SUBSIDENCE CONTROL BY HIGH VOLUME GROUTING

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ABSTRACT

Various grouting techniques have been used over the years to stabilize existing structures and new construction over abandoned coal mines. The purpose of any mine grouting program is to provide additional support at mine level to control future mine subsidence. Mine grouting programs generally fall into two general methods: flushing and grout columns. With the flushing method, the entire mine under the area to be protected is filled. Grout columns are used to shorten the free span of a mine roof to the point where arching will prevent any spalling from progressing to the ground surface. Because of its fineness and low cost, flyash is commonly used as a bulk filler in both methods. Cement and sometimes coarse aggregate are utilized with the flyash to form the mine grout mixture. Based on conditions encountered at the mine, the consistency and proportions of flyash-cement grout can be modified to suit the mine conditions. The compressive strengths of various flyash-cement grouts used for mine grouting are presented in this paper. The use of high volume grouting techniques utilizing flyash-cement grout slurries for mine subsidence control are discussed. A recent project is discussed to illustrate the techniques, equipment and the grout mix that can be utilized.

INTRODUCTION

The activities of the coal mining industry have resulted in different types of structural and environmental damage to the land. Deep coal mines collapse over a period of time and, under the right conditions, the collapse progressively works its way to the bedrock surface, and overburden soil falls or washes in with consequent subsidence and damage to structures founded at the surface. In general, mine subsidence is inherent in older and, in particular, abandoned mining operations. Due to increasing public awareness, better technology and stricter enforcement of mining laws, newer mining operations tend not to result in these problems.

The states of Pennsylvania and West Virginia, with heavy concentrations of mining industry, received aid from several Federal agencies and have taken a leading role in solving the subsidence and pollution problems of coal mines. Recently, the Federal Government's Office of Surface Mining, a division of the Department of the Interior, has taken the funding lead for these types of problems. There has been extensive research on techniques and there are various methods to combat each of the above-mentioned problems. This paper concentrates on solutions which involve high volume grouting with fluid flyash-based slurry grouts.

Grouting is the injection of a fluidized suspension of colloidal particles into the underground soil and rock profile. Grout holes are drilled to the desired point of treatment and grouts are pumped through grout pipes into the treatment zone. Grout mixes can vary in consistency and strength and may be altered in the field to suit the conditions encountered. Since mine-related problems require a blanket solution on the basis of data gathered at scattered points, the flexibility of grouting makes it valuable as a solution. Contracts are normally written as unit-price, with the bids being compared on the basis of quantities derived from an engineer's estimate. Actual quantities installed may vary significantly as the grouting program is altered to suit conditions actually encountered.

The types of grouting discussed in this paper usually involve much greater quantities of materials than other more sophisticated types of grouting, e.g. dam foundation grouting and grouted structural underpinning. A typical job may involve the injection of thousands of tons of dry materials. The type of equipment used is suitable for high volume materials handling. Frequently, significant economics can be achieved by relaxing some procedural and material specifications from "normal" grouting practice. For example, in most of the areas of Western Pennsylvania, large diameter air-rotary drill rigs can drill grout holes at a fraction of the cost of water-flush drill holes. Some sacrifice may be made in the cleanliness of fissures in the sides of the drill hole but, in cases where large cracks and voids are the major concern, there is little technical disadvantage.

On many projects, flyash is used as a bulk filler. Flyash with the most consistent quality is normally delivered dry in bags or pneumatic trucks. In the dry form, the ash is difficult to handle because of dusting problems. It is usually cost effective to use "wet" or "conditioned" ash that has sufficient moisture to hold together in a pile dumped on the ground by conventional trucks and handled with earth moving equipment. Wet ash that is excavated from flyash holding ponds may contain rock and bottom ash lumps. This loss of uniformity has virtually no importance when grouting all but the smallest fissures. The use of flyash provides a neat environmental symmetry. The ash is returned to its source, resolving two environmental issues simultaneously: disposal of the ash and solving a coal mine-related problem.

SUBSIDENCE

The causes and effects of subsidence over mined-out areas have been discussed in numerous publications, a few of which are included in the attached reference list. The type of mining with which this paper is concerned is where "rooms" and tunnels are cut into the coal seam, leaving coal in place as pillars and the "walls" of the rooms for support. The amount of coal left in place is usually enough to sustain the total weight of rock and soil overhead without crushing. However, the span of mine roof between pillars may be quite large and may, with time, begin to spall off. If the pillars are far enough apart and the rock surface is close enough so that arching does not control the progressive spalling and collapse of the mine roof, it will eventually work its way to the bedrock surface. Overburden may then wash into the mine, causing sink holes and damage to surface structures. In the bulk of the Western Pennsylvania areas where subsidence has caused damage, the mines are only 100 feet (30 meters) deep and in many cases, much less. The maximum depth to which surface subsidence has occurred in the United States as a result of mine subsidence is 700 feet (213 meters). This record depth was experienced on a project near Birmingham, Alabama (Ryan, 1983).

