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REPORT OF INVESTIGATIONS/1991

Laboratory Evaluation of Cable Bolt Supports

(In Two Parts)

2. Evaluation of Supports Using Conventional Cables With Steel Buttons, Birdcage Cables, and Epoxy-Coated Cables

By J. M. Goris

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

in	inch	pct	percent
in^2/in	square inch per inch	psi	pound per square inch
lbf	pound (force)	s	second

LABORATORY EVALUATION OF CABLE BOLT SUPPORTS
(In Two Parts)

2. EVALUATION OF SUPPORTS USING CONVENTIONAL CABLES WITH STEEL BUTTONS, BIRDCAGE CABLES, AND EPOXY-COATED CABLES

By J. M. Goris[1]

ABSTRACT

The U.S. Bureau of Mines is conducting research on cable bolt ground supports to assess their material and support properties, to provide design criteria for using cable bolt supports as roof control systems under various types of underground mining conditions, and to develop a mathematical model of cable bolt support systems. Part 1 described laboratory studies of the support properties of conventional steel cable bolts. Part 2 describes the strength characteristics of conventional cables with steel buttons, single and double birdcage cables, and epoxy-coated cables.

[1]Mining engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

INTRODUCTION

Cable bolts were introduced to the mining industry around 1970 as a means of reinforcing ground prior to mining. The basic support consisted of a high-strength steel cable(s) grouted into a drill hole in advance of mining. As the popularity of this type of support grew, researchers began to study load characteristics and failure mechanics, as well as methods to increase the load-carrying capacities of the supports. Most researchers concentrated on improving pullout resistance along the grout-cable interface by either improving the quality of the grout or by enhancing the configuration of the cable. At the U.S. Bureau of Mines, researchers focused specifically on several topics associated with cable bolt supports:

1. Impacts of components of cable bolt supports, such as breather tubes, on the behavior of these supports.
2. Modification of grouts to improve support strength.
3. Use of conventional cables with steel buttons.
4. Use of birdcage cables.
5. Use of epoxy-coated cables.

Part 1 of this report (Bureau RI 9308) reviewed topics 1 and 2 and presented data on the evaluation of conventional 0.625-in-diam single and double cables; effects of different embedment lengths, water-cement ratios, and grout curing temperatures on support strength; effects of use or nonuse of breather tubes; pumpability and water-bleeding properties of grouts; and the strength properties of sand-cement grouts. Part 2 is a continuation of the cable bolt study and examines the behavior of cable bolt pull-test samples containing either conventional cables with steel buttons attached, birdcage cables, or epoxy-coated cables (topics 3, 4, and 5) (fig. 1). The results were then compared with results from the tests on both single and double conventional cables as described in part 1.

