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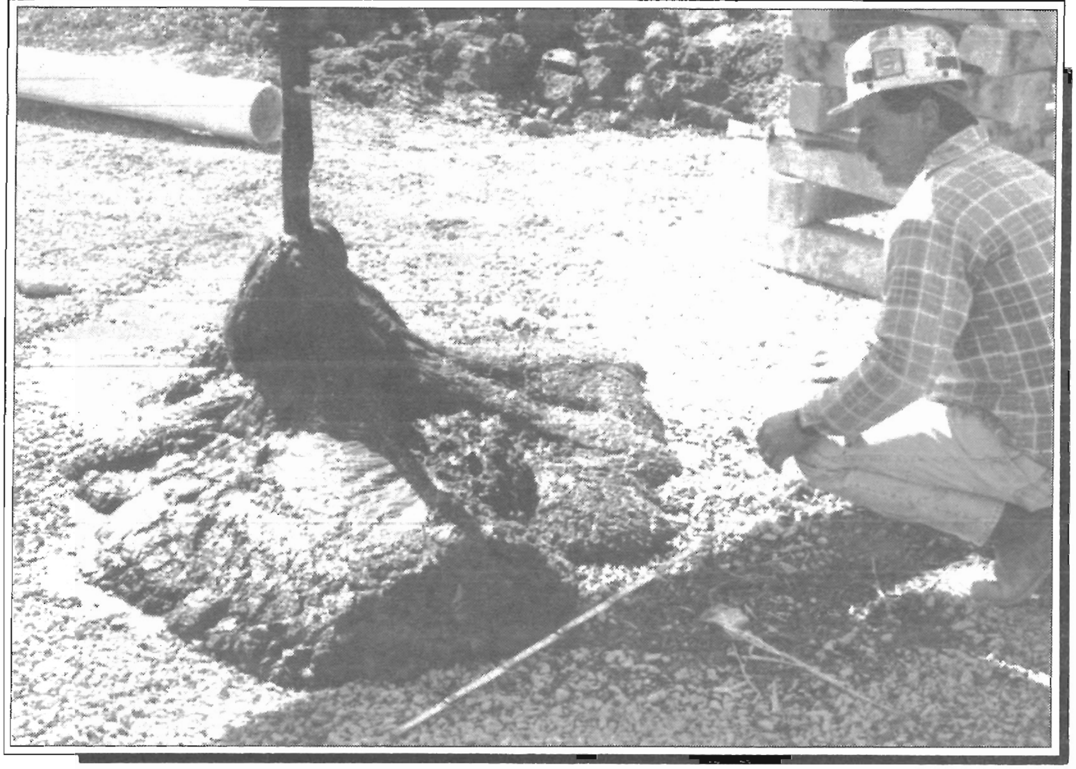
REPORT OF INVESTIGATIONS/1994

Full-Scale Evaluation of the Strength and Deformation of Grout Column Supports for Mine Subsidence Abatement

By Thomas M. Barczak and David F. Gearhart



UNITED STATES DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

BUREAU OF MINES

U.S. Department of the Interior Mission Statement

Cover Photograph: Surface formation of a grout column support at the U.S. Bureau of Mines Subsidence Abatement Investigation Laboratory.

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CONTENTS

Page

Abstract 1
Introduction 2
  Objectives 3
  Scope of work 4
Acknowledgments 4
Description of column construction and test parameters 4
  Columns constructed at the SAIL 5
  Columns constructed in the MRS 6
Test results 9
  SAIL specimens 9
    Small-scale cylinders 9
    Large-scale cylinders 9
    Full-scale columns 10
  MRS specimens 10
    Small-scale cylinders 10
    Large-scale cylinders 11
    Small-scale cones 11
    Full-scale columns 12
    Grout bags 13
Analysis of test results 13
  Wet environments 13
  Size 13
  Shape 13
  Deficiencies of sodium silicate 14
  Roof contact area 15
  Grout strength 15
Conclusions 15
References 16

ILLUSTRATIONS

1. Early attempts at forming point supports by grouting loose piles of aggregate 2
2. The USBM's Mine Roof Simulator 3
3. SAIL facility at Lake Lynn 5
4. Nozzle used for application of sodium silicate and cementitious grout in column construction 5
5. SAIL columns in MRS prior to testing 7
6. Unstable column formed in "pillow case" grout bag 8
7. Improved stability of grout bags provided by tying end of bag that makes contact with mine floor 8
8. Small-scale truncated cone specimens 8
9. Strength tests of small cylinder specimens of grout materials used for construction of columns at SAIL . . 9
10. Inclusions of gelled sodium silicate in small-scale specimens 9
11. High concentrations of sodium silicate collecting at top of large-scale cylindrical specimens 10
12. Load-deformation response of full-scale grout columns constructed at SAIL 10
13. Small-scale cylinder strength tests of grout samples used for MRS column construction 11
14. Maximum load and displacement for small-scale cone specimens 11
15. Relationship between material volume and specimen strength for small-scale cone specimens as a function of cone angle 12

ILLUSTRATIONS—Continued

Page

16. Initial failure of MRS columns 12
17. Decreased stiffness of grout column after first failure 12
18. Load-deformation response of grout bag columns 13
19. Variable cross-sectional area of confinement effects of cone-shaped structures 14
20. Layering of grout caused by sodium silicate 14
21. Initial failure of MRS grout columns as a function of roof contact area 15

TABLES

1. Description of grout columns constructed at the SAIL 6
2. Description of support columns constructed in the MRS 6
3. Description of grout bag columns 7

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	kN/cm	kilonewton per centimeter
cm^2	square centimeter	kPa	kilopascal
cm/min	centimeter per minute	kPa/s	kilopascal per second
deg	degree	lb	pound
ft	foot	m	meter
in	inch	m^2	square meter
in^2	square inch	m^3	cubic meter
in/min	inch per minute	pct	percent
kg	kilogram	psi	pound per square inch
kip	1,000 pounds	psi/s	pound per square inch per second
kips/in	1,000 pounds per inch	yd^3	cubic yard
kN	kilonewton		

FULL-SCALE EVALUATION OF THE STRENGTH AND DEFORMATION OF GROUT COLUMN SUPPORTS FOR MINE SUBSIDENCE ABATEMENT

By Thomas M. Barczak[1] and David F. Gearhart[2]

ABSTRACT

This U.S. Bureau of Mines (USBM) report evaluates the load supporting characteristics of grout columns used as point supports for mine subsidence abatement. The cone-shaped columns were constructed with sodium silicate and cementitious grout in both wet and dry environments. The scope of work included the testing of seven full-scale grout columns in the USBM's Mine Roof Simulator from which the load-deformation and failure characteristics were determined. The performances of grout columns are 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. Limited tests were also conducted on cylindrical columns constructed in fabric bags. 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.

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INTRODUCTION

Mine subsidence creates erratic and differential movement of ground that disrupts water tables and damages surface structures and subsurface utilities. The U.S. Bureau of Mines (USBM) estimates that in 1975, 5.2 million acres of land in 25 states was at risk to coal mine subsidence damage and 1.9 million acres had already been affected (*1*).[3] Considering the expanse of coal mining and urban development into rural areas, it is likely that the threat of damage from mine subsidence will increase significantly in the future and could restrict the growth of the U.S. coal mining industry. The severity of this problem has prompted the National Research Council to assign a high priority to research for improving the prevention and remediation of mine subsidence (*2*). Pursuant to this need, the USBM is conducting research to improve mine subsidence abatement technology.

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 (*3*). 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 (*4*). For example, a 4,000-m^2 (1-acre) area where 75 pct of a 1.8-m (6-ft) thick coal seam has been mined would require 5,400 m^3 (7,063 yd^3) of grout material to completely fill the mine voids. Assuming the use of 50 boreholes on 9.1-m (30-ft) centers for grout injection, only 1,040 m^3 (1,361 yd^3) of material would be required for point supports constructed as cone-shaped grout columns with a cone angle (as measured from a vertical plane) of 45° that provides a 1.8-m (6-ft) diameter roof contact area.

Early attempts at forming point support systems for subsidence abatement by grouting loose piles of aggregate placed down a borehole (see figure 1) were largely unsuccessful. The loose aggregate provided a poor angle of repose that required large amounts of material and inadequate roof contact area (*4*). It was also difficult to grout the aggregate after the pile was formed. The next generation of point supports were 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.

