FULL-SCALE EVALUATION OF THE PERFORMANCE OF GROUT COLUMN SUPPORTS FOR MINE SUBSIDENCE ABATEMENT[1]

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Abstract: This U.S. Bureau of Mines report evaluates the load performance characteristics of grout columns used as point-supports for mine subsidence abatement. Several full-scale grout columns were constructed at the Subsidence Abatement Investigation Laboratory (SAIL) in water-filled pools to determine the optimum sodium silicate concentration for a flooded mine environment. The scope of work included the testing of seven full-scale grout columns in the Bureau's Mine Roof Simulator (MRS) from which the load-deformation and failure characteristics were determined. The performance of grout columns is analyzed with respect to (1) the amount of roof contact established during column construction, (2) shape effects produced by the truncated cone geometry, (3) size effects in reference to grout strength and full-scale column capacity, (4) the effect of wet environments on grout strength, (5) the effect of the sodium silicate on the grout strength and full-scale column behavior, and (6) the stiffness of the grout column. Recommendations for point-support construction using sodium silicate technology and the need for additional research to develop improved containment devices for column construction are addressed in the report.

Additional Key Words: grout columns, point-supports, subsidence abatement.

Introduction

Mine subsidence creates erratic and differential movement of ground that disrupts water tables and damages surface structures and subsurface utilities. In room-and-pillar mining, the subsidence is unplanned and generally occurs when unmined pillars of coal deteriorate. The subsidence may take years to decades to manifest itself, and is frequently a problem in abandoned coal mines. The lack of access to these abandoned workings makes remediation efforts difficult. The most common method for control and abatement of abandoned mine subsidence is to fill the mine voids and overburden fissures with a low-strength cementitious grout, which is pumped into the mine in slurry form through several surface boreholes (Gray et al., 1974). Ground stabilization by filling all the voids in the affected area often requires several thousand cubic yards of grout, resulting in abatement costs in the hundreds of thousands of dollars. It has long been recognized that strategic placement of point-support columns would substantially reduce the volume of material and cost of abatement (Michael et al., 1989).

Early attempts at forming point-support systems for subsidence abatement by grouting loose piles of aggregate placed down a borehole (fig. 1) were largely unsuccessful. The loose aggregate provided a poor angle of repose that required large amounts of material and inadequate roof contact area (Michael et al., 1989). It was also difficult to grout the aggregate after the pile was formed. The next generation of point supports was formed using a low-slump cementitious grout. However, placement problems were also experienced with this design, particularly in wet environments where the grout was dispersed by the water before a column could be formed. The most recent approach to grout column formation is the use of

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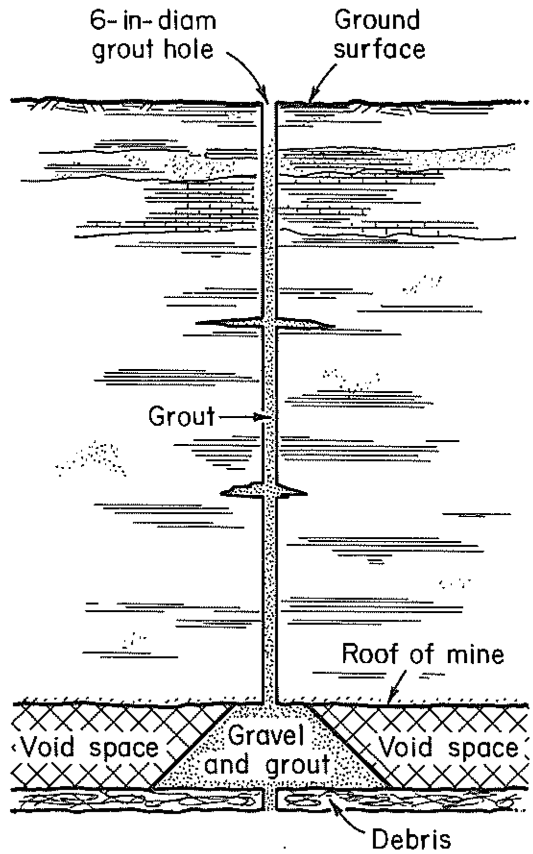

Figure 1. Early attempts at forming point supports by grouting loose piles of aggregate.

sodium silicate as an admixture to a cementitious grout. The sodium silicate accelerates the setting of the grout, providing a stiffer mix, and acts as a barrier to water, allowing truncated cone-shaped columns to be formed in completely flooded mine voids (Reifsnyder et al., 1988).