Grouting has been used in cases where subsidence has already begun to cause surface damage, and in cases where sites are treated in advance of construction to counteract potential subsidence. Designing a solution to mine subsidence problems is usually complicated by the fact that the original mine voids are no longer empty. Often the mine roof may be partially collapsed. There may be water standing or flowing on the mine floor or the mine may be completely flooded. Frequently, mine voids are partially backfilled with "gob" which may be rock fragments placed there as a result of later mining operations or sedimented by the action of water. The gob may be very soft but stiff enough that it cannot be easily displaced. The actual state of any mine can be complicated by any of the above conditions, the extent of which may be difficult to determine through the use of exploratory borings.

TREATMENT METHODS

The types of treatment basically fall into two general methods: flushing and grout columns. With the flushing method, the entire mine under the area to be protected is filled. Grout columns are used to shorten the free span of mine roof to the point where arching will prevent any spalling from progressing to the ground surface. Details of the two methods and their relative technical and economic advantages are presented in the paragraphs below. In both cases, the zone of treatment is usually taken as the area projected downwards at a fifteen-degree angle of influence outside the structure (Ackenheil and Dougherty, 1970).

Flushing consists of backfilling the entire mine void in the treatment zone with a weak grout. Holes are drilled around the perimeter, usually on fifteen to twenty-five foot (4.5 to 7.5 meter) centers. The perimeter is grouted first to contain the grout that will be subsequently pumped in the central area. A thicker grout or crushed stone may be used on the perimeter to help prevent excess grout from flowing out of the treatment zone. Once the perimeter barrier has been established, central holes are drilled, usually on twenty to twenty-five foot (6 to 7.5 meter) centers and a weak grout is "flushed" (pumped at a fast rate) into the mine until refusal (Figure 1). Usually, grout is allowed to come to the surface so as to fill voids in the rock that may be present due to the early stage of roof collapse. The grout that is used for this application should be designed to withstand crushing by the weight of overburden. Typically, flyash-cement grouts with ratios in the range of 8:1 by dry weight are used. The flushing technique provides the following technical and economic advantages:

- Lowest cost per unit volume of materials due to maximum use of cheap fillers such as flyash.
- Absolute lowest requirements for quality control of materials. If the grout mix can be pumped, it is probably suitable.
- Lowest reliance on the strength of any gob present, since the overburden pressure is distributed over the widest area possible.
- Essentially yields full roof contact; does not rely on arching to prevent progressive collapse.

The flush-grouting technique has disadvantages where the perimeter of the area is difficult to seal or where the height of the void means that the volume of material becomes prohibitive. In general, this method is best applied in situations where the mine void is low or where it is mostly backfilled with gob. It is also useful in cases where the void is so close to the surface that point support methods (like grout columns) cannot rely on arching to develop between supported points.

