BACKFILLING OF HIGHWALLS FOR IMPROVED COAL RECOVERY

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Abstract

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

Introduction

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

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

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

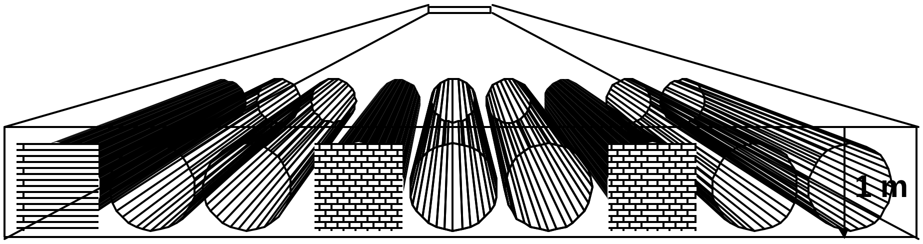
The project was completed in two phases. Laboratory ash/grout testing, hydrologic monitoring, and evaluation of emplacement methods occurred in Phase I, whereas the field demonstration and economic analysis was completed for Phase II.

Laboratory Testing Procedures

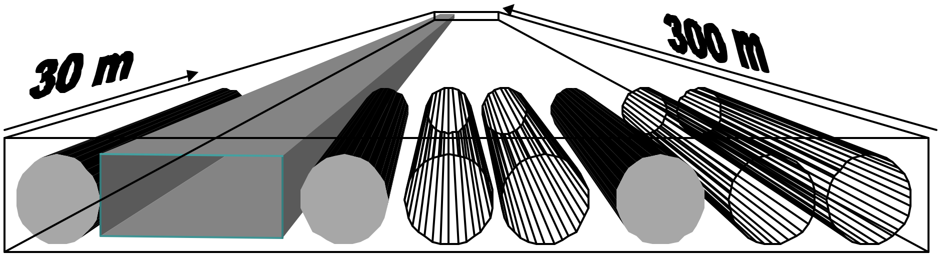
Materials

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

Stage 0 Augered Coal Seam



Stage 1 Grout Fill Every 3rd Auger Hole



Stage 2 Highwall Mine Between Filled Holes

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

Cylinder Preparation and Curing

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

Unconfined Compressive Strength Testing

Unconfined compression testing was selected as the most preferred geotechnical test for this study because it best represents the type of loading that the grout will encounter in an auger hole. A finite element analysis indicated that a compressive strength of 500 PSI would be sufficient to support the rock strata overlying the coal. The strength testing was conducted as per ASTM C 39, C 192, and C 617/C 1231, using a triaxial compression machine containing a 10,000 lb. load cell.

Chemical and Mineralogical Characterization

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

Laboratory Results

Chemical and Mineralogical Composition

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

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

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

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

Table 2. Crystalline Phases Identified in FBC Ash and Grout

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

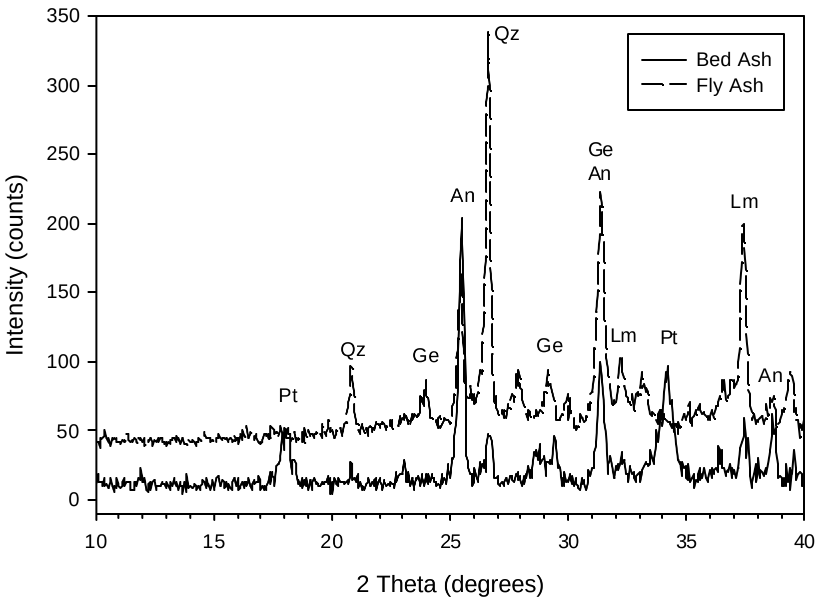


Figure 2. XRD spectra of Cedar Bay bed ash and fly ash.