Objectives

The purpose of this research was to determine the formation requirements and supporting characteristics of grout columns through full-scale testing. Previous research has been limited to material strength tests and observation of full-scale column construction. Full-scale strength testing of grout columns has not been attempted prior to this study.

Scope of Work

The scope of work included the construction of four full-scale grout columns at the SAIL in water-filled pools to determine the optimum sodium silicate concentration for flooded mine environments. The scope of work also included the testing of seven full-scale grout columns in the MRS from which the load-deformation and failure characteristics of the structures were determined. The MRS load frame incorporates 6- by 6-m (20- by 20-ft) platens and can simulate loads of up to 13,334 kN (3 million lb). The material strength of the grout as a function of time was determined from controlled loading of 15-cm (6-in) diameter, 20-cm (8-in) high, cylindrical grout specimens for each of the grout mixes. Size effect relationships were evaluated by testing 61-cm (24-in) diameter, 122-cm (48-in) high, cylindrical specimens and comparing their strength to that of the 15-cm (6-in) diameter specimens. The measured strength of the 15-cm (6-in) diameter cylinders was reduced by 6 pct in accordance with ASTM specifications for specimens with an aspect ratio of less than 1.8. Load-deformation tests were also conducted on three small-scale cone specimens where the geometry of the cone was controlled by sheet metal forms. Truncated cone geometries were formed with cone angles of 15°, 30°, and 45° (angles measured with respect to vertical plane from top cone surface). The cones were all 39 cm (12 in) high with a 15-cm (6-in) diameter top surface. The variable cone angle simulates different angles of repose, which permits examination of the contribution of material outside the central core to the support capacity.

Description of Column Construction and Test Parameters

Four full-scale columns were constructed at the Bureau's SAIL at Lake Lynn and three columns were constructed on the platens of the MRS load frame at the Pittsburgh Research Center. The columns were constructed from a fly ash-cement grout and sodium silicate. The cementitious grout was supplied by Lambert Construction Co., which was employed as a contractor to construct the grout columns. The design mix for the MRS columns consisted of 3,114 N (700 lb) of Portland I cement, 7,517 N (1,690 lb) of fly ash, and 3,558 N (800 lb) of water with a design strength of 10,276 kPa (1,490 psi) at 14 days. The grout mix for the SAIL columns was 1,672 N (376 lb) of Portland I cement, 7,993 N (1,797 lb) of fly ash, and 2,224 N (500 lb) of water with a design strength of 6,207 kPa (900 psi) at 7 days.

Figure 2. Nozzle used for application of sodium silicate and cementitious grout in column construction.

The grout and sodium silicate were delivered through a 5-cm (2-in) diameter nozzle. This nozzle is a common design in the industry for sodium silicate application. The sodium silicate is pumped through a separate line and is injected at the nozzle, where it is dispersed through the outer nozzle annulus to encapsulate the grout stream coming out of the nozzle (fig. 2). The volumetric ratio of the grout to sodium silicate is controlled by controlling the pumping rate of the grout and sodium silicate. The grout is tremied in place by initially placing the nozzle at the floor and slowly raising it as the column grows in height.

Tests were conducted under controlled-load conditions to evaluate the strength of the grout materials and the structural response of grout columns. Material strength tests were conducted on the 15-cm (6-in) diameter specimens at a load rate equivalent to 138 kPa/s (20 psi/s) in accordance with ASTM specifications. The 61-cm (24-in) diameter cylindrical specimens and the full-scale columns were tested at a controlled displacement of 1.3 cm/min (0.5 in/min), chosen from past experience with large-scale concrete specimens and the load frame limitations.

