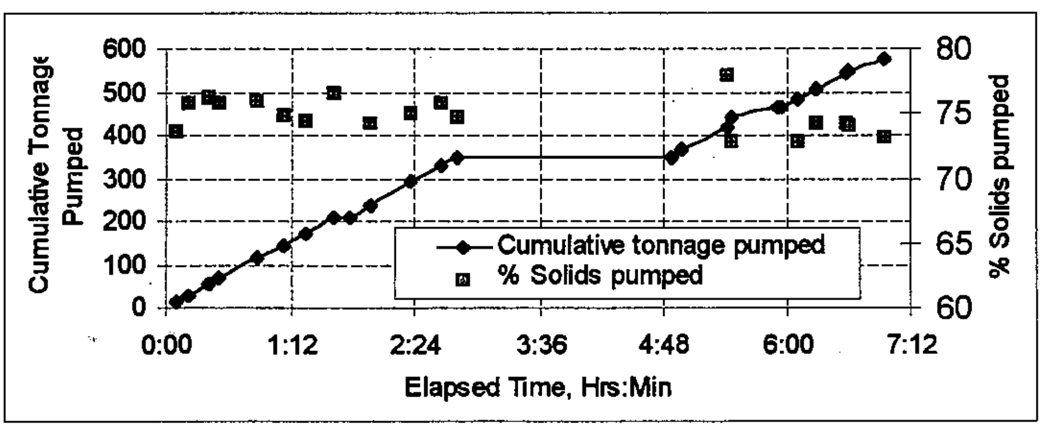

Figure 5 Percentage solids pumped in a typical pumping day

Table 3 Summary of grout properties

Proportions of pumped materials	48 % scrubber sludge 52% fly ash/bottom ash mixture 2%-3% lime
Solids content of grouts	71%-75%
Slump	7.8-10.0 inches
Bleed	2.0%-4.7%
Compressive strength (7-day curing)	60-80 psi
Elastic modulus (7-day curing)	2,000-3,500
Compressive strength (14-day curing)	220-250 psi
Elastic modulus (14-day curing)	3,500-5,000 psi
Compressive strength (28-day curing)	300-350 psi
Elastic modulus (28-day curing)	14,000-16,000 psi

Figure 6 shows the frequency distribution of slump data. Approximately 28% data show slump values between 8.6- to 9-inches. Eighteen percent data showing slump values in 10.1 to 10.5 inches range were obtained during the period when the grout was pumped through the vent hole. Figure 7 shows measured slump values against percentage solids in the grout. Percentage solids were calculated from the actual moisture test and data obtained from the control panel (amounts of as-received solids and water added during 10 to 15 minute periods). Scattering of slump and solids content data indicates a wide variation in the characteristics of as-received materials, notably the particle size distribution of fly ash/bottom ash mixture. However, for slumps in the range of 7.8-inch to 10.5-inches, the solids content of grouts is in the range of 71-78%.

Figure 8 shows the relationship between slump and bleed. Scattering of slump and bleed data indicates earlier suspicion of wide variation in as-received material characteristics. However, bleed was less than 4% for slump values less than 9.0 inches and less than 5% for slump values between 10.0-10.5 inches. Figure 9 shows a typical stress strain profile of cured and cored samples for different curing periods. The stiffness of the material (elastic modulus) after 7- and 14-day curing is very low, indicating mostly cohesion controlling the strength. Twenty eight-day cured samples show linear elastic behavior up to the failure point. The strength of samples cored after 60 days and 60-day cured samples show almost the same strength. The increase in strength from 60-day curing to-90 day curing is not very significant.