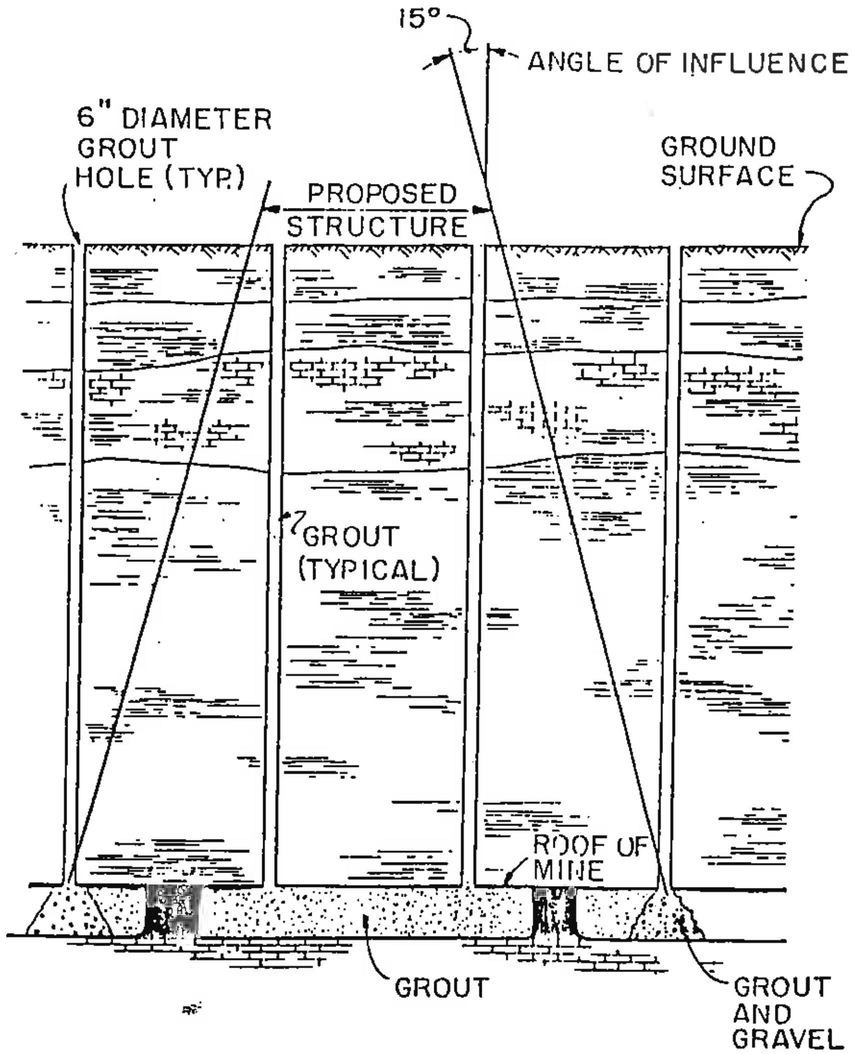
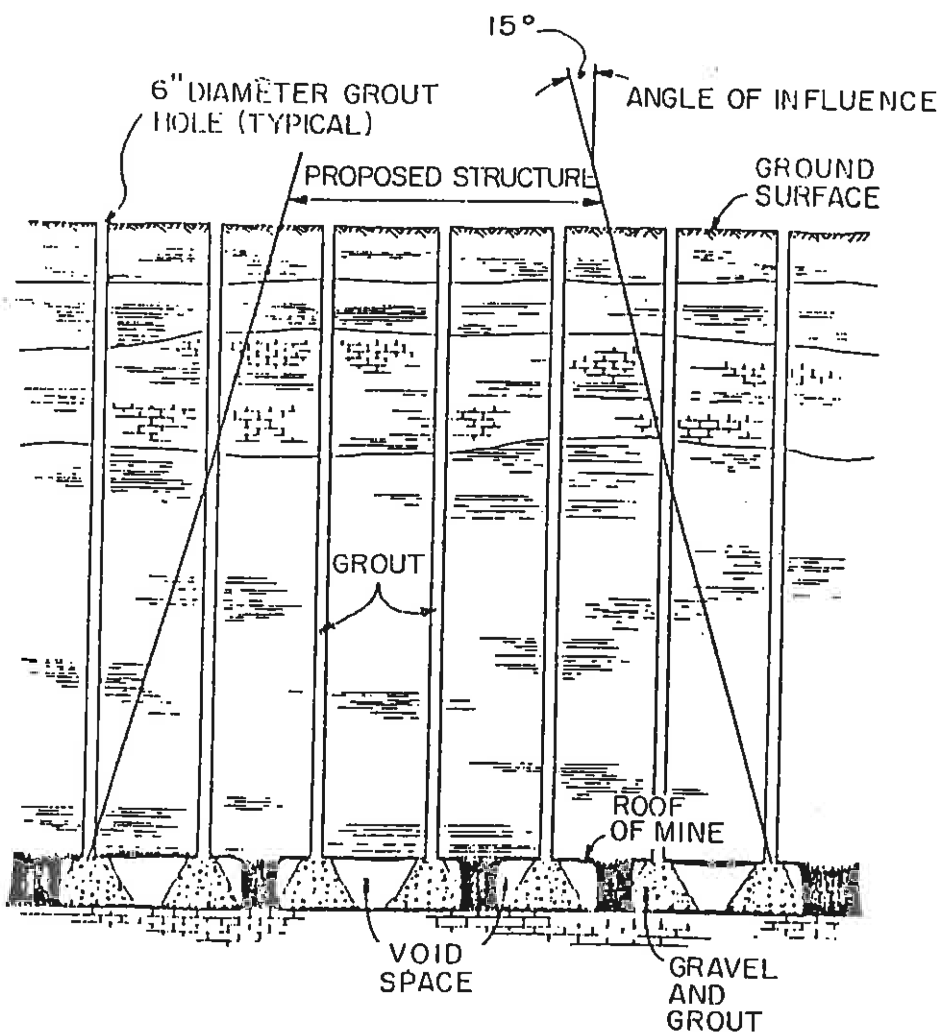


FIGURE 1 - SCHEMATIC OF FLUSH GROUTING FOR MINE SUBSIDENCE CONTROL

Once the void height increases beyond a few feet, it is usually more economical to consider grout columns (also called gravel or stone columns). With this technique, holes are drilled on grid spacings narrow enough so that the mine roof will support itself by arching between columns. Some holes on the grid will encounter solid coal pillars; these are backfilled with grout. The balance of the holes are first filled with a gravel cone; gravel (3/4-inch [2 cm.] crushed slag or stone) is poured down the holes and spread by a jet of compressed air at the bottom. The compressed air maximizes the roof contact.

Once this is done, a grout pipe is driven through the gravel and down into any gob below. Grout is injected into the gob and gravel in measured amounts at one-foot (30 cm.) intervals with the objective of making a grouted cylinder of sufficient diameter to support the mine roof (Figure 2). The gravel may tend to slump during the grouting and additional gravel may have to be added.