Columns Constructed at the SAIL

The grout columns constructed at the SAIL were formed in 5.5-m (18-ft) diameter, 1.2-m (4-ft) high, water-filled swimming pools to simulate a flooded mine environment. One column was constructed in a dry environment to evaluate the interaction of the sodium silicate with the grout in the absence of water. The grout and sodium silicate were pumped from ground level to a height of approximately 9 m (30 ft) to simulate borehole drop velocities during grout placement.

The control parameter for these column constructions was the volumetric ratio of fly ash-cement grout to sodium silicate. The purpose of these tests was to determine the optimum sodium silicate concentration for a flooded environment. Four grout-to-sodium silicate ratios were evaluated: 5:1, 7.5:1, 10:1, and 12.5:1. The 10:1 concentration provided a moderate cone angle of 50° (measured from vertical) in the wet environment, while forming a solid foundation that resulted in a symmetrically shaped, truncated cone structure. The 12.5:1 ratio did not have sufficient sodium silicate to prevent dilution of the cementitious grout in the wet environment, resulting in an unacceptable cone angle. The 7.5:1 ratio provided a cone angle similar to the 10:1 ratio, but the structure was more asymmetrical. When the sodium silicate concentration was increased to 5:1 ratio, there appeared to be a surplus of sodium silicate. The cone angle provided by the 5:1 ratio was less than the 7.5:1 and 10:1 ratios, but the base area was considerably smaller. Based on these observations, a 10:1 grout-to-sodium silicate ratio is a reasonable lower limit in the required sodium silicate concentration necessary to provide a well-shaped point support in a flooded environment.

Four SAIL columns were transported to the Pittsburgh Research Center for full-scale testing in the MRS. A physical description of each column and the construction parameters are provided in table 1.

Table 1. Description of grout columns constructed at the SAIL.

	Column 1	Column 2	Column 3	Column 4
Grout-to-sodium silicate ratio	7.5:1	5:1	10:1	10:1
Environment	Wet	Wet	Wet	Dry
Material volume . . . . m^3. . . .	1.0	1.7	1.1	2.4
Height of column . . . . cm	122	117	122	152
Cone angle, deg from vertical	45	38	50	40
Area of base . . . . m^2. . . .	2.3	3.5	3.4	2.6

Columns Constructed in the MRS

Three columns were constructed on the platens of the MRS. The grout-to-sodium silicate ratio was controlled to approximately 10:1 for all three columns. The columns were constructed in a dry environment. An artificial roof with a 15-cm (6-in) diameter hole was provided to simulate a borehole and underground roof contact. A description of the three columns constructed in the simulator is provided in table 2.

Table 2. Description of support columns constructed in the MRS.

Column		Column 1	Column 2	Column 3
Roof contact area	cm^2 . .	1,290	2,829	7,354
Grout to sodium silicate ratio	. . . . .	10:1	10:1	10:1
Material volume	m^3 . .	2.3	3.1	3.8
Height of column	cm . .	137	145	130
Cone angle	deg . .	42	42	45
Borehole condition	. . . . .	Open	Closed	Closed

Test Results

SAIL Specimens

The load-deformation responses of the four full-scale grout columns constructed at the SAIL are compared in figure 3. Columns constructed from the 10:1 grout-to-sodium silicate material exhibited significantly higher strength and stiffness than columns constructed with other concentrations of sodium silicate. At 15 cm (6 in) of displacement, the load capacity of the columns constructed with 10:1 grout-to-sodium silicate material was 334 kN to 445 kN (75 to 100 kips), compared with 44 kN (10 kips) for the 5:1 and 7.5:1 material column constructions.