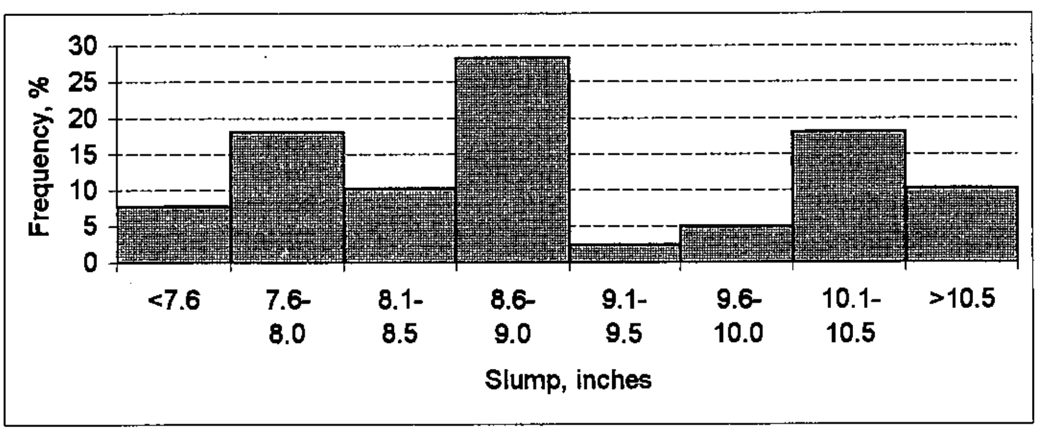

Figure 6 Frequency distribution of slump measurements

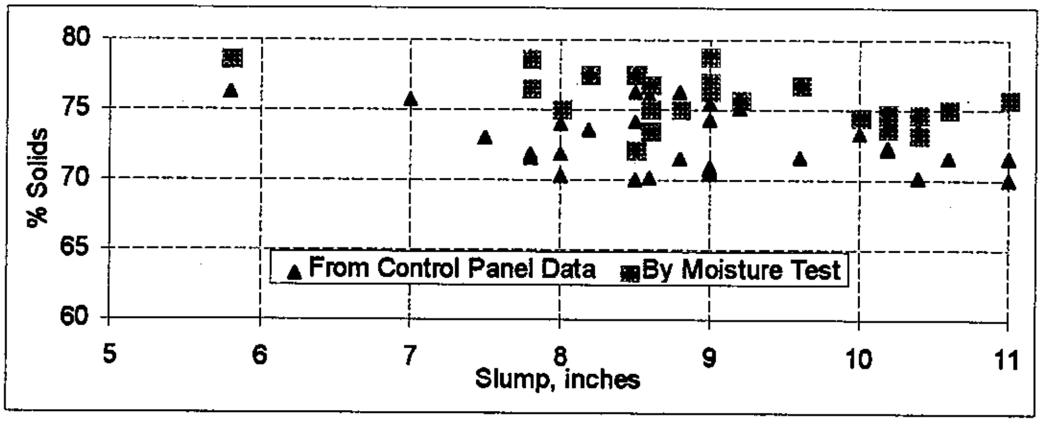

Figure 7 Slump vs. % solids of grouts

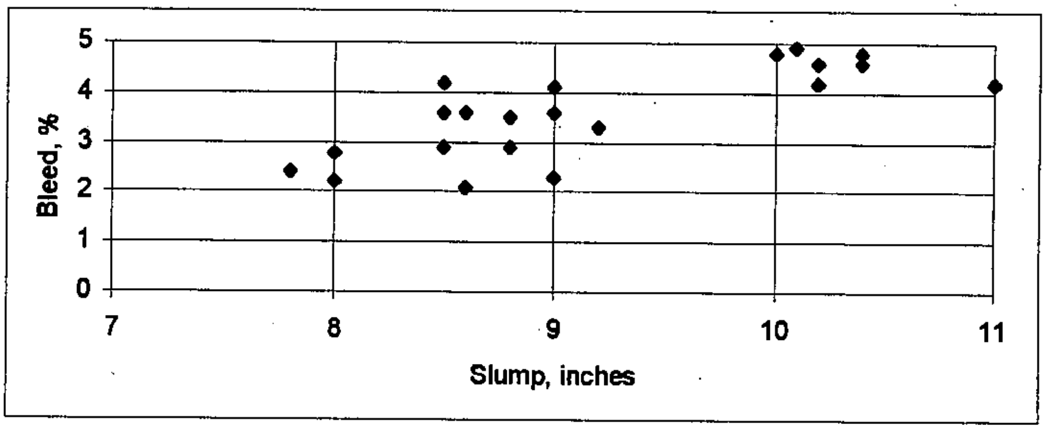

Figure 8 Relationship between slump and bleed

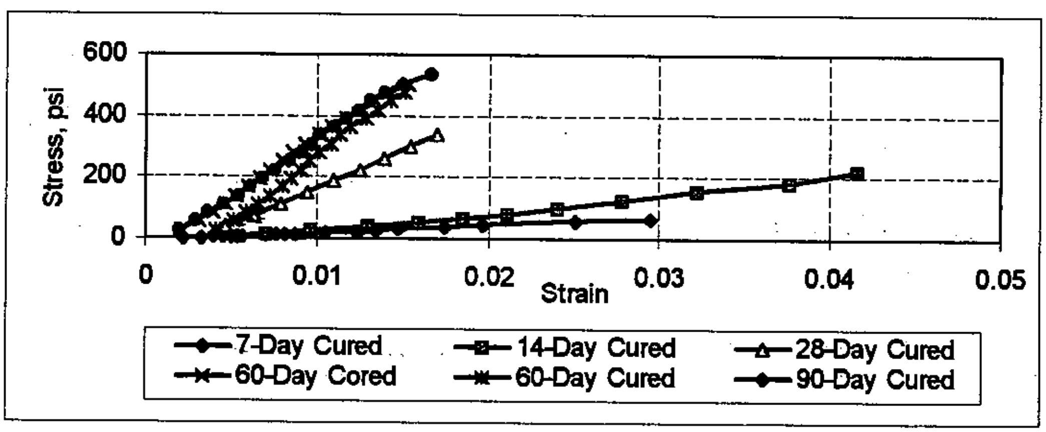

Figure 9 Typical stress-strain profiles of samples

Concluding Remarks

A complete system for underground management of CCBs to control surface subsidence has been developed and tested in the field with success. The developed hydraulic system performed extremely well and a high rate of pumping (average 105 tons/hour) was achieved using the system. Cores obtained from the placed materials indicated compressive strength in the range of 300 to 400 psi after 60-days of curing. The stiffness of the cured materials reached approximately 35,000 psi 60 days after placement. The success of the project has initiated another demonstration project that involves backfilling in an active underground mine in order to enhance mining productivity. The pillar sizes in a panel section of an active mine will be reduced to enhance recovery and productivity. The area will be subsequently backfilled using mixes of CCBs and coal processing wastes to prevent time dependent surface subsidence concomitant with the pillar size reduction.

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