<u>FIGURE 2 - SCHEMATIC OF GROUT COLUMNS FOR MINE SUBSIDENCE CONTROL</u>

This process is more expensive on a unit-volume basis than flush-grouting because there is a considerable amount of work needed to be done "down-the-hole", i.e., the grout is injected through grout pipes and measurements of the top of the stone are needed frequently. Also the grout is typically a more expensive 3:1 flyash-cement grout by dry weight.

Good control of material quality is needed since small lumps can plug the grout pipes or prevent the stone column from being properly grouted. Grout columns do present the following advantages, however:

- Lower cost in some cases because only a small percentage of the mine void is actually treated.
- No reliance on creating barriers to seal off the treatment zone.
- Flexibility in spacing to suit load factors and differing degrees of risk.

A major drawback of the technique has always been that there is no way to reliably check the roof contact area upon completion. Adequate roof contact area is difficult to achieve in mines that are completely flooded. Experience on experimental columns in open, dry mines and where borehole photography has been used, has shown that good technique does result in good contact. Of course, as the void height increases, the volume of the stone columns themselves increase dramatically to the point of becoming uneconomical compared to other systems (caissons, etc.) For this technique, as with flush grouting, a reasonably thorough exploration program to lay out the work as well as on-going engineering control during the grouting program is necessary to ensure a good end-product.

FLYASH BASED GROUT SLURRIES

In the United States, more than 60 million tons (55 million metric tons) a year of flyash are produced as a by-product from coal-burning power plants. Presently, only about twenty percent of the higher quality ash is being used in concrete (Glogowski and Kelly, 1987). The remaining eighty percent, although not conforming to all of the ASTM requirements, and normally requiring disposal, serves as a readily available, low cost filler for mine subsidence control projects.

ASTM divides flyash into two classifications, Type F and Type C. Type F flyash is commonly found in the eastern states where local bituminous and anthracite coal is burned in the power plants. Type C flyash is produced from the burning of subituminous and lignite coal located in the western portion of the United States. Both types of flyash have pozzolanic properties. Type C flyash contains lime which gives it cementious characteristics. When mixed with only water, Type C flyash will set without any addition of cement. A majority of the writers' experience is with the use of Type F flyash.

Figure 3 presents in graph form the approximate relationship of compressive strength to grout slurries of various flyash-cement ratios using Class F flyash. Typical water to solids ratios (WSR) by weight for flush grouting projects vary from 0.4 to 0.6. A 0.4 WSR corresponds to a water content of about 100 gallons per cubic yard (500 liters per cubic meter) of grout. Depending on the amount of overburden and other factors, the flyash-cement ratio of the grout used in flush grouting typically varies from 7:1 to 11:1 by weight.