The small top surface area, due to the lack of roof contact, and uneven bottom surface degraded the supporting capability of these columns. The application of controlled displacement to the specimen caused the top of the column to crumble, which allowed the area of the top surface to gradually increase. The larger contact area provided an increase in capacity with increased displacement. When the stress exceeded the material strength, the columns would split from top to bottom, and the column would shed load as broken segments of the column were pushed apart. When confinement reduced the lateral expansion of the broken segments, the load would gradually recover and continue to increase until the next failure. This cycle continued through several inches of displacement, as shown in figure 3.

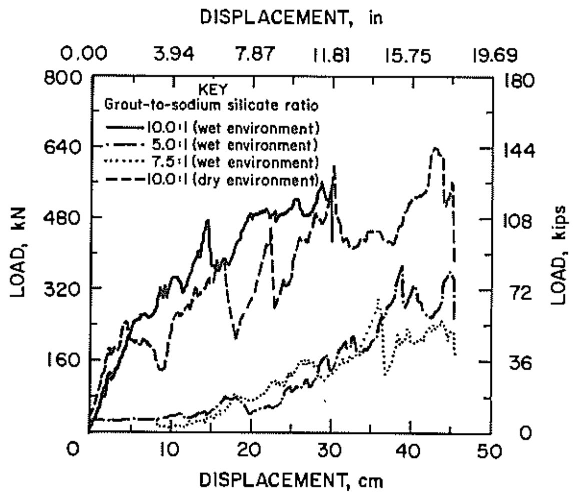

Figure 3. Load-deformation response of full-scale grout columns constructed at the SAIL.

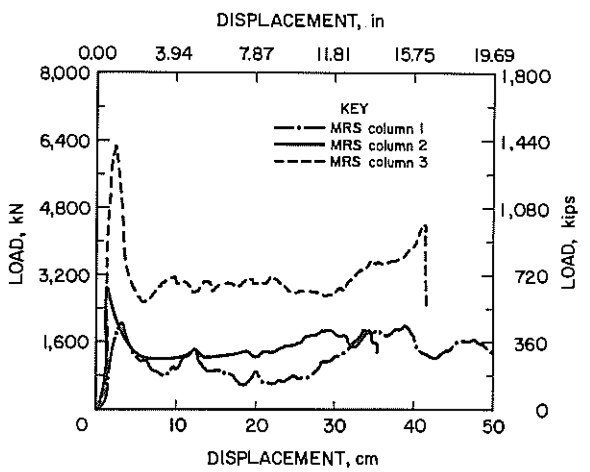

Figure 4. Load-deformation response of MRS columns.

MRS Specimens

All of the columns constructed in the MRS used a 10:1 ratio of grout-to-sodium silicate. The design strength of the grout was 10,275 kPa (1,490 psi) after 7 days, which was verified by tests on 5-cm (2-in) cube specimens by the commercial supplier. However, the measured strength from the 61-cm (24-in) diameter specimens was 4,276 kPa (620 psi). Columns constructed in the MRS avoided the problem of an uneven bottom surface, which degraded the performance of the columns constructed at the SAIL. The MRS columns were also constructed against an artificial roof to provide roof contact and a measurable top surface area. Unlike the columns formed at SAIL without roof contact, the MRS columns exhibited a high initial stiffness as they developed significant resistance with little displacement, as shown in figure 4. All columns began to fail as the top surface stress approached 7,241 kPa (1,050 psi). After the initial failure, the stiffness of the support structure decreased slightly (fig. 5), while the load capacity continued to increase with increasing displacement. Maximum load occurred when localized failures (cracks) coalesced to fracture the specimen from top to bottom.

Maximum load capacities of 2,002 kN, 2,847 kN, and 6,338 kN (450 kips, 640 kips, and 1,425 kips) were observed for columns 1, 2, and 3 as referenced in table 2. These maximum capacities were attained at less than 2.5 cm (1 in) of convergence. Load resistance after reaching the maximum capacity was reduced by about 50% as the columns split through their cross section and crushed from the continued convergence. The capacity attained with the full-scale columns was lower than expected, based upon the measured 4,276-kPa (620-psi) material strength and the 350 to 400% increase in capacity above the material strength demonstrated in the small-scale cones of a similar geometry. Based upon these measures, the initial failure of the full-scale columns should have occurred at top surface stress levels of 14,966 to 17,103 kPa (2,170 to 2,480 psi), as opposed to the observed initial failure at 7,241 kPa (1,050 psi). Failure of the columns to sustain these stress levels is attributed to the presence of cold joints formed by the sodium silicate and the asymmetrical shape of the structures.