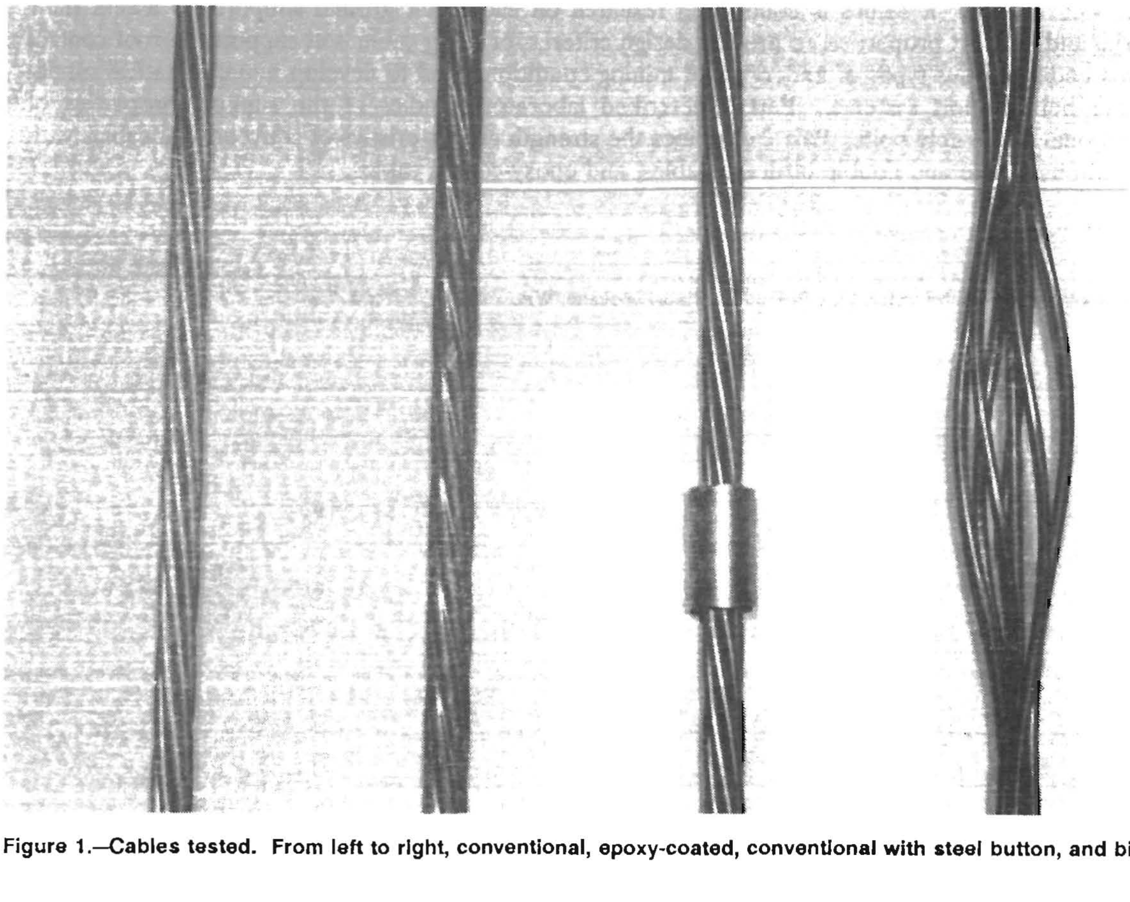

Figure 1.—Cables tested. From left to right, conventional, epoxy-coated, conventional with steel button, and birdcage.

ACKNOWLEDGMENTS

Special thanks go to Ray Anderson, Tom Brady, and Lewis Martin of the Spokane Research Center, who were instrumental in the development of testing procedures, the preparation and testing of test samples, and the evaluation of laboratory test data. Special acknowledgment is also given to the management and technical personnel at the Homestake Mine, Lead, SD, for their guidance with this project.

TEST PROGRAM

In the second part of this test program, each test series contained the appropriate type of cable, a neat cement grout with a water-cement ratio of 0.45, and no chemical additives. For each series, 15 pull-test samples were made, and 5 samples were tested for each curing period of 3, 7, and 28 days to determine the load-displacement characteristics of the samples. From such data, engineers determined maximum load, shear stress, elastic zones, and residual load-carrying characteristics for each sample. To control the quality of the samples, the physical condition of the cables was monitored closely. Compressive and tensile strengths and flow properties were determined for the grout in each test series. Summaries of the test series are shown in table 1.

Table 1.—Test series conducted during laboratory evaluation of supports with various types of cables

Test series	Variable being studied	Description of test samples
1[1]	Cable.	Single conventional cable.
7[1]	.. do.	Two conventional cables.
9A	Steel buttons. ...	Single conventional cable with steel button embedded 2 in.
9B	.. do.	Single conventional cable with steel button embedded 4 in.
9C	.. do.	Single conventional cable with steel button embedded 6 in.
10A	Cable	Single birdcage cable with antinode at junction of pipes.
10B	.. do.	Single birdcage cable with node at junction of pipes.
11A	.. do.	Two birdcage cables with antinode at junction of pipes.
11B	.. do.	Two birdcage cables with node at junction of pipes.
12	Epoxy coating. ..	Single epoxy-coated cable.
13	.. do.	Two epoxy-coated cables.

[1]Test series 1 through 8 are described in detail in Part 1 of this report. Data on test series 1 and 7 are provided here for comparison with test series 9A through 13.