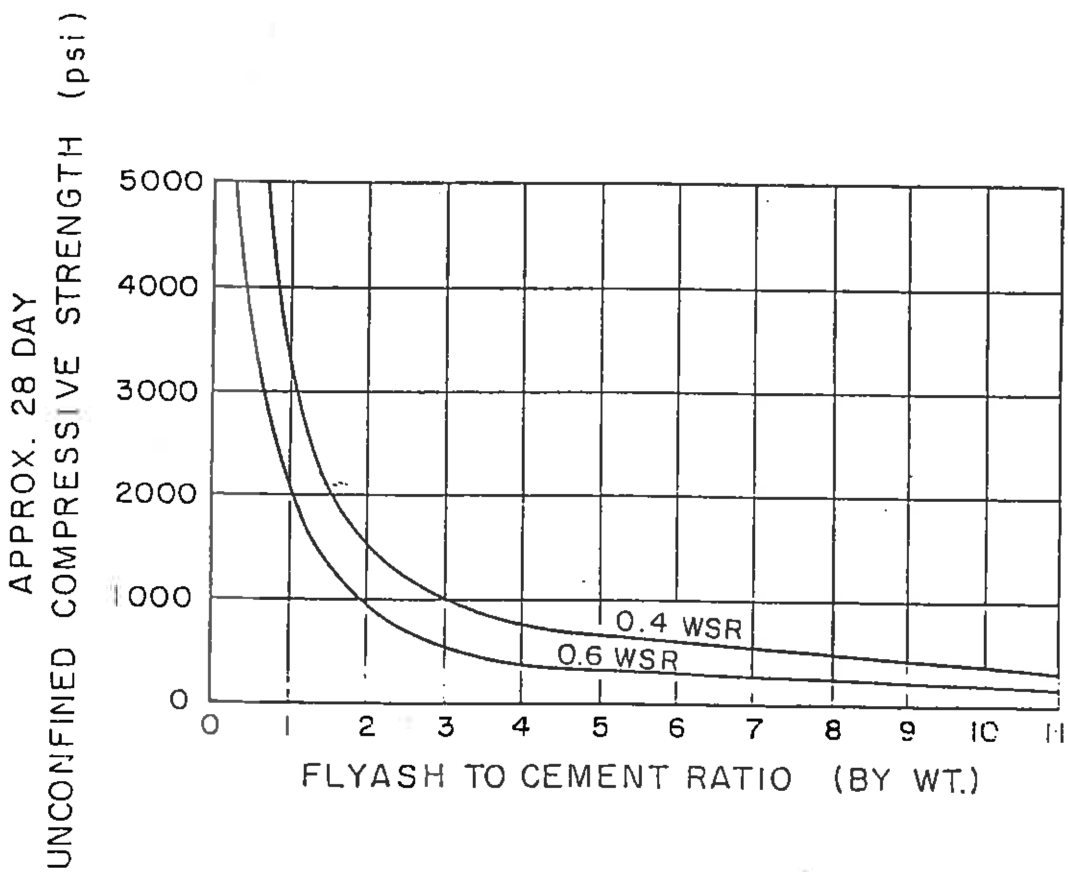


FIGURE 3 - RELATIONSHIP OF STRENGTH TO FA/C RATIO FOR CLASS F FLYASH SLURRIES

The primary factor in determining the unconfined compressive strength of flyash-cement grout mixes is the cement to water (C/W) ratio (Glogowski and Kelly, 1987). Figure 4 presents a curve which can be initially used when selecting a C/W ratio to meet a desired strength requirement. Because flyash sources vary in quality, a preconstruction testing program is recommended to determine the strength of the grout mixes using materials from the proposed sources.

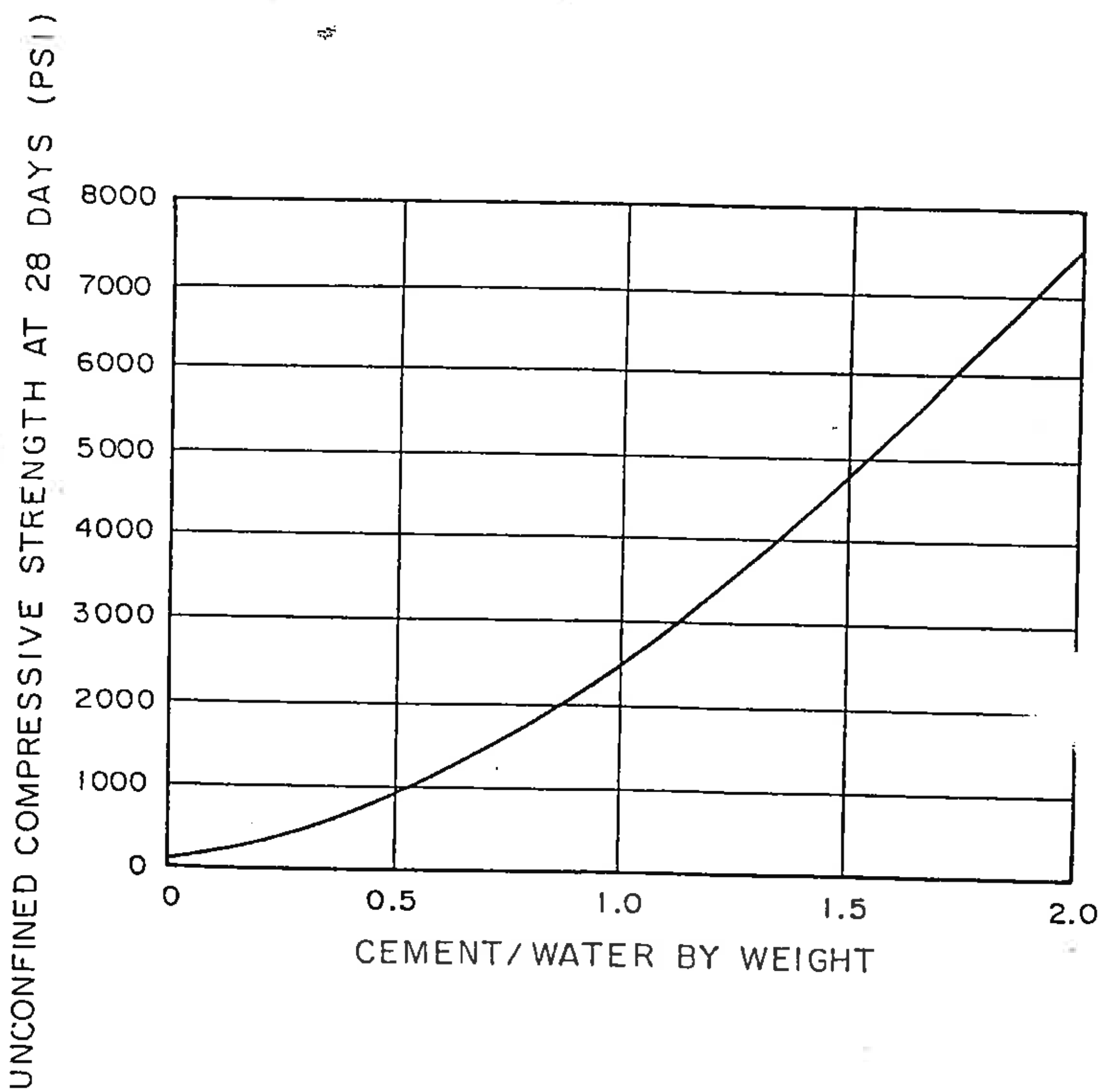


FIGURE 4 - RELATIONSHIP OF STRENGTH TO C/W RATIO FOR CLASS F FLYASH SLURRIES

(From Flyash Slurry Testing Programs Draft Report, GAI Consultants.)