Analysis of Test Results

Several factors have been identified that affect the performance of these support structures. These include (1) wet environment, (2) size effects, (3) shape effects, (4) deficiencies of sodium silicate, (5) roof

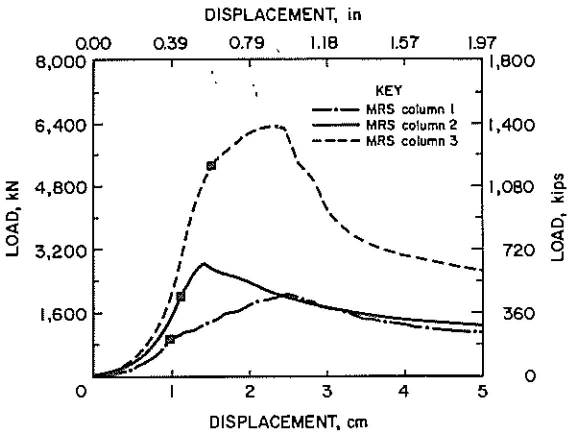

Figure 5. Decreased stiffness of grout column after first failure.

contact area, and (6) material strength. Other design considerations include the stiffness and mode of failure of the support structure.

Wet Environments

The test data indicate that a wet environment reduces the grout strength. Both 15-cm (6-in) diameter and 61-cm (24-in) diameter grout specimens that were poured and cured in water were found to be of lower strength than samples cured in a dry environment. The effect of the wet environment was more substantial on the smaller samples, where the compressive strength was reduced by approximately 75%, compared with approximately 50% reduction for the large-scale samples. The reduced strength of the samples cured in wet environments is possibly due to the heat loss during the curing process (American Concrete Institute 1986).

Size Effects

Previous research has shown that a 50% reduction in strength of concrete materials is observed when the specimen size exceeds 61 cm (24 in) in diameter in comparison to 15 cm (6 in) diameter or smaller specimen sizes (Mindred et al., 1981, Glucklish 1990). Tests on 61-cm (24-in) diameter grout column material specimens have shown this strength reduction can also be expected for full-scale grout column supports. The initial failure of the MRS columns occurred when the top surface stress approached 7,241 kPa (1,050 psi), which is 30% less than the grout design strength. Therefore, the material strength should be reduced by a factor of 1.5 to 2 to provide a conservative estimate of grout column capacity hased on the top surface area and material strength.

Shape Effects

Previous research in materials science and rock mechanics has shown that lateral confinement significantly increases the strength of the specimen by changing the state of stress from uniaxial to triaxial during load development (Mindress et al., 1981). Since confinement is partly dictated by the shape of the structure, shape effects are a primary consideration in large-scale structural evaluations. The conical shape of grout column structures enhances the load capacity of the support by providing lateral confinement to the core of the support column.

Figure 6 shows a 350 to 400% increase in capacity for small-scale cones with a 15-cm (6-in) diameter top surface area and a 35° to 40° cone angle as compared to a cylindrical specimen with the same top surface area. The relationship between load and cone angle is nonlinear with the strength improvement diminished as the cone increases in cross-sectional area at larger cone angles. However, this increase in capacity due to the cone geometry was not fully realized in the full-scale grout columns. Full-scale grout columns provided a strength increase of about 75% in relation to the material strength measured from 61-cm (24-in) diameter specimens, or a 5% increase in capacity in relation to material strength measured from 15-cm (6-in) diameter specimens. Failure of the columns to reach the expected level of strength is attributed to the presence of cold joints formed by the sodium silicate and to the asymmetrical shape of the structure.