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

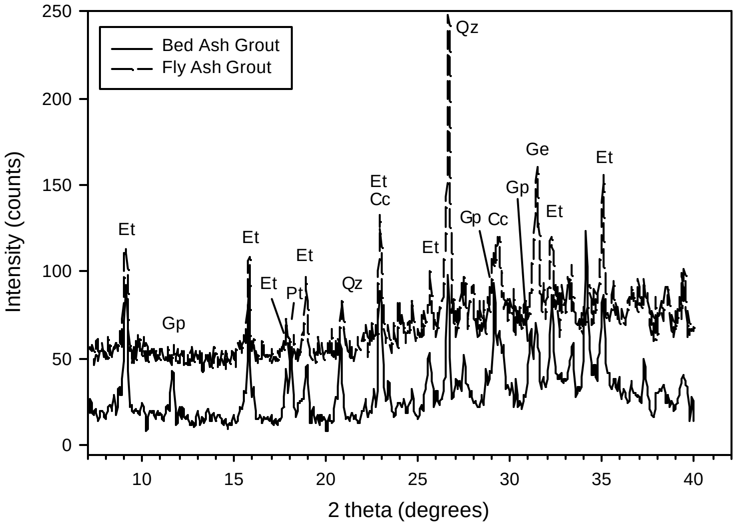


Figure 3. XRD spectra of bed ash- and fly ash-based grouts.

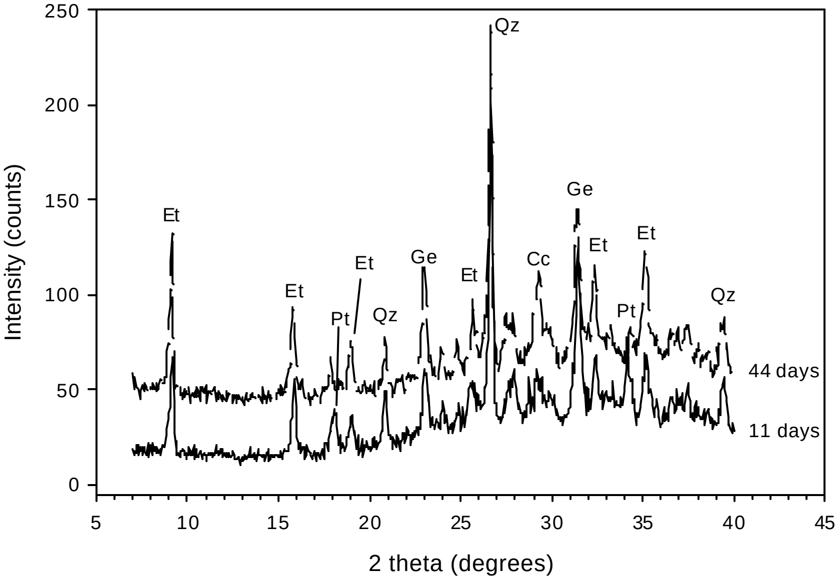


Figure 4. XRD spectra of FBC fly ash-based grouts at different curing intervals.

Unconfined Compressive Strength

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

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

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

Field Demonstration

Site Preparation

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

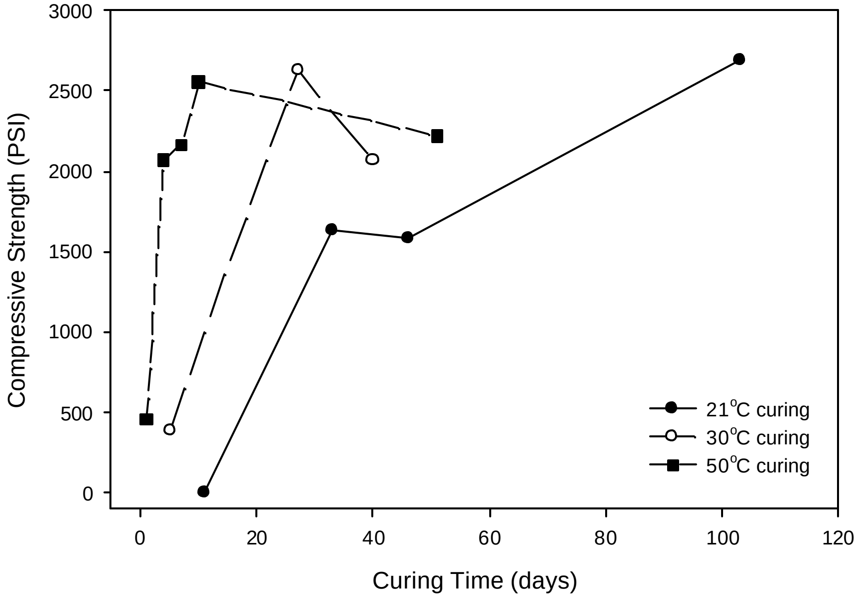


Figure 5. The effects of temperature on unconfined compressive strength of fly ash-based grout prepared with a water:solid ratio = 0.62 (38.3% moisture).

