USE OF COAL COMBUSTION BY-PRODUCTS IN ABANDONED MINE LAND RECLAMATION

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INTRODUCTION

Indianapolis Power & Light Company (IPL) began researching the use of fluid placement techniques of fixated scrubber sludge (FSS) for reducing surface subsidence from underground coal mines as an economic alternative to low strength concrete grout. Abandoned underground coal mines surround property adjacent to IPL's coal combustion by-product (CCBP) landfill at the Petersburg Generating Station. Landfill expansion into these areas is in question because of the high potential for sinkhole subsidence to develop. Sinkholes manifesting at the surface would put the integrity of a liner or runoff pond containment structure for a CCBP disposal facility at risk. The goals of the project were to produce a flowable FSS grout which could be pumped a minimum of 100 feet from an injection borehole and which would develop an ultimate unconfined compressive strength of 100 pounds per square inch (psi). All equipment utilized for the injection work was to be readily available rental equipment not requiring significant modification to be used for injection.

SITE SELECTION

All of the abandoned underground coal mines found on the Petersburg Generating Station property are in the Illinois Basin No. V coal seam. The mines were ranked on the basis of the following criteria: probable open voids, ability to isolate the area to receive injected material, ability to locate mine voids by the use of mine maps and land surveying, and surface conditions. The Arnold Willis "City" Mine was selected primarily because of its small size, available mine maps, easy surface access, and proximity to the power plant. The coal was removed from this mine in the late 1940's to early 1950's at extraction rates varying from 50% to 65%.

The initial boreholes drilled verified the accuracy of the City mine map and determined the condition of the mine workings. Figure 1, a map of the Arnold Willis "City" Mine, depicts the existing surface topography and coal seam elevations determined from boreholes drilled during the project. Depth to the mine voids varied from 32 to 64 feet. Mine void heights/coal thickness varied from 2.0 to 7.0 feet (average 5.0 feet). Boreholes encountered both dry mine and flooded conditions. The average mine pool elevation was 436.5 feet.

FIXATED SCRUBBER SLUDGE - FSS

FSS is a scrubber by-product blended with dry fly ash and quicklime. The Petersburg Generating Station burns bituminous coal mined in Indiana. The resultant fly ash is a good quality pozzolan meeting ASTM C-593. The flue gas desulfurization systems are wet limestone scrubbers. These are inhibited oxidation scrubbers which produce a by-product which is primarily a calcium sulfite hemihydrate, containing minor quantities of calcium sulfate dihydrate (gypsum) and silicon dioxide (as quartz). The pozzolanic activation additive is calcitic quicklime (calcium oxide) with minor quantities of magnesium oxide and silicon dioxide (as quartz).

FSS materials are chemically active in the sense that the main constituents (i.e., fly ash, scrubber sludge, lime and water) react over time with each other to form other distinct chemical and mineralogical phases. These phases are responsible for the "self-cementing" action which produces the physical strengths in the FSS by-products after they have "cured".

BENCH SCALE TEST PROGRAM

To meet the goals of the demonstration, placement of FSS had to completely eliminate the mine void space with a minimal number of injections points. To accomplish this, the FSS mix design had to be optimized for flowability and strength development. A bench scale test program was developed and conducted to provide information focused toward determining the best compositions for mine injection. Fixated scrubber sludge compositions for mine injection differ from those intended for surface disposal in fluidity. Dispersion in underground voids is necessary if the voids are to be filled. In addition, limiting quantities of supernatant fluid after settling, and resistance to acidic mine water are critical criteria.