Two advantages that flyash provides in a grout mix include strength gain and flowability. Strength gains from 28 to 365 days can exceed 300% on certain flyash-cement grout mixes. Figure 5 shows effects of curing time on strength of several Class F flyash mixes. Typical strength gains from 28 to 365 days usually range from 25% to 75% for Type F flyash-cement grout slurries with cement contents in the 5% to 10% range by weight (Glogowski and Kelly, 1987).

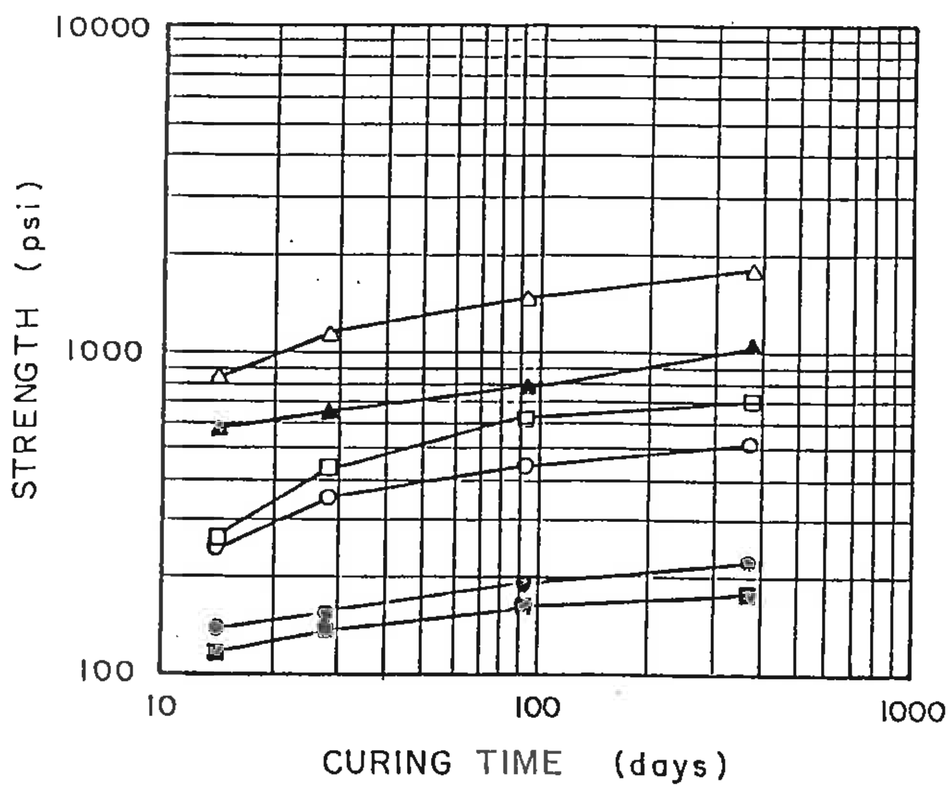


FIGURE 5 - EFFECT OF CURING TIME ON STRENGTH OF SEVERAL CLASS F FLYASH MIXES

(From Flyash Slurry Testing Programs Draft Report, GAI Consultants.)

Because flyash has a spherical particle shape, flyash-based mixes will flow better with less water than neat cement grouts. This characteristic provides a grout that can penetrate fractures, roof fall material and mine gob backfill effectively. Figure 6 illustrates the improved flowability of several grout mixes as their flyash content is increased and their water to solids ratio is held constant.