Other efforts to construct point support systems for mine subsidence abatement include the use of grout bags. Grout bags contain the grout during placement and minimize the material usage. However, several problems have precluded their widespread use. These problems include (1) uncertainty of bag deployment during remote placement, (2) lack of lateral rigidity to maintain stability during column formation, (3) tendency to tear when in contact with jagged roof and floor strata, and (4) difficulty in achieving adequate roof contact (*4-7*).

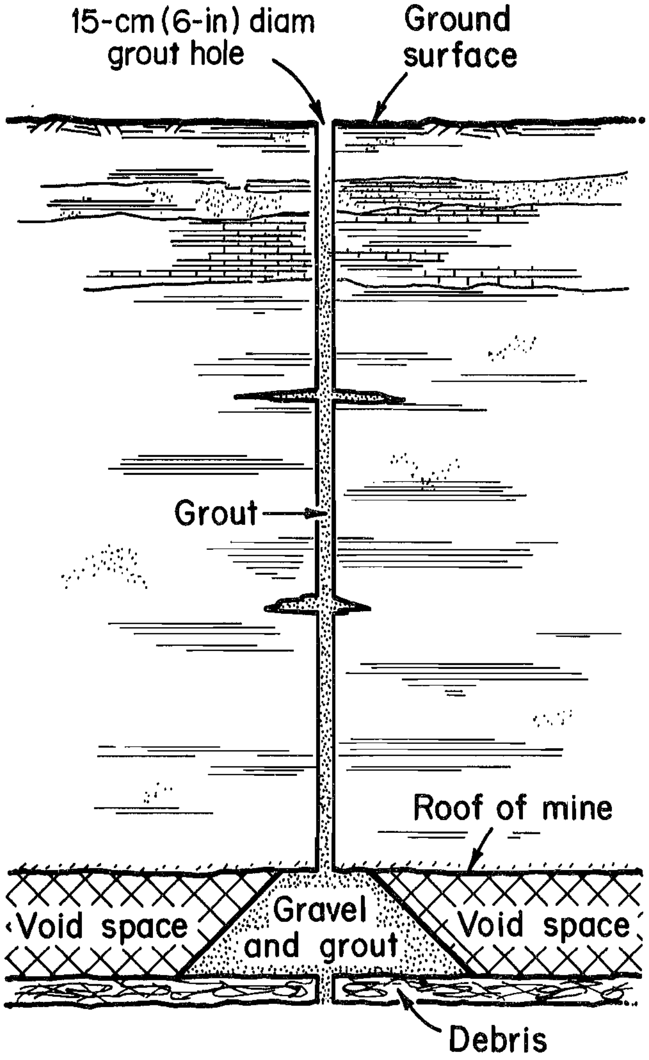

Figure 1.—Early attempts at forming point supports by grouting loose piles of aggregate.

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[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

The most recent approach to grout column formation is the use of 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 grout columns to be formed in completely flooded mine voids (7).

Despite the improvements provided by the sodium silicate technology and potential of the grout bag technology, point support systems are still not widely used. A primary reason for the reluctance to use point supports is uncertainty about the supporting capability. Remote and often blind placement of supports requires the use of well-defined support technology.

OBJECTIVES

The purpose of this research is to determine the supporting characteristics of grout columns through full-scale testing of these support structures in the USBM's Mine Roof Simulator (MRS) as shown in figure 2. The long-term goal is to develop design criteria for the construction and optimum employment of grout columns for mine subsidence abatement. This requires knowledge of the load-deformation characteristics of the grout column. Previous research pertaining to grout columns as point supports for mine subsidence abatement 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.

The capacity of a support column must be known to determine the acceptable spacing of the columns so that the required support resistance for subsidence abatement can be provided. Full-scale testing is necessary to determine the effective area of a cone-shaped column so that a point support of the required capacity can be designed based on the material strength of the grout. Full-scale testing is also needed to evaluate reductions in load capacity of the support due to size effects associated with full-scale

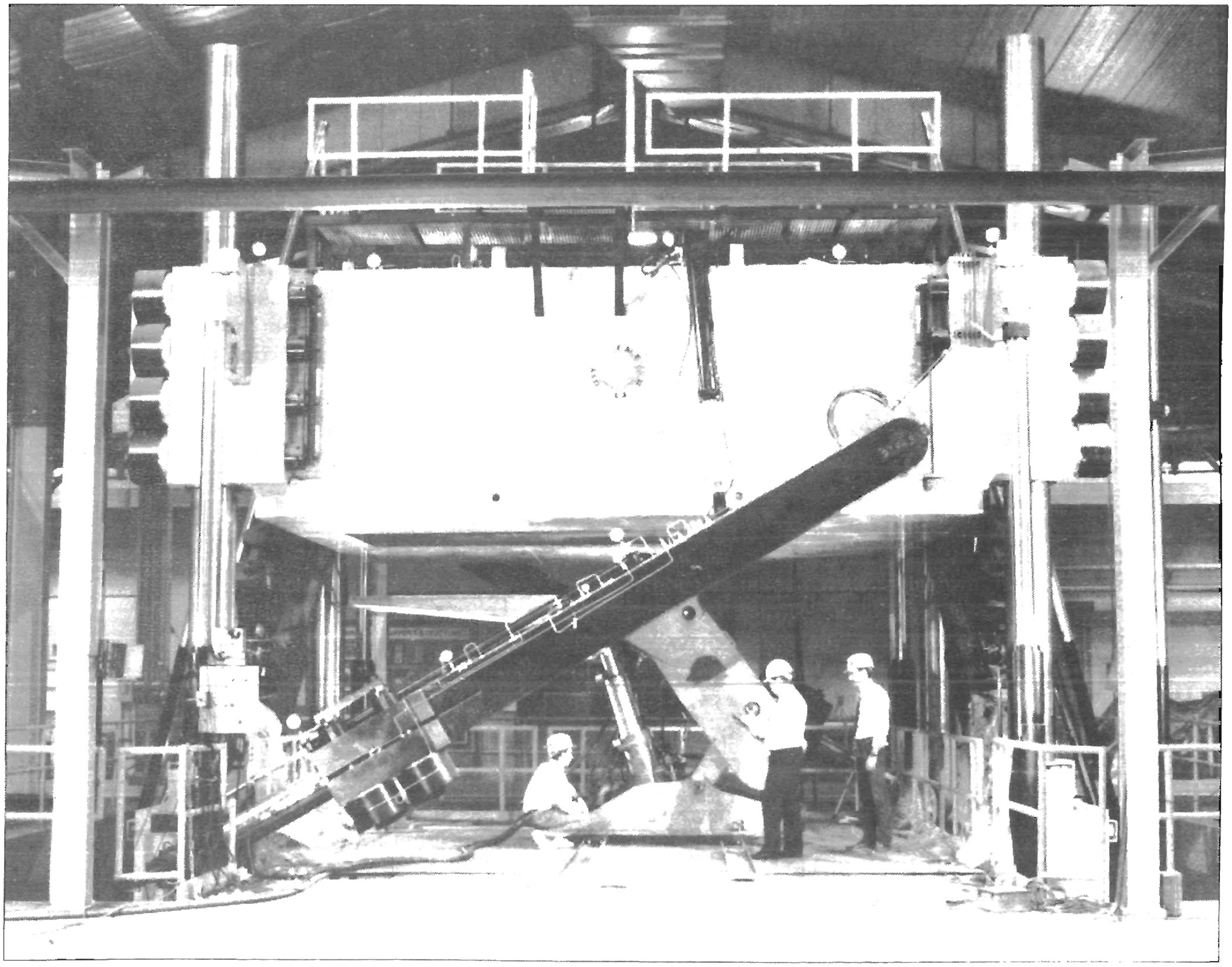

Figure 2.—The USBM's Mine Roof Simulator. (Photo shows testing of a longwall shield.)

structures in comparison with laboratory measures of material strength. In addition, the stiffness and postfailure behavior of the support column are important design considerations, and these parameters can only be determined through full-scale testing of the support structure.