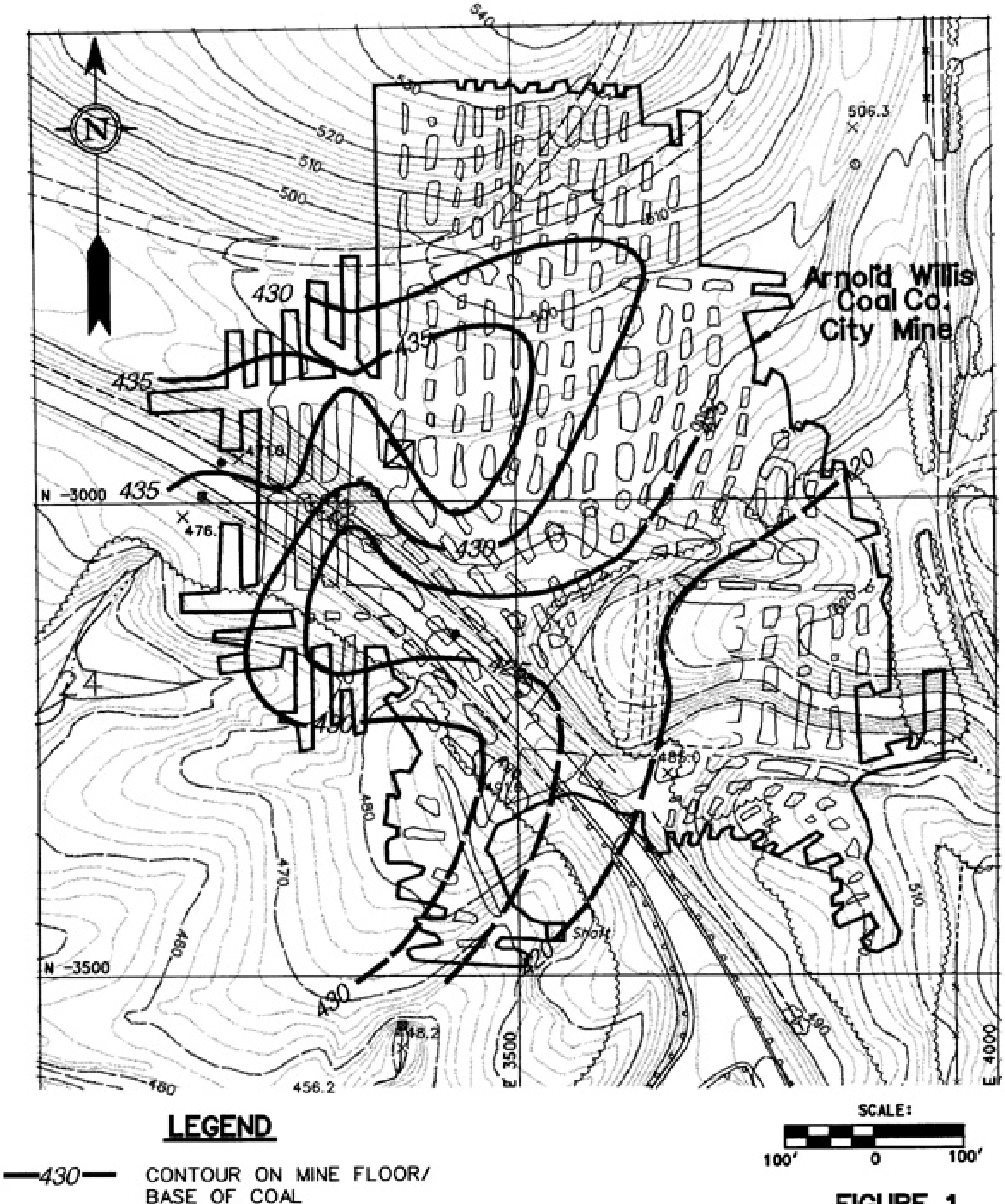

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FIGURE 1
MINE MAP

The bench scale test program studied 36 test compositions. The freshly prepared compositions were evaluated for viscosity, density as blended, density after settling, flowability in a one-dimensional "tunnel flow" protocol, and angle of repose. There was a discernable trend indicating that higher fly ash to filtercake ratios yield higher strength. Similarly, increasing lime contents increased unconfined compressive strength.