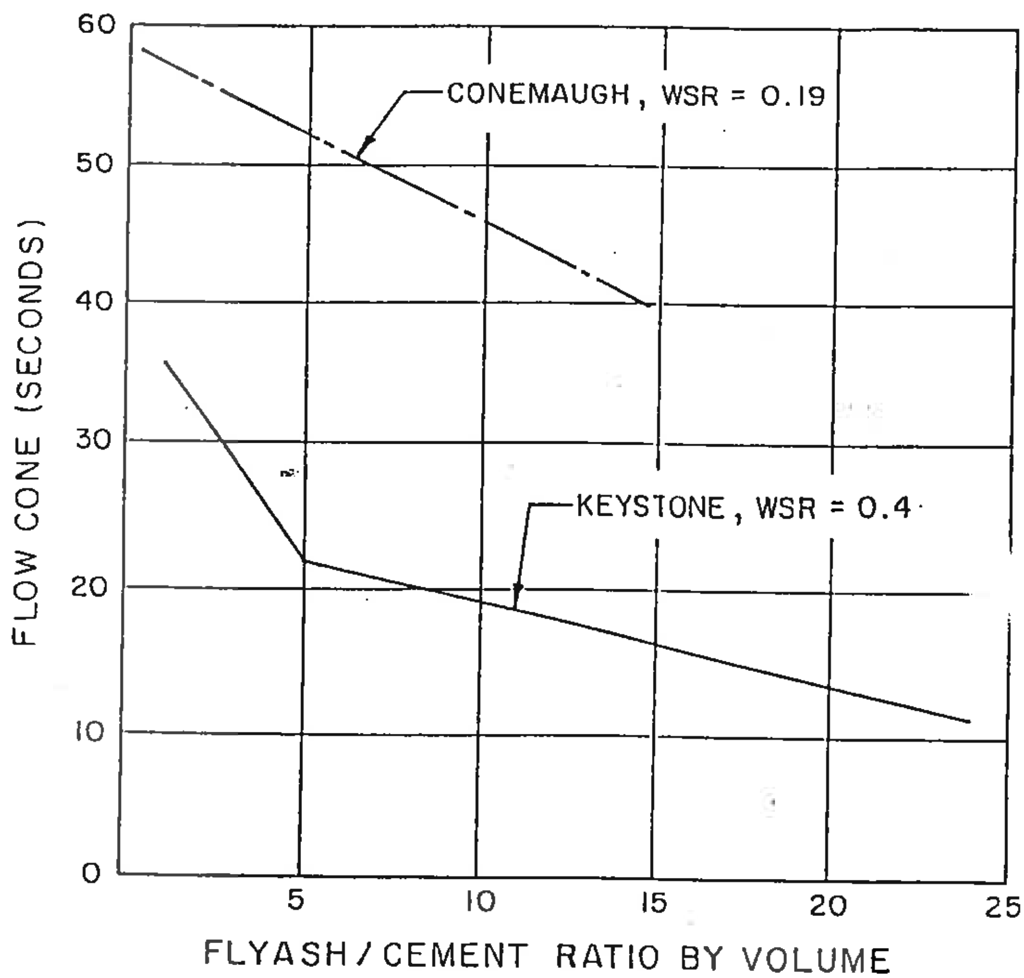


FIGURE 6 - RELATIONSHIP OF FLOW TO FLYASH/CEMENT RATIO FOR TWO FLYASH SOURCES

EQUIPMENT

The equipment used for both flush grouting and grout column techniques are similar. Large air-rotary rigs drilling a 6 inch (15 cm.) diameter hole (Figure 7) usually provide the cheapest drill-hole. In cases where surface access is obstructed, smaller air-tracks or skid rigs may be used. Grout may be delivered in ready-mix trucks and held in an agitation tank or grout materials can be delivered and mixed on site (Figure 8). Grout pumps are usually of the positive displacement type, either piston or progressive cavity type pumps. In cases where gravel is to be injected, it is placed in a hopper and forced down the hole with compressed air.