SCOPE OF WORK

The scope of work 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 parameters that were controlled during these full-scale tests included (1) the volumetric ratio of grout to sodium silicate, (2) the method of grout placement, and (3) the volume of material used in the column construction. In addition to these full-scale tests of support columns, 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 with 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. The controlled geometry of these specimens provided information on the effective area of the truncated cone geometry common to full-scale grout column construction.

Load-deformation tests in the MRS were also conducted on three grout support columns formed in fabric bags. These preliminary tests were intended to evaluate the effectiveness of current grout bag technology. The reader is cautioned that the grout bag support results reported here are based on limited testing; while they identify some of the problems and potential of point supports using grout bag technology, these results may not be representative of the performance of state-of-the-art grout bag support systems.

ACKNOWLEDGMENTS

The authors wish to acknowledge Don Lambert, Jr., president, and associates of Lambert Construction Co., Bridgeville, PA. Lambert Construction Co. was awarded a contract by the USBM to construct the grout columns for this research program. Mr. Lambert and his associates have several years of experience in mine subsidence abatement including the construction of point support systems. Mr. Lambert assisted in the grout design mix and required sodium silicate concentration for the full-scale column constructions both at the Subsidence Abatement Investigation Laboratory (SAIL) and in the MRS. Lambert Construction Co.'s experience was a valuable asset to this program and enhanced our goal of simulating state-of-the-art grout column construction for this test program.

DESCRIPTION OF COLUMN CONSTRUCTION AND TEST PARAMETERS

Full-scale columns were constructed at the USBM's SAIL at Lake Lynn (see figure 3) and on the platens of the MRS load frame at the Pittsburgh Research Center (PRC). 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 317.5 kg (700 lb) of Portland I cement, 766.4 kg (1,690 lb) of fly ash, and 362.8 kg (800 lb) of water with a design strength of 10,275 kPa (1,490 psi) at 7 days. This grout strength is within the range of material strengths used in support design for abandoned mine subsidence abatement, which is typically between 3,448 and 10,345 kPa (500 and 1,500 psi). This grout strength was chosen to provide a 1.2-m (4-ft) high support column with a load capacity less than 75 pct of the 13,334-kN (3,000-kip) capacity of the MRS to ensure testing of the support to failure. The grout mix for the SAIL columns was 170.5 kg (376 lb) of Portland I cement, 815.0 kg (1,797 lb) of fly ash, and 226.7 kg (500 lb) of water with a design strength of 6,207 kPa (900 psi) at 7 days.

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 (see figure 4). 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.

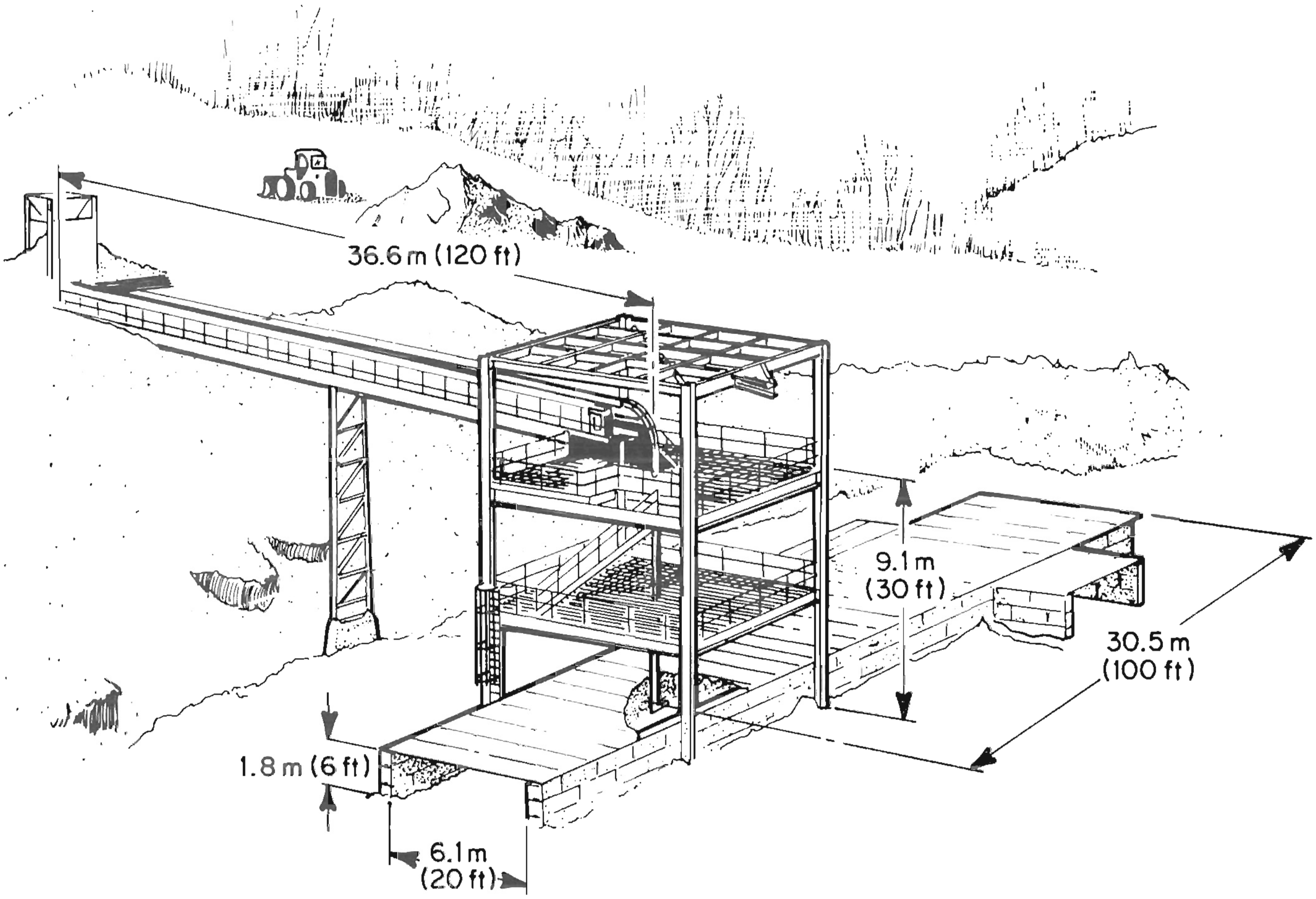

Figure 3.—SAIL facility at Lake Lynn.

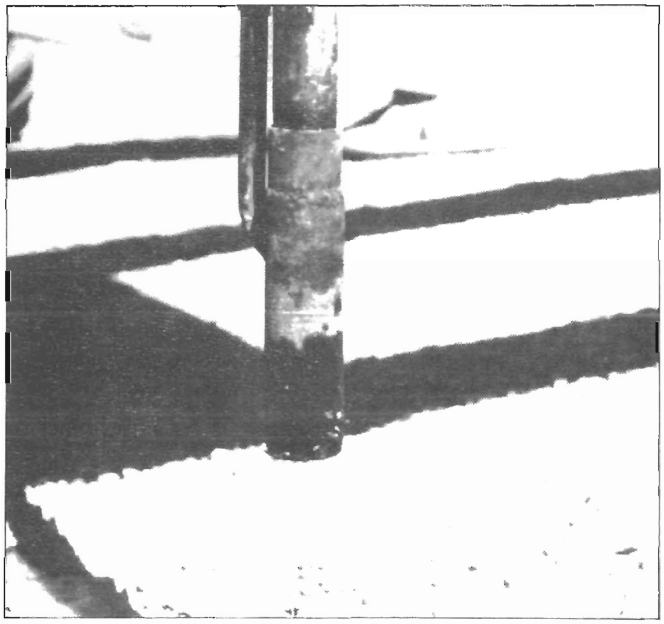

Figure 4.—Nozzle used for application of sodium silicate and cementitious grout in column construction.

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: (1) 5:1, (2) 7.5:1, (3) 10:1, and (4) 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 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. This column was not tested in the MRS. The 7.5:1 ratio provided a cone angle similar to that of 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 of the 5:1 ratio was lower than those of the 7.5:1 and 10:1 ratios, but the base area was considerably smaller. Based on these observations, it appears that 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. Since the sodium silicate adds cost to the support design, the goal is to minimize the amount of sodium silicate.