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

Grouting Procedure

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

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

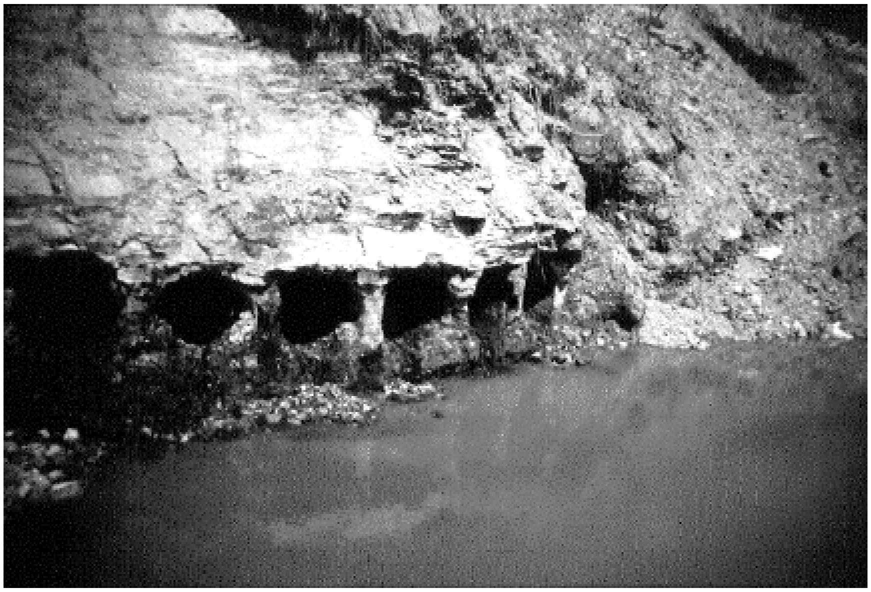


Figure 6. Abandoned highwall containing auger holes. Holes were initially plugged with rock and soil, and were exposed for this project. Each hole is approx. 3 ft. in diameter.

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

Grout Emplacement

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

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

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

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

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

Geotechnical, Chemical, and Mineralogical Monitoring

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

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

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

Table 3. Physical Properties of Several Field Demonstration Grouts

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

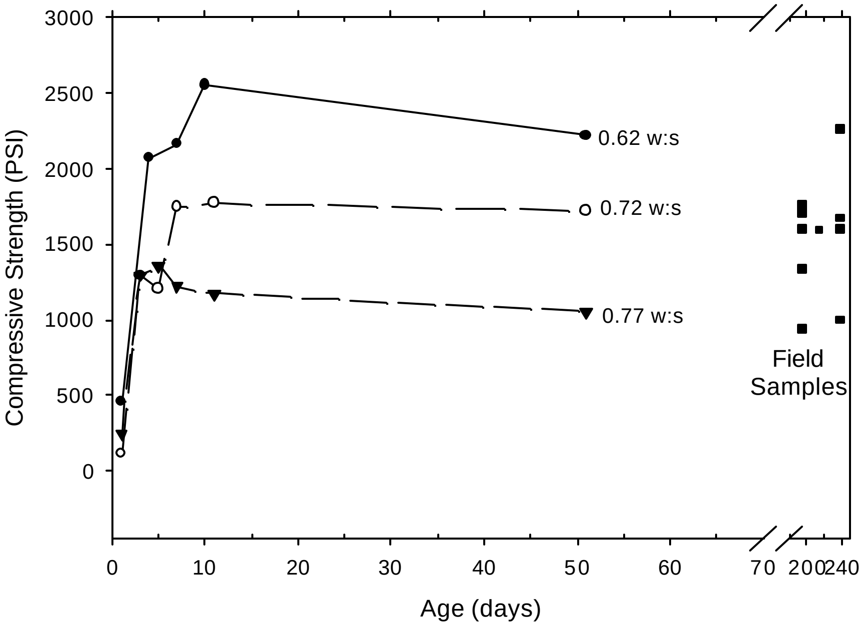


Figure 8. Unconfined compressive strength of lab grouts cured at 50°C, with water:solid ratios between 0.62 and 0.77 (38%-44% moisture), compared with field demo (auger hole) grouts.

Economic Analysis

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

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[1] Bob Rathbone is a research scientist at the University of Kentucky Center for Applied Energy Research. He has been involved with many aspects of coal combustion product (CCP) research and characterization, including studies of ammonia in fly ash, the effects of fly ash carbon on air entrainment in concrete, the use of fluidized bed combustion ash as a low-cost grout in mine voids, and the potential use of fly ash carbon as a boiler fuel. He has authored or co-authored publications in many professional journals and conference proceeding related to CCP research, and serves on the Program Committee for the International Ash Utilization Symposium in Lexington, Kentucky.