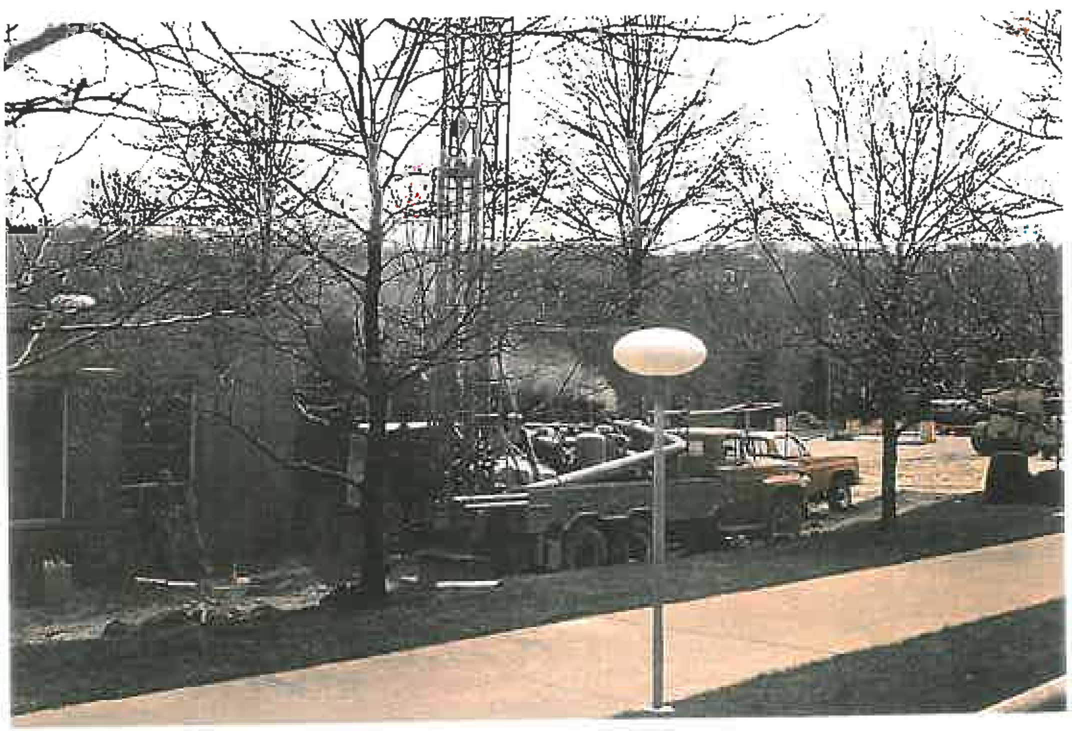


FIGURE 7 - AIR ROTARY DRILL

FIGURE 8 - ON-SITE MIXING

RECENT PROJECT

Grove City College, in Western Pennsylvania, had planned the expansion of the College's recreation hall facility. During the initial investigation for this expansion, it was determined that several of its existing structures were heavily undermined. The mined coal seam was located approximately 50 to 65 feet (15 to 20 meters) beneath the existing structures.

After initial investigation, an emergency two phase mine grouting program utilizing grout columns was put out for bid. Phase one consisted of the construction of grout columns using a thick concrete type grout. Phase two would then consist of filling the remaining mine spaces with sand for additional support. A one phase alternative using the flush grouting method was submitted and accepted, which resulted in a lower overall cost and could be completed in less time than the original specified program which utilized grout columns.

The alternative program consisted of initially drilling barrier holes around the perimeter of the existing structures and injecting a pea gravel to form a barrier. Drilling these holes was accomplished using truck-mounted air rotary drill rigs. Pea gravel was chosen instead of crushed limestone because the rounded pea gravel resulted in flatter side slopes for the barrier which resulted in a tighter containment structure. In addition, the pea gravel was finer grained which reduced the amount of grout which could penetrate and potentially flow through the barrier. During placement of the gravel down each barrier hole, compressed air was injected into the mine via a steel pipe to aid in spreading the gravel at mine level.

After creation of the gravel barrier, a fluid flyash-cement grout slurry was injected within the barrier to provide the necessary support. This grout was pumped through pipes lowered into angled injection holes which extended beneath the existing structures. The drilling of the angled interior holes was accomplished using track and small truck-mounted rotary drill rigs. During grouting, the level of the gravel in the barrier holes was monitored for sloughing. Additional gravel was placed in these holes as required.

The grout mixture on this project consisted of a 10:1 flyash to cement grout by weight with an average water to solids ratio of 0.4. This grout was mixed on-site using two 5 cubic yard (4 cubic meter) mixers. As grout was being pumped from one mixer, the other mixer was mixing the next batch of grout, thus providing a continuous source of prepared grout.

Production rates of mixing and placing the grout on this project peaked at several hundred cubic yards per day. Pumping was accomplished using a large progressive cavity pump.

Conditioned or damp ash was loaded into the mixers from stockpiles using a front end loader. Cement from an overhead silo was batched into the mixers via a weigh scale. Water which was pumped from the flooded mine was used in grout mixing and was monitored by a flow meter.

During grouting operations, the level of the grout within the mine was monitored on a daily basis by sounding various boreholes within the work area. On-site testing of the grout mix included density testing using a mud balance, and testing the grout's viscosity using a flow cone. In addition, water quality tests were performed on the mine water, and grout cubes and cylinders were prepared for compressive strength testing.

The results of the compressive testing yielded an average grout strength of 128 p.s.i. (9.0 kg. per sq. cm.) at 28 days. The bearing capacity of this grout backfill can be estimated conservatively at three times its unconfined compressive strength (Czmola and Voytko, 1986). Using the

28 day strength of 128 p.s.i. yields a bearing capacity of approximately 384 p.s.i. (27 kg. per sq. cm.). Since the total maximum overburden load above mine level is only in the range of 70 p.s.i. (4.9 kg. per sq. cm.), the grout backfill has more than adequate strength to support the overburden loads.

CONCLUSION

In this paper, the use of high volume grout techniques are shown to be of significant economic and practical benefit when applied to coal mine subsidence problems. The basic advantages that apply are:

- Minimum Disturbance

  The problems are treated remotely without major excavations; in cases where structures exist on the surface, angle holes can be drilled beneath the structures.

- Flexibility of Technical Solution

  A relatively large number of holes provide information to the engineer on subsurface conditions. Mix ratios, pumping rates and pressures can all be varied to produce desired effects.

- Economical Results

  The cruder types of grouting that have been discussed in this paper enable large volumes of material to be placed at low cost.

A secondary benefit is the rather neat environmental solution that sees the waste product of burning coal, flyash, returned to the mines from where it came to reduce other coal mine related environmental damage. It is certain that grouting will continue to play a major role in reducing damage from coal mine pollution and subsidence problems.

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KEY WORDS:

Grouting, coal mines, subsidence, flushing, grout columns, flyash, flyash-cement, grouts, grout strengths, grouting techniques.