PULL-TEST APPARATUS

The pull-test apparatus (fig. 2) consists of two 2.62-in-diam steel pipes through which a cable is run. The portion of the cable embedded in the 12-in (bottom) pipe is the segment actually being tested; approximately 4 in of

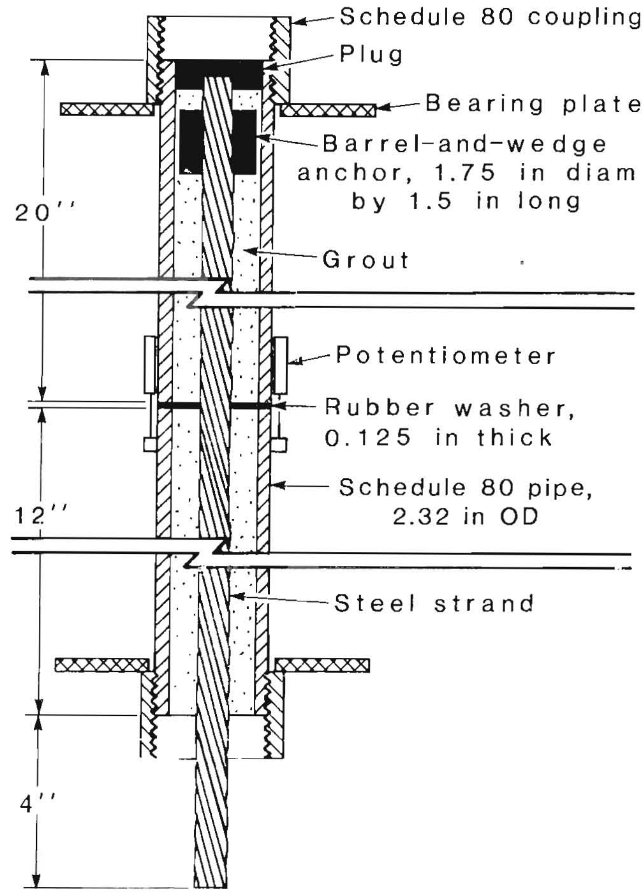

Figure 2.—Pull-test apparatus.

cable extend beyond the end of this pipe. To prevent slippage of the end of the cable embedded in the 20-in (upper) pipe, a 1.75-in-diam by 1.5-in-long barrel-and-wedge steel anchor was attached to the cable, and a load of 25,000 lbf was applied to set the anchor prior to making the pull-test sample. This apparatus was adopted from one used by Fuller and Cox in Australia;[2] however, some modifications were made, such as use of the barrel-and-wedge anchor.

The purpose of using the pipe apparatus was to confine both ends of the cable to prevent rotation during testing. Cable rotation causes the cable to unscrew from the grout column. The pipes were inexpensive and provided great flexibility in making, handling, and storing test samples. The major drawback was that the load-displacement curve for the cable bolt sample was not likely to be exactly what support systems experience in a large rock mass because the stress-strain behavior of pipe is different from that of rock. However, the relative behavior of one laboratory test sample compared with another should approximate the behavior of cable bolts in rock.

PREPARATION OF PULL-TEST SAMPLES

Preparation of pull-test, compression, and tensile samples is discussed in detail in part 1 of this report. All procedures were identical regardless of the components of the test samples. The only variation in the configuration was that the small pipe (fig. 2) was 10 in rather than 12 in long and the large pipe was 22 in rather than 20 in long for the double conventional, double birdcage, and double epoxy-coated cables. The reason was that high pullout loads were associated with double-cable pull-test samples.

PULL-TEST PROCEDURES

Figure 3 shows a sample being tested. The important data being collected are the amount of uniaxial load applied to the sample, which forces the cable to slip, and the displacement or degree of slippage taking place. Loads were recorded in the form of an electrical signal from a load cell within the test machine. Displacement was obtained from two potentiometers attached to the pull-test sample (fig. 3) and from a linear variable differential transformer (LVDT) attached to the head of the test machine. Output from the potentiometers and the LVDT, which serve as backups to one another, was approximately the same. A third potentiometer was attached to the portion of the cable extending past the end of the shorter pipe. This potentiometer was used to sense when the entire length of the cable embedded in the smaller pipe began to slip, thereby indicating that the bond had broken along the entire length of the cable. For every sample tested, shear failure occurred between the cable and the grout. No detectable slippage took place between the grout and the pipe.