DEVELOPING A UNIVERSAL CONCEPT OF THE TECHNOLOGY

Although a considerable amount of information has been generated by the utility industry and others on the chemical and physical properties of FSS by-product materials (e.g., strength, permeability, leachability), very little is known about the fluid and/or paste FSS materials used for injection. This part of the research project aimed at optimizing the strength and the flowability of FSS mixes.

Microstructure was evaluated to determine cementation and stability in the long-term when placed in the mine environment. Understanding the chemical, mineralogical and microstructural properties of the FSS material was critical to determine what transformation could occur underground. The optimization of strength of FSS mixes in the laboratory testing determined the range of strengths available from different FSS mix designs conforming to the flow characteristics developed by the bench scale testing. A higher strength mix could be designed when added ground or lateral support is required; and a lower strength used when bulk filling large underground void.

Three surface water sources (ash pond, abandoned surface mine and cooling tower) along with acidic mine water were considered, characterized, and tested as the dilution water of the FSS blend.

PROJECT DEMONSTRATION

The full scale field demonstration was designed to be a continuous operation requiring large inventories of the FSS. During the demonstration approximately 250 to 600 cubic yards of FSS was placed each eight hour working day for a total of **16,351** cubic yards over an eight week period. The demonstration plant was operated one shift a day and five days per week.

Thirty-five air rotary boreholes were drilled prior to or during injection to evaluate the mine conditions and to serve as injection or monitoring points. Twenty-four of the boreholes encountered mine workings and 11 encountered in-place coal. Nine additional boreholes, all of which encountered mine workings, were drilled to obtain samples of the grout after injection was completed.

Process Equipment

Freshly produced FSS was trucked to the demonstration site and stored on a small temporary storage pad adjacent to the dilution plant. The dilution plant used for this full scale demonstration was a tractor trailer mounted unit manufactured by Excel Machinery Company. The mobility of this unit allows set up in various areas for injection on very large projects. For this demonstration the mobile unit was centrally located over the City Mine and was not moved for the entire eight week period. The slurry piping was flexible and was moved to the various injection points, some located as far as 300 feet from the mobile unit. Water for mixing was pumped from a nearby abandoned surface mine and held in a temporary storage impoundment built next to the dilution plant.

A front end loader was used to transfer the FSS from the temporary storage pad to the feed hopper of the dilution plant. The FSS was then pumped into the mine voids using a Schwing trailer mounted concrete pump (maximum capacity of 127 cubic yards an hour). The positive displacement injection pump delivered the FSS through overland slurry lines to the various injection points. A 900 elbow directed the FSS down the injection borehole through a pipe and into the mine workings.

Injection into the mine workings was monitored at the injection site utilizing a pressure gauge mounted on the 900 elbow at the top of the borehole. Pressure would gradually build up as injection continued and then suddenly fall off to zero, after which the pressure would begin to increase again and the process would repeat itself. Injection continued until the borehole refused by blowing FSS out the top of the borehole between the casing and the injection pipe or when the sustained injection pressure became high enough to cause concern over possibly bursting the pipe. At the completion of injection each day, water was pumped through the dilution plant, concrete pump and injection piping to both clean all the equipment and to erode a flow path through the FSS in the mine workings for start-up the next day.

Injected FSS Monitoring

During the field demonstration, monitoring for FSS and/or changes caused by the FSS consisted of three different procedures. FSS advance was monitored by noting depth changes in boreholes in the mine workings. Water level changes were monitored to evaluate mine pool variations created by injection. Mine pool chemistry was monitored by taking water samples and determining the pH and specific conductance of the water. All three types of monitoring were conducted throughout the field demonstration but because of the large number of boreholes and wells, not all of them were monitored every day. Monitoring was concentrated around the injection points and one or two readings per day were taken from the surrounding boreholes. All open boreholes into the mine workings were monitored every few days and all of the boreholes and the wells were monitored on a weekly basis. The borehole locations are shown on Figure 2.