Four columns were transported to PRC for full-scale testing in the MRS. A physical description of each column and the construction parameters are provided in table 1. Photographs of the columns in the load frame prior to testing are shown in figure 5.

COLUMNS CONSTRUCTED IN THE MRS

Three columns were constructed on the platens of the MRS at PRC. The grout-to-sodium silicate ratio was controlled to approximately 10:1 for all three columns. The columns were constructed in a dry environment to safeguard against contamination of the load frame's open hydraulic system. An artificial roof with a 15-cm (6-in) diameter hole was provided to simulate a borehole and underground roof contact. The artificial roof was removed prior to testing. The primary control variable for the column construction was the amount of roof contact, which was controlled by the amount of material and placement technique.

Column 1 achieved minimal roof contact because of grout infiltration into the borehole when the column height reached the artificial roof. Roof contact in column 1 was also limited by the amount of material used in the column construction. Nozzle plugging problems were also experienced when the nozzle became buried in the grout when roof contact was made. Additional roof contact was established in columns 2 and 3 by closing off the open area in the borehole around the grout nozzle. A description of the three columns constructed in the simulator is provided in table 2.

Three supports were also formed by injecting grout without sodium silicate into grout bags. A description of the three supports formed in grout bags is provided in table 3. Sodium silicate was not used since the bags contain the grout during the support formation, allowing the use of the high slump grout mix that was used in previous column formations. The grout bags were geotechnical bags with a rectangular geometry in which two sections of fiber cloth are sewn together on three sides similar to a feed sack. This geometry is not well suited to column formation since it does not have a flat bottom. The bags lack lateral rigidity, which also degraded stability (see figure 6). Stability was improved by tying the end of the bag in a knot to provide a flatter base for constructing a cylindrical structure. Columns 1 and 3, as designated in table 3 and shown in figure 7, were constructed using this approach. The top portion of the bag was tied around the nozzle feedpipe and allowed to slide downward as the bag expanded during filling.

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

Parameter	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

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

Parameter	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 from vertical..	42	42	45
Borehole condition	Open	Closed	Closed

Table 3.—Description of grout bag columns

Parameter		Column 1	Column 2	Column 3
Diameter	cm	61	123	61
Height	cm	152	91	61
Material	m^3	0.4	1.1	0.15

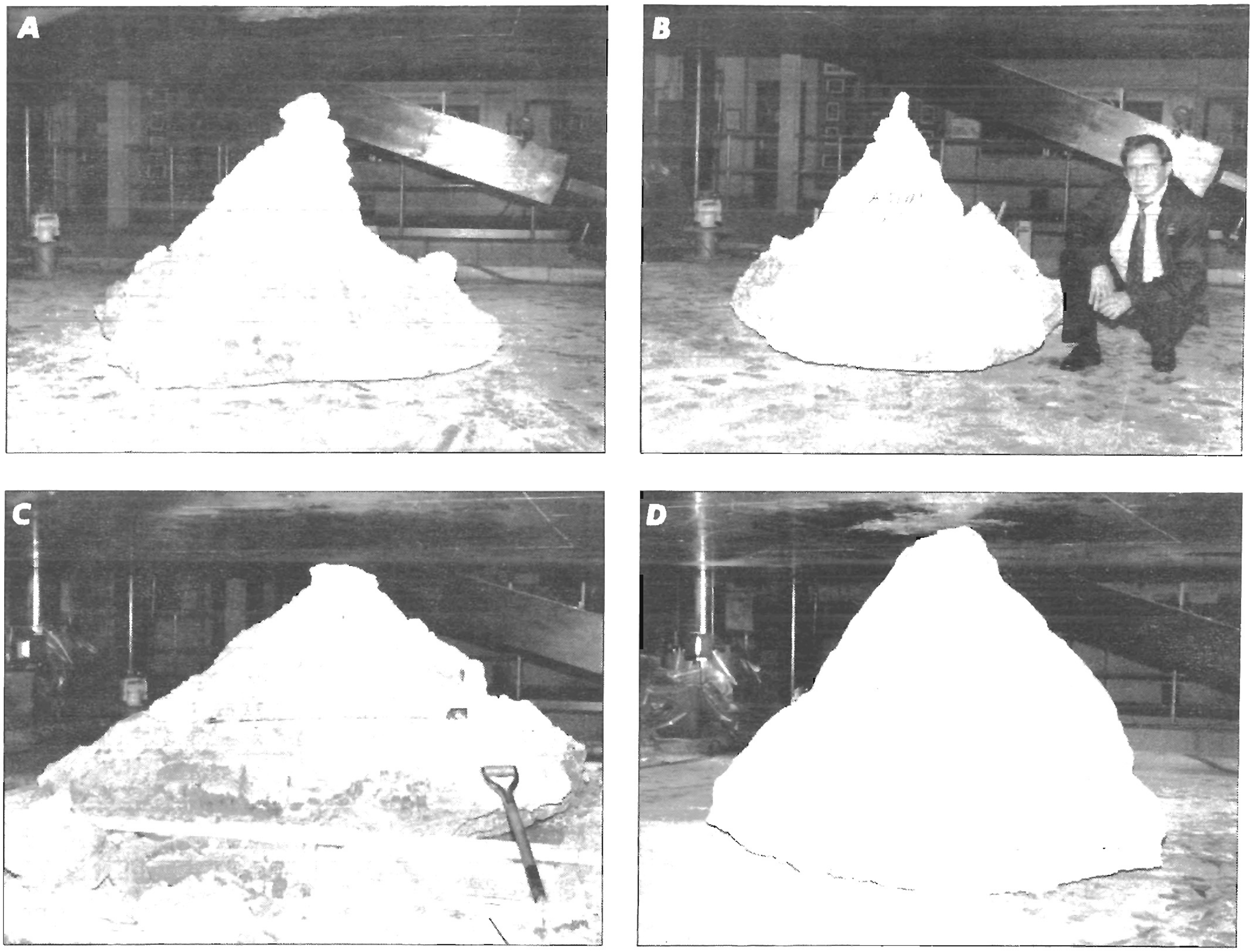

Figure 5.—SAIL columns in MRS prior to testing. *A*, Column 1; *B*, column 2; *C*, column 3; *D*, column 4.

In addition to the full-scale grout columns, several small-scale specimens were constructed in which the geometry of the structure was the control variable. Truncated cone geometries were formed with cone angles of 15°, 30°, and 45° (see figure 8). The cones were all 30 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.

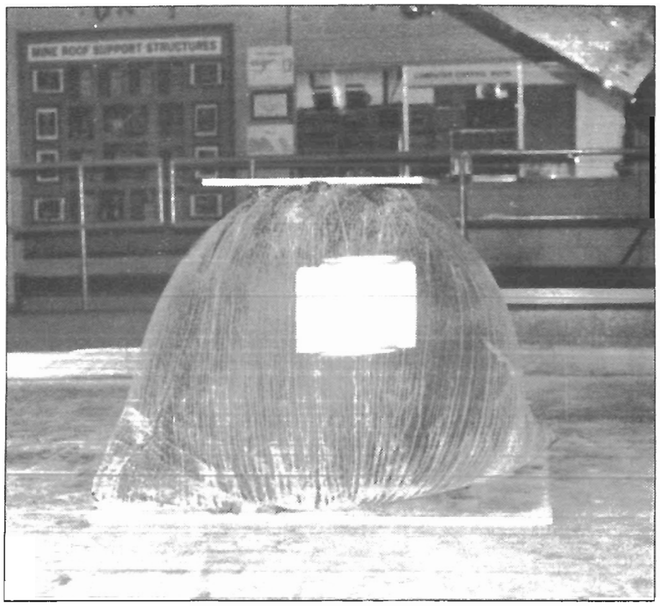

Figure 6.—Unstable column formed in "pillow case" grout bag.