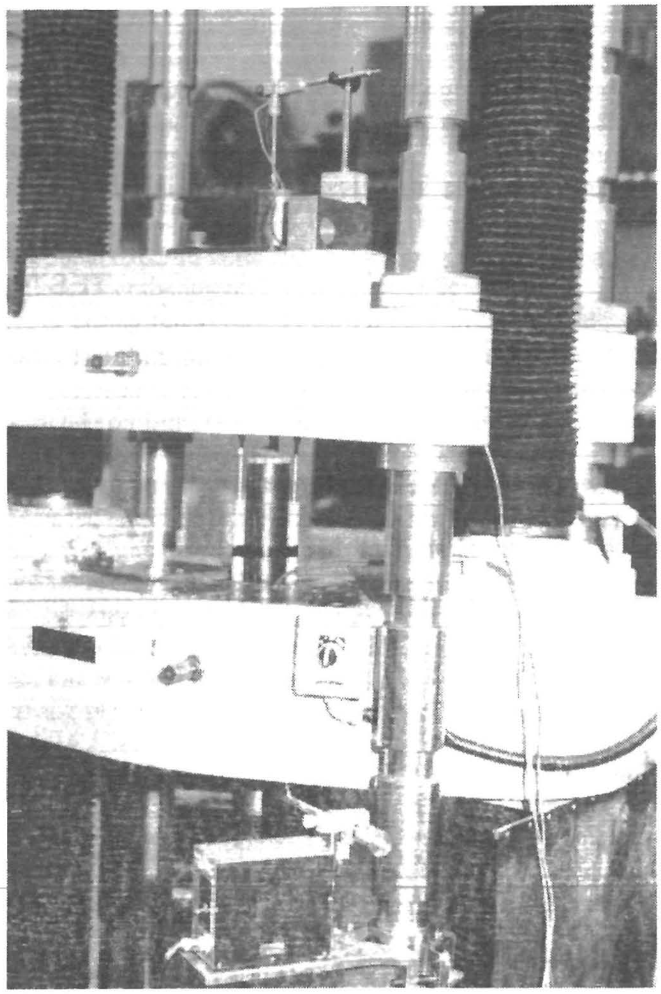

Figure 3.—Hydraulic test machine with pull-test sample.

Rotation of the two pipes and the cable in each pull-test sample was monitored visually during the test by etching common reference lines on the bearing plates of the test apparatus and on each pipe, as well as on the cable protruding from the bottom of the lower pipe (fig. 2). Horizontal displacement of these reference lines with respect to one another during the test would indicate rotation.

ANALYSIS OF TEST DATA

The pull tests were expensive and very time consuming; consequently, the number of tests run for each test series was limited to five samples from each curing period, that

[2]Fuller, P. G., and R. H. T. Cox. Mechanics of Load Transfer From Steel Tendons to Cement Based Grout. Res. Paper No. 262, Div. Appl. Geomechanics, CSIRO, Melbourne, Australia, 1975, pp. 189-203.

is, 3, 7, and 28 days. Analysis of the test results, therefore, was very critical because sample populations were small. The pull-test procedure and the data obtained were analyzed first by observing the performance of each sample as it was tested. The data were then plotted and the load-displacement behavior of each sample was evaluated. Next, the maximum shear stresses and/or maximum loads were analyzed statistically to provide an indication of the similarity of the samples in each series and as a guide for comparing the performance of one set of test samples with another.

Once the test data were compiled, various statistical tests were conducted to determine if the samples had been made and tested in a consistent manner, and if there were significant differences between given sets of data. An explanation of these statistical tests is covered in detail in part 1. Statistical tables used to calculate Z-values for the Student's T-tests were obtained from Dixon.[3]

[3]Dixon, W. J., and F. J. Massey, Jr. Introduction to Statistical Analysis. McGraw-Hill, 1957, pp. 384, 396-403.

TEST RESULTS

The shear stress developed along the grout-cable interface for a given load during a pull test was calculated by dividing that load by the contact area between the cable and the grout. The circumference of a 0.625-in-diam cable was 2.62 in, as calculated by the equation

$$C = N \times 3.14 \times D \times [\sin(360/2N)/(\sin(360/2N) + 1)] \times (0.5 + 1/N),$$

where C = circumference of the cable, in,

N = number of outer wires of the cable,

and D = diameter of the cable, in.[4]

For the conventional cables used in this laboratory study, N = 6 and D = 0.625 in; therefore, C = 2.62 in. The contact area was therefore 2.62 in multiplied by the length of embedded cable in the pipe. For the epoxy-coated cables, N = 6 and D = 0.60 in; however, the epoxy coating added another 0.06 in to the diameter, and consequently, D = 0.66 and C = 2.77 in. Circumferences for the birdcage cables were not calculated because of the varying configurations of the cables.