The results of the monitoring provided good indications of FSS movement. Once the FSS arrived at a monitoring borehole, the grout level in the borehole rose to the mine roof within one to two days. occasionally the FSS level would rise a few feet above the mine roof. FSS travel was in excess of 100 feet. Water levels in the mine varied little during injection but on occasion, a rise in the mine pool of about one-tenth of a foot was noted at the end of a day of injection. The mine pool would be at its normal level the next morning. No evident changes were noted in the pH or specific conductance of the mine pool until FSS was actually measured in a particular borehole.

Injection rates varied from about 280 to 650 cubic yards of FSS per day, with the lower rates occurring primarily during the first two weeks of injection and the rates generally increasing thereafter as the system operation and material properties were refined. Overall, 16,351 cubic yards of FSS was injected during the eight week field demonstration with 6,782 cubic yards in B-10 (coverage approximately 1.3 acres), 4,318 cubic yards in B-20 (coverage approximately 1.1 acres), 4,874 cubic yards in B-35 (coverage approximately 1.2 acres) and 304 cubic yards in B-15. Borehole locations are shown on Figure 2. All of the injection boreholes were filled to refusal except B-15, which was started on the last day of injection. The FSS fluid placement material contained about 55% to 60% solids, variable fly ash to filter cake ratios depending on the plant production (generally 0.7 to 1 or higher as circumstance allowed), and more than 4% total lime content.