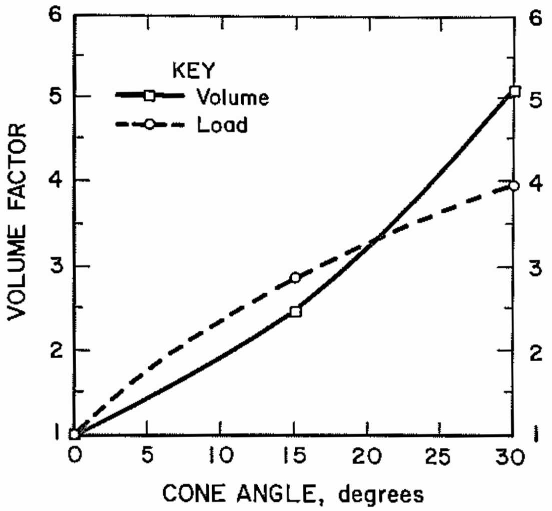

Figure 6. Relationship between material volume and specimen strength for small-scale cone specimens as a function of the cone angle.

Deficiencies of Sodium Silicate

The use of sodium silicate enables a structure to be formed in a water-filled environment that could not be formed without it. However, there are some deficiencies associated with the use of sodium silicate. Inadequate mixing of the sodium silicate with the cementitious grout produces pockets or layers of sodium silicate gel that reduce the load capacity of the support structure. During column construction, grout flows through the path of least resistance and down a small area on the side of the cone. As this section of the cone builds, increased resistance diverts the grout flow to a different area where the grout has already set, and the newly placed grout does not fully react with the previously placed material. The resultant layering creates planes of weakness in the structure that reduce the load capacity of the column. The sodium silicate accelerates the setting time for the grout, which is advantageous for column construction, but the accelerated setting time also increases the tendency for plugging.

Roof Contact Area

Roof contact area largely determines the capacity and stiffness of grout columns. As shown in figure 7, the initial failure of the grout columns tested in the MRS is linearly related to the roof contact area. Hence, the capacity of the support is directly related to the area of roof contact established during column construction. The material strength achieved in the full-scale column can be determined from the slope of the load versus contact area plot. For the MRS columns depicted in figure 7, the material strength was 7,241 kPa (1,050 psi).

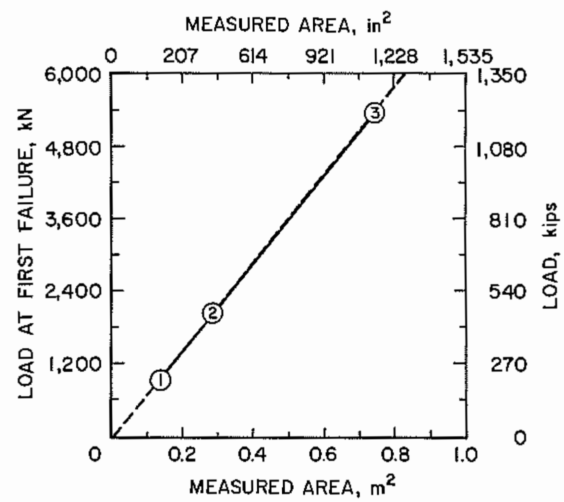

Figure 7. Initial failure of MRS grout columns as a function of roof contact area.

The stiffness of the grout column is also highly dependent on the roof contact achieved during column construction. Stiffness is an important design consideration because it indicates how much convergence must take place before the grout column provides a specified magnitude of resistance. The significance of roof contact area to the stiffness of the column was clearly demonstrated by comparison of the SAIL columns, which were formed without roof contact, and the MRS columns, which attained 1,290 to 7,354 cm^2 (200 to 1,140 in^2) of roof contact. The initial stiffnesses of the MRS columns were two orders of magnitude higher than those of the SAIL columns. The initial stiffness ranged from approximately 1,750 kN/cm (1,000 kips/in) for MRS column 1 to 6,567 kN/cm (3,750 kips/in) for MRS column 3, increasing as the top surface area increased.