STANDARD TEST SAMPLES

Test series 1 and 7 (table 1) represent the standards against which all other results were compared. These pull-test samples contained a cement grout with a water-cement ratio of 0.45, either a single or a double 0.625-in-diam cable, but no breather tube or chemical additives. Results from the pull tests on cable bolt samples and strength tests on the grout are shown in table 2.

[4]Stheeman, W. H. A Practical Solution to Cable Bolting Problems at the Tsumeb Mine. CIM Bull., Feb. 1982, pp. 65-77.

The pull-test samples in test series 1 and 7 were also the least complicated and provided a basic understanding of the failure mechanics of such supports under uniaxial loads. Their behavior under uniaxial load is covered in great detail in part 1 of this report.

Table 2.—Summary of 28-day test results for all test series

Test series	Pull tests: Max. load, lbf	Pull tests: Max. shear stress, psi	Grout tests: Compressive stress, psi	Grout tests: Tensile stress, psi	Grout tests: Flow time, s
1	[1]19,820	668	6,940	588	14.0
7	[2]41,080	838	6,748	610	13.8
9A ...	26,500	([3])	7,375	590	14.5
9B ...	55,840	([3])	7,337	597	15.1
9C ...	53,950	([3])	7,470	483	14.4
10A ..	[4]33,960	([3])	7,600	471	15.4
10B ..	[4]25,760	([3])	7,357	481	14.9
11A ..	[4]77,300	([3])	7,775	520	15.0
11B ..	[4]79,750	([3])	7,250	510	14.6
12 ...	27,875	878	7,094	558	14.4
13 ...	[4]57,550	1,144	7,061	452	15.0

[1]Based on 11.3 in of embedment.
[2]Based on 9.36 in of embedment.
[3]Not calculated because of cable configuration.
[4]Based on 10 in of embedment.

CONVENTIONAL CABLE WITH STEEL BUTTON

Conventional cables with steel buttons attached were developed and used in Canada to help improve the pullout resistance of cable bolts when developers realized that pullout resistance could be increased by adding a bearing surface perpendicular to the axis of the cable. The device selected was a steel button, 1.00 to 1.25 in. in diameter by 1.5 to 1.75 in long; however, the barrel-and-wedge anchors used for pretensioned and posttensioned cables can also be used for this purpose. The buttons are pressed onto the cables at specified intervals at a load of approximately 200,000 lbf. Resistance of these cables to pullout depends to a great extent upon surface conditions of the cable, grout and rock properties, direction of applied load, and location of the button on the cable.

The spacing of buttons along the cable depends on the number of fractures in the rock mass because the location of the buttons with respect to rock failure planes greatly influences the pullout resistance of the system. If, for example, the button lies above the failure plane (fig. 4*A*), it will have no affect on the ability of the cable to carry the rock mass below the failure plane; if the button lies within an inch or so of the failure plane (fig. 4*B*), the grout column between the button and the failure plane will be too short to take much load. The further the button is from the failure plane (fig. 4*C*), the more load the grout column will be able to withstand. It seemed logical to assume that, at a given point along the cable, the button would reach its maximum effectiveness. Consequently, three test series were run where the buttons were positioned at different places along the cables, starting at 2 in from the junction of the pipes and continuing at increments of 2 in. Series 9A, 9B, and 9C (table 1) have buttons positioned at 2, 4, and 6 in, respectively, from the junction of the pipes. Because each cable contained a button, the maximum load per foot of embedment was used rather than shear stress for comparing these supports with supports with conventional cables. Statistical data on the test results are shown in table 3.

The data indicate that the buttons made a significant difference in rock behavior. This was verified statistically by first looking at the coefficients of variation to see if the data within each set were consistent and then conducting a T-test on data from samples containing no buttons (series 1) and samples containing buttons. As seen previously, the coefficients of variation for the four test series were less than 15 pct, which indicates consistency in the fabrication and testing of the samples.