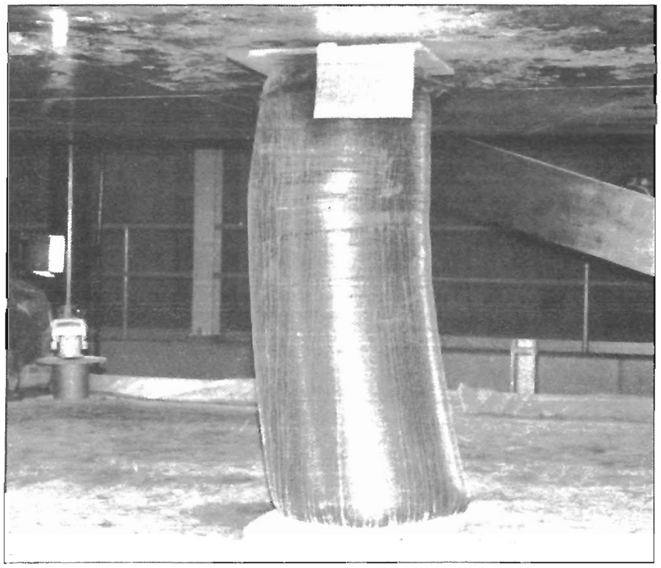

Figure 7.—Improved stability of grout bags provided by tying end of bag that makes contact with mine floor.

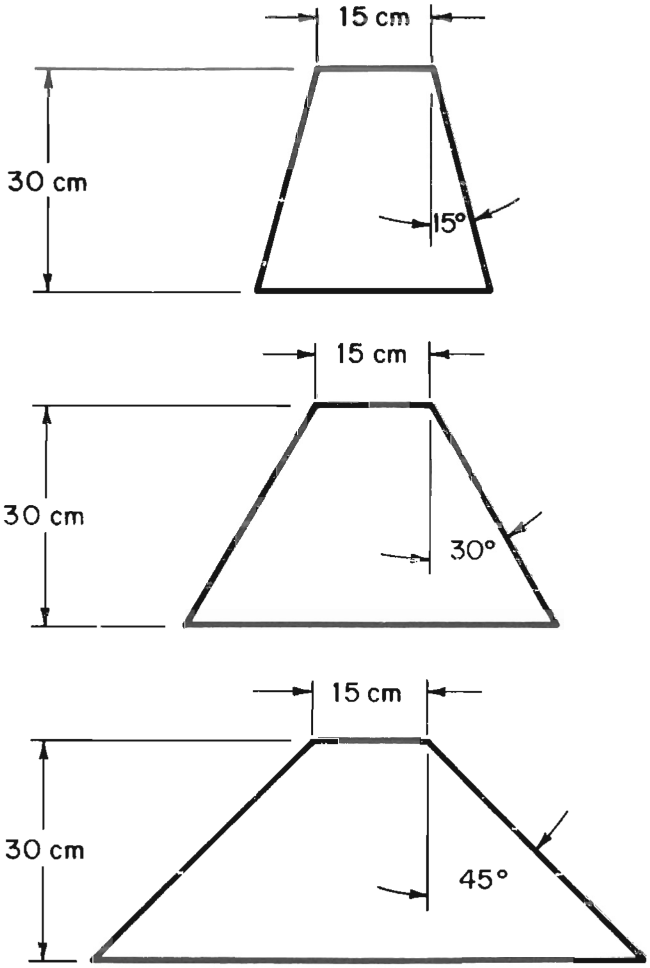

Figure 8.—Small-scale truncated cone specimens.

TEST RESULTS

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 in a 13,334-kN (1-million-lb) load frame at a load rate equivalent to 138 kPa/s (20 psi/s). The 61-cm (24-in) diameter cylindrical specimens and the full-scale columns were tested in the MRS at a controlled displacement of 1.3 cm/min (0.5 in/min), chosen from past experience with testing of large-scale concrete specimens and the load frame limitations.

SAIL SPECIMENS

Small-Scale Cylinders

Samples of grout mixes used for column construction at the SAIL were poured in 15-cm (6-in) diameter, 20-cm (8-in) high cylinders to evaluate the effect of sodium silicate on grout strength. The results are shown in figure 9. While the results are inconsistent, it appears that the sodium silicate, if adequately mixed with the grout to prevent inclusions of gelled sodium silicate, increased the grout strength. However, the effects of the sodium silicate on the hydration of the cement and the curing process were not studied in detail, and the effects of the sodium silicate on the grout strength remain uncertain. The design strength for the grout was 6,207 kPa (900 psi) after 7 days. All of the specimens, with the exception of 5:1 grout-to-sodium silicate sample and the 10:1 grout-to-sodium silicate sample in a wet environment, exceeded 6,207 kPa (900 psi) after 7 days. Inclusions of gelled sodium silicate were evident in the 5:1 samples (see figure 10). The gelled sodium silicate has very little tensile and shear strength, and it significantly reduced the strength of these specimens. Samples of the 10:1 grout-to-sodium silicate material that were poured and cured in water also exhibited significantly reduced strength, possibly due to the heat loss during the curing process. Samples of the 10:1 material poured in a dry environment exhibited strengths in excess of 10,345 kPa (1,500 psi).

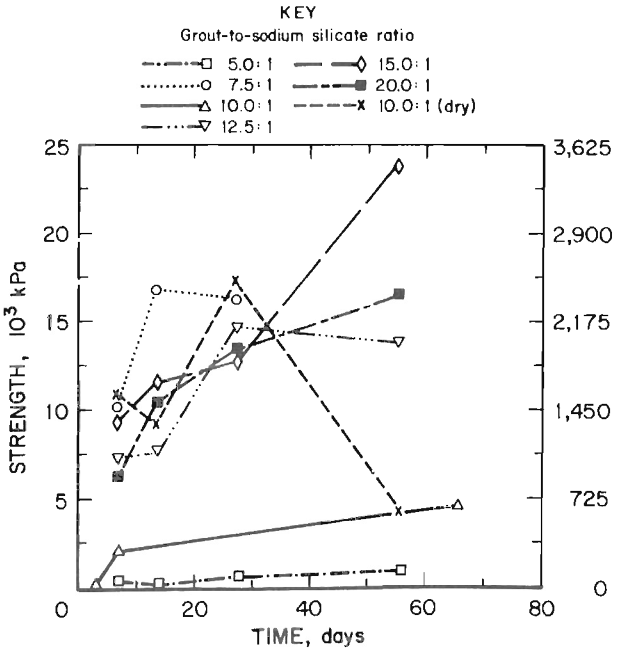

Figure 9.—Strength tests of small cylinder specimens of grout materials used for construction of columns at SAIL.

Large-Scale Cylinders

Four 61-cm (24-in) diameter, 122-cm (48-in) high, cylindrical specimens of the same mix as the small-scale cylinders were also tested. One specimen contained grout without any sodium silicate, two specimens of the 10:1 grout-to-sodium silicate material were poured and cured in a dry environment, and one specimen of the 10:1 grout-to-sodium silicate material was poured and cured underwater.

The grout specimen without sodium silicate attained the design strength of 6,207 kPa (900 psi) in 7 days. The two 10:1 grout-to-sodium silicate specimens formed in a dry environment produced an average strength of 3,103 kPa (460 psi), and the specimen formed underwater exhibited a strength of 1,379 kPa (200 psi). The reduction in strength in the sodium silicate specimens is believed to be

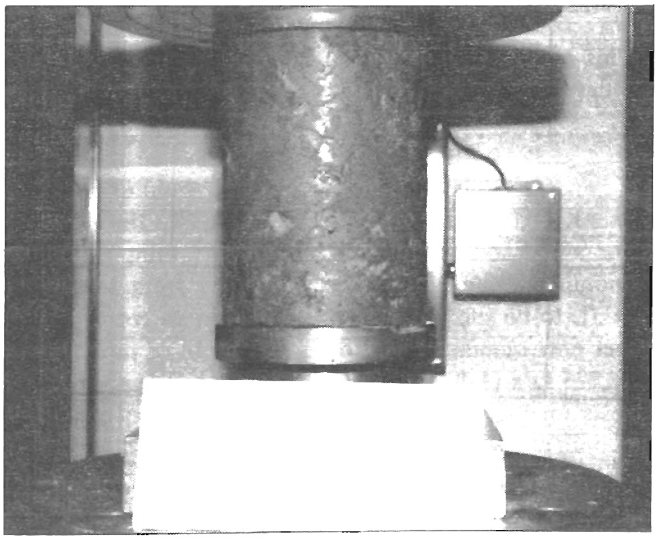

Figure 10.—Inclusions of gelled sodium silicate in small-scale specimens.

due to the excessive quantity and poor mixing of the sodium silicate with the grout. The 10:1 grout-to-sodium silicate ratio works well in an unconfined environment, such as a full-scale column construction, because the silicate forms a sheath over the grout with limited time to react with the grout, and the excess sodium silicate simply disperses to another area. However, when the specimen is contained, the excess sodium silicate forms inclusions of silicate gel in the specimen. Large quantities of sodium silicate collect at the top of the specimen during pouring, which significantly weakens the structure (see figure 11).