Grout Strength

The grout strength obviously affects the capacity of the support column. Grout strength is primarily determined by the amount of cement in the grout mix but is affected by many other factors. However, as previously indicated, the sodium silicate tends to reduce the effective grout strength in the full- scale column by creating planes of weakness where the sodium silicate is not properly mixed with the grout. In high concentrations, the sodium silicate forms a gel that has very little tensile or shear strength.

Conclusions

Sodium silicate allows a grout column to be constructed in a wet environment, provided there is sufficient concentration and proper mixing of the sodium silicate with the cement-fly ash grout. A 10:1 ratio of grout to sodium silicate provides the most effective point support in a wet environment.

The most important construction requirement to provide effective support from grout columns is to achieve adequate roof contact area. Roof contact should be as large as possible to maximize the capacity and stiffness of the support. Two important conditions must exist in order to maximize the top surface area: (1) an adequate base must be formed consistent with the angle of repose of the material to provide a foundation for achieving the desired roof contact area and (2) when initial roof contact is achieved, the grout must be able to be delivered at sufficient pressure to expand the roof contact area without plugging the nozzle or sealing the borehole.

The borehole can be sealed by using a packer or collar to prevent premature filling of the borehole with grout before adequate roof contact has been established. Grout should only be permitted to flow into the borehole when the top surface area has expanded to the required area to support the expected loads. Then grout can be used to seal the borehole and consolidate fractured roof material. Consolidation of the roof strata improves its stiffness and support characteristics.

Less sodium silicate should be used at the start of construction to allow the grout to flow freely into the voids in broken rubble on the floor of the mine opening and to consolidate the floor material to provide a solid foundation for column formation. Too much sodium silicate applied with the fly ash grout at the beginning of construction can result in a steep cone (small cone angle as measured from vertical) and an inadequate base to provide column formation with the required roof contact area.

From a construction cost perspective, the increased strength advantage of a larger cone angle is diminished by the rapidly increasing volume of material when the cone angle is greater than 20°. A 20° cone angle represents a very steep column that is difficult to construct and results in a structure with limited stability. Cone angles in the range of 30° to 45° yield more stable structures and are attainable using sodium silicate technology. Since the added strength advantage of a larger cone angle is diminished by the larger volume of material, a practical optimum cone angle is 30°. A 4-ft-high, 30° column with a 4-ft-diameter top surface will attain 91% of the capacity of the 45° column with 46% less material.

While the sodium silicate allows a column of cementitious material to be formed in a flooded mine environment, it degrades the strength and thereby reduces the capacity of grout columns as supporting structures for mine subsidence abatement. Based on these observations, it is recommended that further research be pursued to develop containment devices for grout column construction so that grout columns could be formed without sodium silicate or with a much lower concentration.

References

American Concrete Institute, ACI. 1986. Manual of concrete practice. Pt 1, sec. 207.1, Detroit, MI.

Glucklish, J. 1990. Strain energy size effect. NASA Tech. Rep. 32-1438, 27 p.

Gray, R. E. 1974. State-of-the-art of subsidence control. PA Department of Environmental Resources and Appalachian Region Commission, December 1974. NTIS PB-242 465. p. I-14-I-21.

Michael, P. R., A. S. Lees, T. M. Crandall, and J. L. Craft. 1989. Controlled grout columns; a point-support technique for subsidence abatement. Assoc. of Eng. Geolo. Symp. Series, No. 4. p. 111-125.

Mindress, S. and J. F. Young. 1981. Concrete. Prentice-Hall, Old Tappen, NJ. p. 420.

Reifsnyder, R. H., R. A. Brennan, and J. F. Peters. 1988. Sodium silicate grout technology for effective stabilization of abandoned flooded mines. p. 390-398. In Mine Drainage and Surface Mine Reclamation Symposium Proceedings, Pittsburgh, PA, 1988. BuMines IC 9184.

http://dx.doi.org/10.21000/JASMR88020390