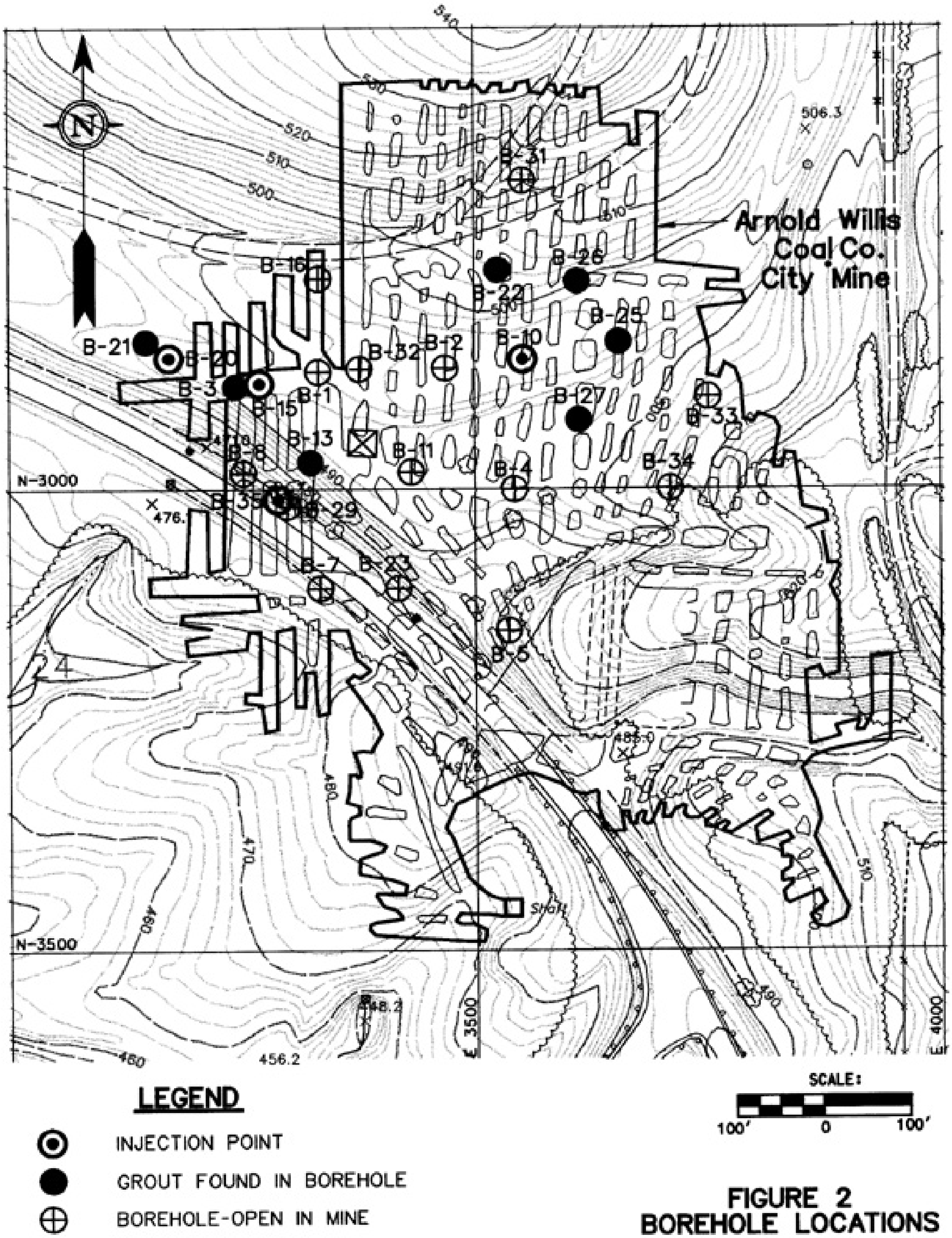

FIGURE 2
BOREHOLE LOCATIONS

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Ground-Water Monitoring

The objectives of the ground-water monitoring were to define baseline conditions existing prior to the fixated scrubber sludge injection and to monitor changes in water levels, flows and water quality during and after the injection. Monitoring wells were placed close to the mine workings so that any water quality impacts would be readily detected and evaluated. A total of nine sampling events were completed during which each monitoring point was sampled and tested for twenty-two different water quality parameters.

In examining the post-injection ground-water monitoring data as compared to leachate data for the FSS, the constituents that emerged as the most useful or as primary indicators of water quality changes related to the FSS injection were, in order of decreasing significance, sodium, potassium, calcium, boron, chloride, and magnesium. Sulfate, TDS, and specific conductance were secondary indicators of FSS injection effects, i.e., changes in these parameters were observable at some monitoring sites but were generally of lesser magnitude and frequency. Arsenic, cadmium, chromium, lead, selenium, aluminum, barium, nitrate, and sulfide were relatively unaffected by the injection. The pH (6.0 to 7.5) and acidity of the mine pool were not significantly affected by the injection of FSS into the mine, suggesting that the mine water's buffering capacity effectively resisted changes in these parameters.

The following general statements can be made regarding water quality affects with respect to well type and location within the injection area:

- The water in the mine pool (voids) exhibited lower pre-injection concentrations of measured chemical constituents than ground water in surrounding rock or unmined coal.
- Water in mine voids tended to exhibit more readily observable chemical changes related to the FSS injection than water in the non-void wells, both in magnitude and in the number of chemical constituents affected; these changes were more pronounced in closer proximity to FSS injection points and to areas in the mine where FSS was documented.
- Ground water in rock and unmined coal tended to exhibit no increases or only subtle, attenuated increases in constituent concentrations and in the number of affected chemical constituents compared to water in mine voids; the changes that were observed were more pronounced in closer proximity to FSS injection points and to areas in the mine where FSS was documented.
- Comparisons of leaching-test and field-monitoring data suggest the laboratory data can be employed as broad indicators of probable chemical changes within the mine pool.

Drilling and Sampling Material in Mine

In order to determine the unconfined compressive strength of injected FSS in the mine workings, three episodes of drilling and sampling were conducted. Sampling was conducted in both existing boreholes known to contain FSS and in additional boreholes drilled in areas where injected FSS was suspected to be in the mine workings.