Full-Scale Columns

The load-deformation response of the four full-scale grout columns constructed at the SAIL are compared in figure 12. 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 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 convergence. 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 12.

MRS SPECIMENS

All of the test samples constructed in the MRS that contained sodium silicate used a 10:1 ratio of grout to sodium silicate, since this was found from tests at the SAIL to be the optimum mix for column construction in wet environments. 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.

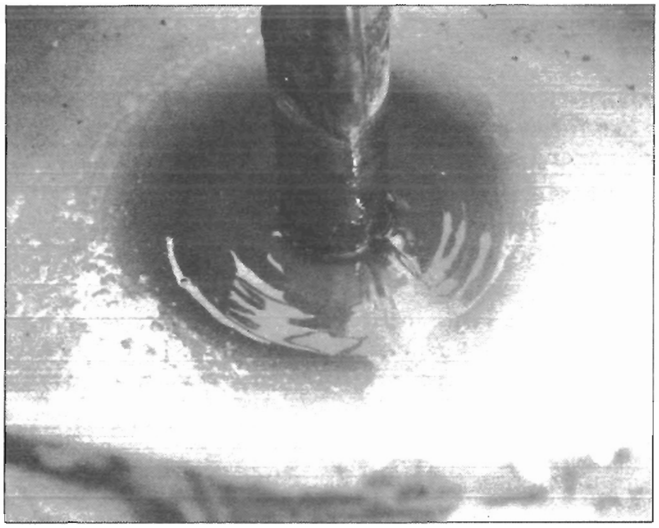

Figure 11.—High concentrations of sodium silicate collecting at top of large-scale cylindrical specimens.

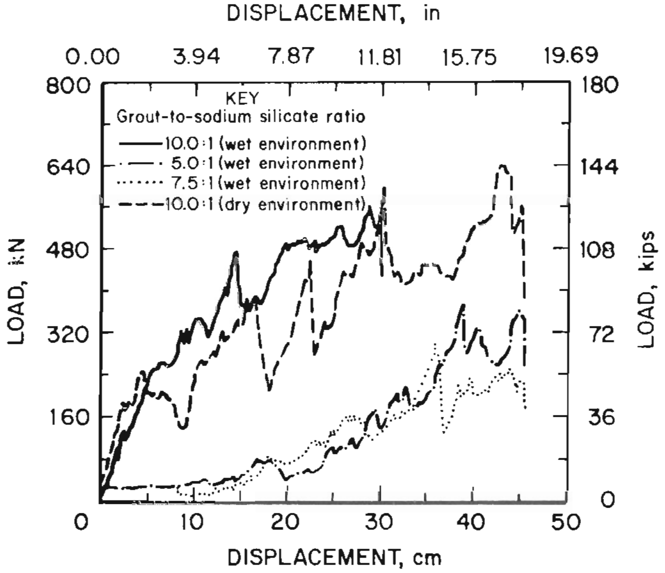

Figure 12.—Load-deformation response of full-scale grout columns constructed at SAIL.

Small-Scale Cylinders

Figure 13 shows the strengths achieved from 15-cm (6-in) diameter, 20-cm (8-in) high cylindrical specimens without sodium silicate. The average of the 7-day strengths was 8,207 kPa (1,190 psi). Cubic specimens have been shown to yield a measure of strength that is 25 pct greater than cylindrical specimens (*8*). Hence, the 8,207-kPa (1,190-psi) strength of the cylindrical specimens in comparison with the 10,276-kPa (1,490-psi) strength of the cubic specimens is within expectations.

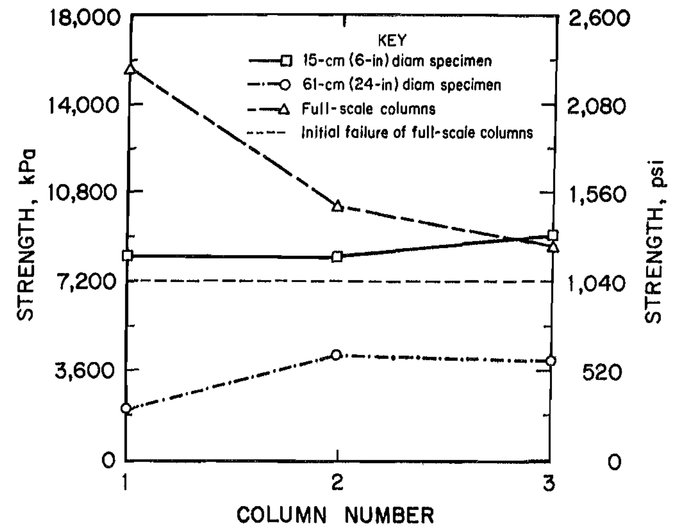

Figure 13.—Small-scale cylinder strength tests of grout samples used for MRS column construction.

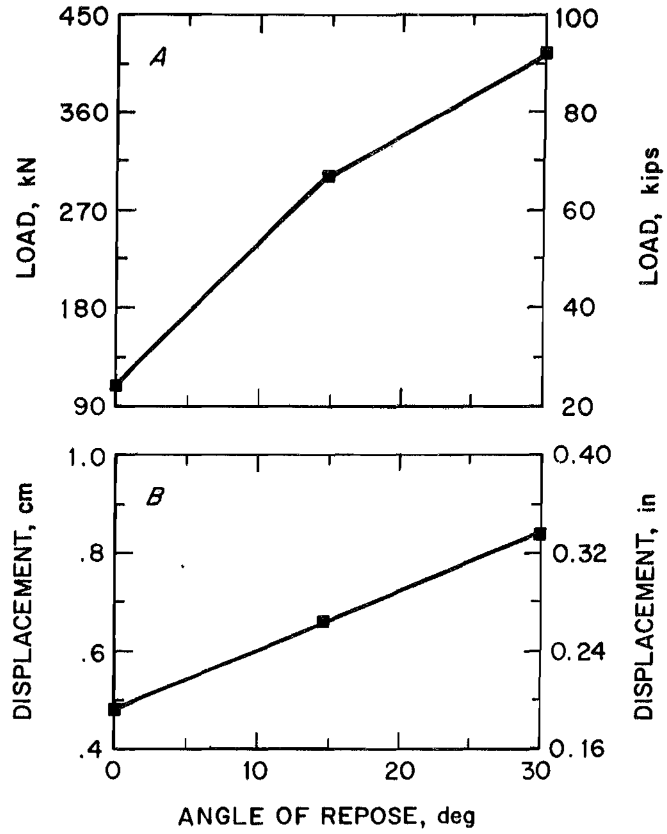

Figure 14.—Maximum load (*A*) and displacement (*B*) for small-scale cone specimens.

Large-Scale Cylinders

Tests on 61-cm (24-in) diameter, 122-cm (48-in) high cylindrical specimens provided varied results. All of the specimens were constructed in a dry environment. Two specimens were poured with sodium silicate and four specimens were poured without sodium silicate. The sodium silicate specimens had inclusions on the outer surfaces after curing, and both samples had shrunk during curing. The first sodium silicate specimen attained a strength much lower than expected, 2,069 kPa (300 psi) after 7 days. This reduced strength is probably due to the shrinkage, which had left a 0.63-cm (0.25-in) deep depression on the top surface that created stress concentrations during testing. Subsequent specimens were capped with a cement-sand mix to improve the load distribution on the specimen. The capped sodium silicate specimen attained a strength of 4,276 kPa (620 psi) after 7 days. Two of the specimens without sodium silicate averaged 4,345 kPa (630 psi) after 7 days and 10,759 kPa (1,560 psi) after 56 days.

The 50-pct reduction in capacity with the 61-cm (24-in) diameter specimens with and without sodium silicate in comparison with the 15-cm (6-in) diameter specimens provides further evidence of a size effect relationship at the larger scale. This magnitude of load capacity reduction has been observed in other concrete specimens of this scale (*9*).

Small-Scale Cones

Small-scale cone specimens were constructed to quantify the effects of the truncated cone geometry that is common to full-scale grout columns. Sheet metal forms were used to construct three cones with 15°, 30°, and 45° cone angles as measured from the vertical plane. The sheet metal forms were removed prior to testing to eliminate the confinement provided by the forms. All specimens had 15-cm (6-in) diameter top surfaces and were 30 cm (12 in) high. The specimen with a 45° cone angle cracked during curing, which degraded its supporting capability, and the specimen was not included in the data analysis.

The maximum load sustained by each cone specimen is shown in figure 14, and the relationship between material volume and specimen strength is shown in figure 15 as a function of the cone angle. A 30° cone angle specimen provided nearly 400 pct greater strength than a cylindrical

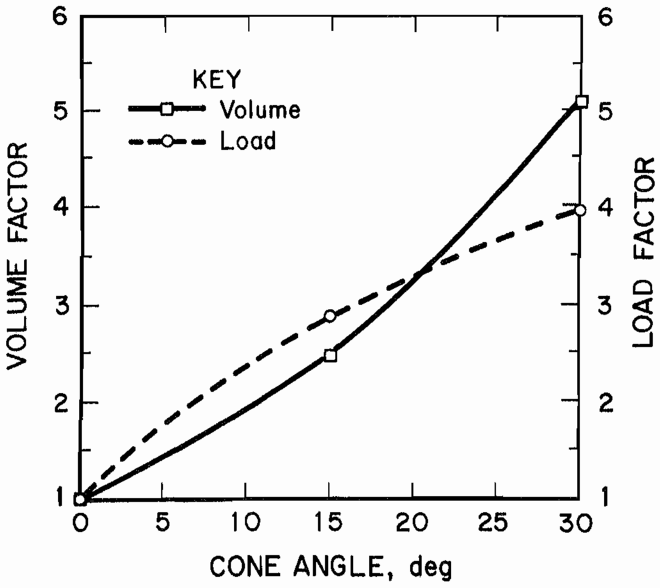

Figure 15.—Relationship between material volume and specimen strength for small-scale cone specimens as a function of cone angle.

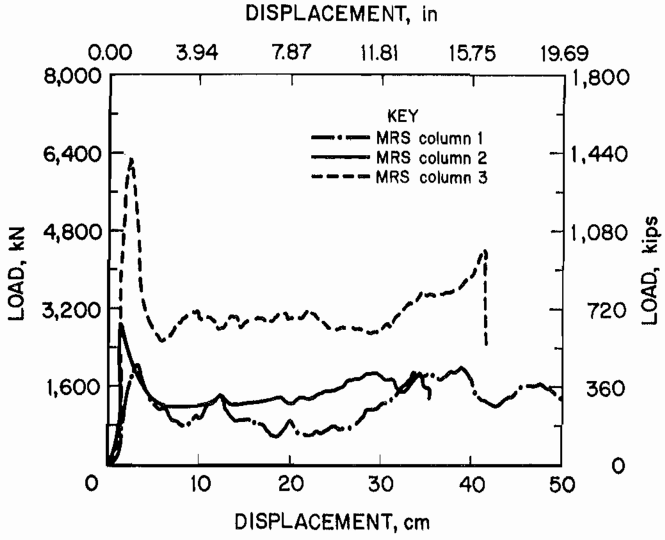

Figure 16.—Initial failure of MRS columns.

specimen. However, the strength improvement provided by the cone geometry diminishes nonlinearly with increasing cone angles. This strength improvement is also gained at the expense of rapidly increasing material volume as shown in figure 15. A specimen with a 30° cone angle has nearly three times the volume of a specimen with 15° cone angle, but less than twice the load capacity.

Full-Scale Columns

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 the SAIL without roof contact, the MRS columns exhibited a high initial stiffness as they developed significant resistance with little displacement as shown in figure 16. 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 (see figure 17), while the load capacity continued to increase with increasing convergence. Maximum load occurred when localized failures (cracks) coalesced to fracture the specimen from top to bottom.

A significant increase in load capacity after first failure was noted in the first column because of the increased area caused by crushing of the top surface. The increase in load in the other two columns after first failure was less than that observed in the first column. Maximum load capacities of 2,002, 2,847, and 6,338 kN (450, 640, 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 displacement. Load resistance after reaching the maximum capacity was reduced by about 50 pct as the columns split through their cross section and crushed from the continued displacement.

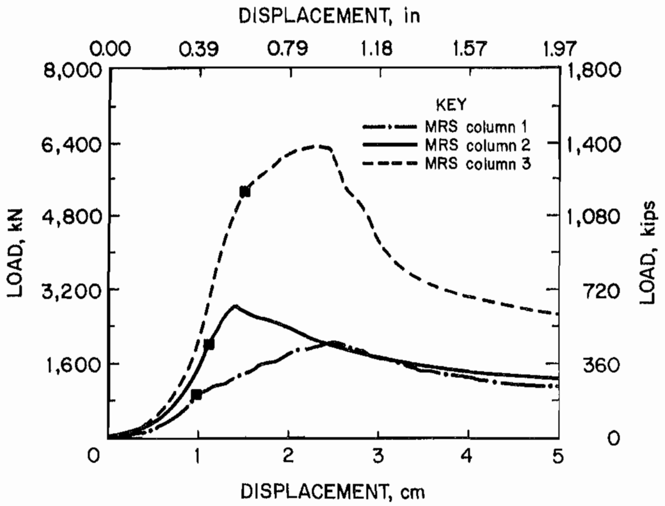

Figure 17.—Decreased stiffness of grout column after first failure. Boxed data points indicate point of initial failure of the grout column.

The capacity attained with the full-scale columns was lower than expected, based upon the 4,276-kPa (620-psi) material strength of the 61-cm (24-in) diameter cylinders and the 350- to 400-pct increase in capacity demonstrated in the small-scale cones of a similar geometry. [Note: These percentages are based on extrapolation of the small-scale cone test data to a 45° cone angle.] 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.

Grout Bags

Test results of the three grout bag columns as referenced in table 3 are shown in figure 18. Column 2 provided a maximum load capacity of nearly 2,669 kN (600 kips) with approximately 1.1 m³ (1.4 yd³) of material. This compares with the 2,002- and 2,847-kN (450- and 640-kip) load capacity of the two full-scale MRS grout columns, which contained 2.3 and 3.1 m³ (3 and 4 yd³) of sodium silicate grout. These results demonstrate the potential for substantial material and cost savings using grout bags for containment during column formation. However, the other two grout bag columns were unstable and provided only 667 kN (150 kips) of load capacity, demonstrating the need for further research in bag design to improve the utilization of this technology.

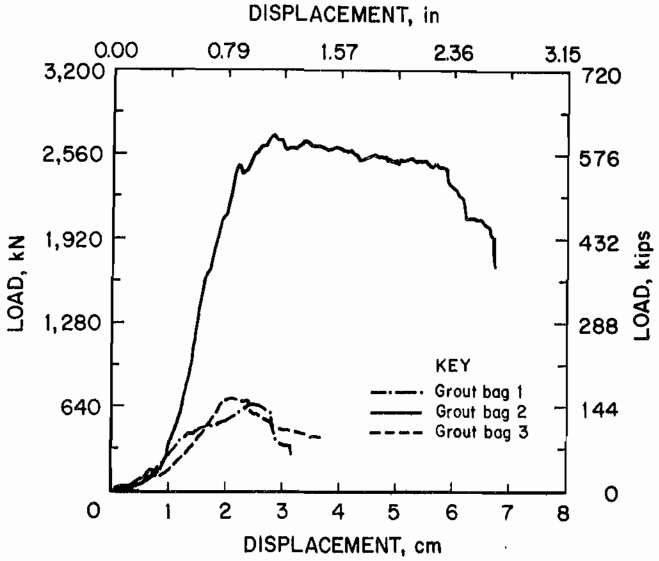

Figure 18.—Load-deformation response of grout bag columns.