Since it was questionable as to what type of sampling tools would be best to recover the FSS in the mine workings, various drilling tools were utilized during the initial round of sampling, including a thin wall (Shelby) tube sampler, a two-inch diameter Denison sampler and a conventional double-tube NX rock core barrel. The results of the initial round of sampling indicated that none of the equipment utilized with the possible exception of the two-inch diameter Denison sampler was acceptable for sampling FSS in the mine. Results of sampling FSS in the existing landfill provided similar results for the thin wall tube sampler: the tubes could be pushed into the material but could not be pulled out. Some success had been achieved in sampling the landfill FSS using a conventional four-inch diameter double-tube rock core barrel with a split inner tube. Subsequent sampling utilizing a similar four-inch diameter core barrel along with the two-inch diameter Denison sampler was successful.

Midway through the second round of sampling, the drilling procedure was standardized. Sampling was first attempted in all boreholes with the two-inch diameter Denison sampler, followed, if sampler refusal was encountered, by the four-inch diameter core barrel.

No tool drops were encountered when the new boreholes were drilled into the mine workings filled with FSS. Also, no changes were noted in FSS levels in the existing boreholes from observations made at the time of injection.

All boreholes on-site were plugged at the completion of sampling except for three boreholes which were retained for future ground-water monitoring purposes.

Laboratory Testing

Unconfined compressive strength tests were conducted on the FSS samples obtained during the in-mine sampling. All of the 11 grout core samples tested were generally at or in excess of 100 psi. In-mine samples which cured below the mine pool exhibited strengths below 200 psi. The only samples with strengths above 200 psi were those which cured above the elevation of the mine pool. Denison samples from within the mine workings were obtained from two boreholes. one sample from one borehole had a strength of 139 psi, and two samples from another borehole had strengths of 18 psi and 35 psi. Only one of the 13 boreholes sampled contained low strength grout and the boreholes sampled within 50 feet of it had grout with strengths at 100 psi or higher. At present, we have not determined why the grout strength was low in the one borehole.

Permeability tests were run on three samples, two grout cores and one Denison. The core samples had permeabilities (unconfined compressive strength) of 3.2×10^{-6} cm/sec (not determined) and 1.4×10^{-7} cm/sec (348 psi), respectively. Permeability from the Denison sample was 3.4×10^{-5} cm/sec (35 psi). As with prior work, there appears to be correlation between higher strength and lower permeability.

Borehole Television

Three rounds of borehole television examination were conducted, the first one during the initial evaluation of the mine, the second during injection and the third during grout sampling. The camera and crew were supplied by the Eastern Technical Center of the Office of Surface Mining, Reclamation, and Enforcement (OSMRE), U.S. Department of the Interior, Pittsburgh, Pennsylvania. The camera was requested from OSMRE through the Abandoned Mine Lands Program of the Indiana Department of Natural Resources. The initial work was used to determine which boreholes had encountered open voids and which boreholes were into obstructed (broken rock) mine workings. The work during injection also included evaluating conditions in the mine but concentrated on observing FSS in the mine. While injecting into B-20, and observing in B-21, movement of FSS was recorded almost from the time the FSS entered the mine room where B-21 was located, until the room filled. The camera showed that the FSS did not move as a mass, but rather flowed in a channel across the top of FSS injected previously. Camera work during sampling involved examining in-place grout in dry portions of the mine.

CONCLUSIONS

The demonstration clearly showed that the FSS flow from the boreholes exceeded 100 feet, and based upon volume estimates, approached 135 feet around B-10.

- Utilization of FSS can reduce the number of injection boreholes needed to stabilize underground mine workings. Areas in excess of one-acre were filled from one borehole as was shown on-site in the three cases where borehole injection refusal was achieved.
- The material does not shrink or settle away from the mine roof and generally achieves unconfined compressive strengths of 100 psi or higher.
- The flowing FSS does not appear to mix with mine water but rather displaces it, only the outer surface is exposed to the mine water.
- Air and water in the voids are displaced by FSS, the potential for acid generation from pyrites and organic sulfides is greatly diminished.
- FSS injection can be accomplished with "off-the-shelf" equipment with minor modification.
- Monitoring results indicate limited chemical effects from FSS on mine water and no chemical effects on surrounding ground water.

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