ANALYSIS OF TEST RESULTS

Several factors have been identified that affect the performance of these support structures. These include (1) wet environment, (2) size, (3) shape, (4) deficiencies of sodium silicate, (5) roof contact area, and (6) material strength. Other design considerations include the stiffness and mode of failure of the support structure.

WET ENVIRONMENTS

Limited tests were conducted to evaluate the effects of the wet environment on grout strength, but 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 pct, compared with approximately 50-pct 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 (*10*).

SIZE

Previous research has shown that a 50-pct reduction in strength of concrete materials is observed when the specimen size exceeds 61-cm (24-in) diameter in comparison with 15-cm (6-in) diameter or smaller specimen sizes (*8-9*). 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 pct 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 based on the top surface area and material strength.

SHAPE

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 (*9*). Since confinement is partially 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.

In cone-shaped structures, each successive "slice" of the cone from top to bottom has slightly larger cross-sectional area than the one above it (see figure 19), which distributes the load acting on the specimen at a reduced stress level. This reduced normal stress reduces the lateral expansion of the material and provides confinement to support core. Hence, the effective area of a cone specimen is greater than the top surface area, and the capacity of the cone structure is increased nonlinearly as the cone angle (when measured from a vertical plane) increases.

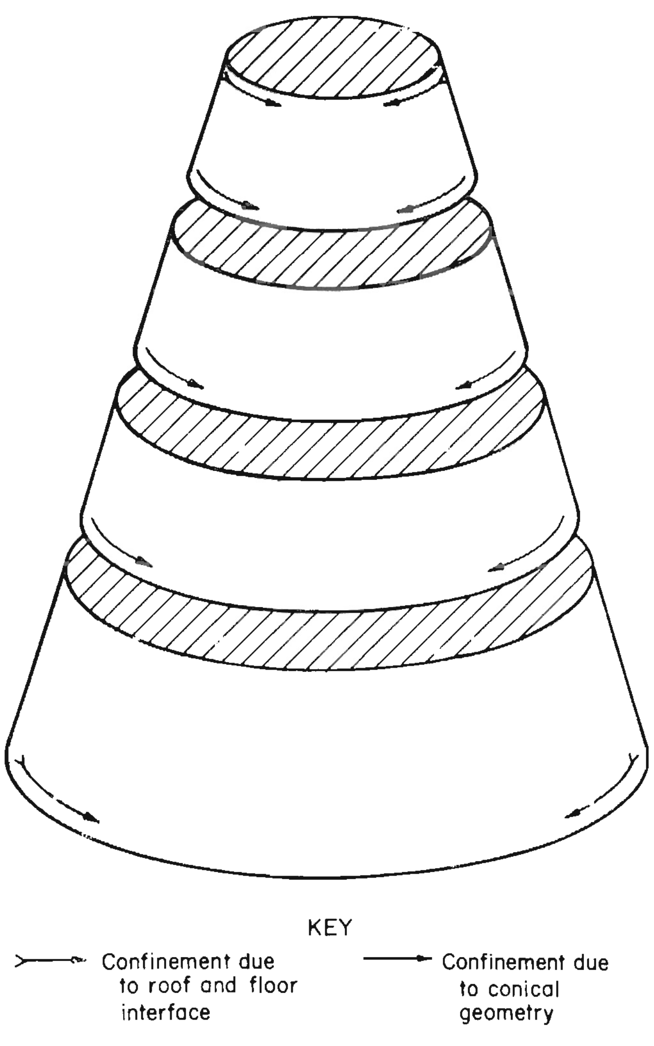

Figure 19.—Variable cross-sectional area of confinement effects of cone-shaped structures.

Figure 15 showed a 350- to 400-pct increase in capacity for small-scale cones with a 15-cm (6-in) diameter top surface area and a 20° to 30° cone angle as compared with 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 pct in relation to the material strength measured from 61-cm (24-in) diameter specimens or a 5 pct increase in capacity in relation to material strength measures 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 the asymmetrical shape of the structure.

DEFICIENCIES OF SODIUM SILICATE

The use of sodium silicate enables a structure to be formed in a water-filled environment that may not be formed otherwise. However, there are some deficiencies associated with this sodium silicate technology. 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, as shown in figure 20, also creates planes of

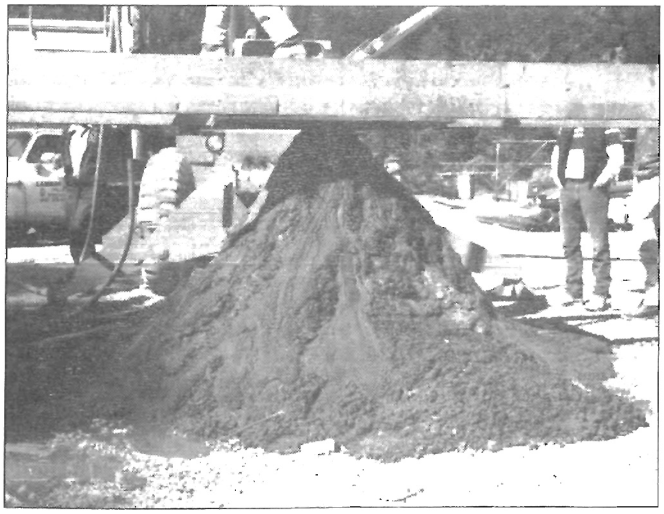

Figure 20.—Layering of grout caused by sodium silicate.

weakness in the structure that reduce the load capacity of the column. This layering during column formation also creates an asymmetrical structure where the side surfaces of the cone are not smooth or continuous. Depressions in the side of the columns create stress concentrations that cause localized failures that reduce the overall capacity of the grout 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. In abandoned mine applications where the grout is pumped from the surface, plugging is an important consideration to grout placement.

ROOF CONTACT AREA

Roof contact area largely determines the capacity and stiffness of grout columns. As shown in figure 21, 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 21, the material strength was 7,241 kPa (1,050 psi).

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 roof and floor 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 7,355 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.

Adequate roof contact is crucial. Columns constructed without achieving adequate roof contact will crush and will not have the stiffness or capacity to control the closure of the mine opening that will contribute to additional subsidence.

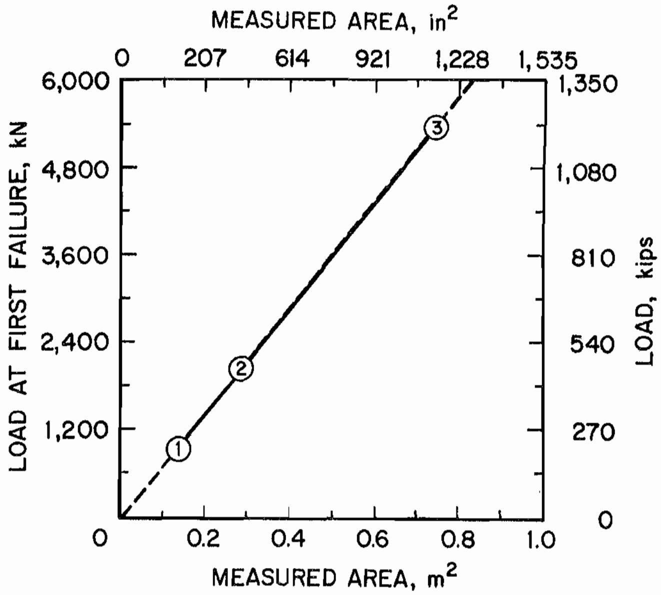

Figure 21.—Initial failure of MRS grout columns as a function of roof contact area. Circled numbers identify columns.

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.

In addition to determining the capacity of the column, the grout strength has some influence on the mode of failure. Cementitious materials are typically characterized by brittle failure. Brittle behavior was observed in the full-scale grout columns as the columns would split from top to bottom at failure. Weaker materials may reduce the stiffness of the support column and tend to crush during load application.

CONCLUSIONS

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, the practical optimum cone angle is 30°. A 1.2-m (4-ft) high, 30° column with a 1.2-m (4-ft) diameter top surface will attain 91 pct of the capacity of the 45° column with 46 pct 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. Preliminary tests with grout bags indicated the shape of the bags needs to be modified to a cylindrical form to enhance the stability of the structure.

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