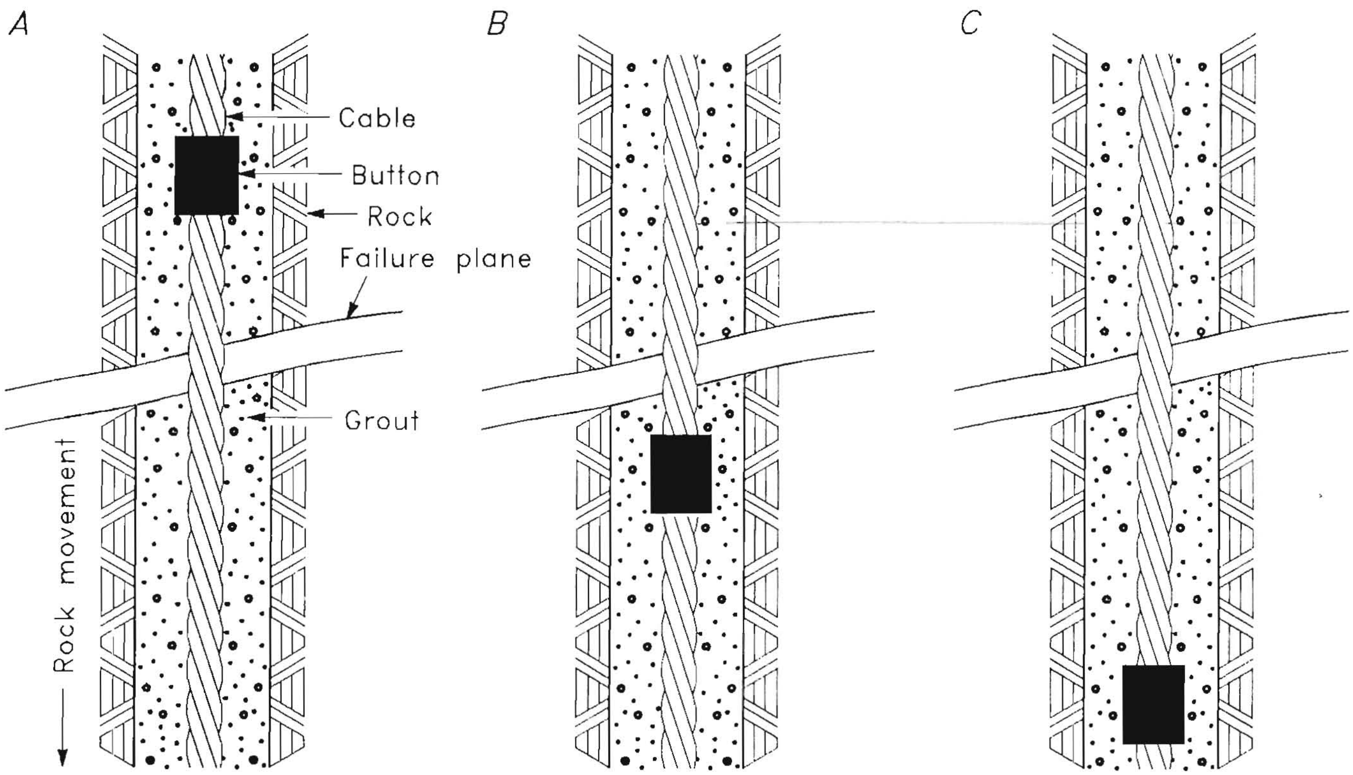

Figure 4.—Location of buttons near failure plane.

Table 3.—Average 28-day test results from series 1, 9A, 9B, and 9C

Statistic	Test series			
	1	9A	9B	9C
Distance of button from pipe junction .. in ..	([1])	2	4	6
Number of samples	5	4	5	4
Mean max. load .. lbf ..	20,999	26,500	55,840	53,950
Standard deviation	710	1,318	3,192	2,763
Max. load .. lbf ..	21,760	27,800	60,200	58,000
Min. load .. lbf ..	20,120	24,700	52,400	52,000
Coefficient of variation .. pct ..	3.4	5.0	5.7	5.2

[1]Samples did not contain buttons.

In conducting a T-test on results for cables with no buttons (series 1) and cables with buttons embedded 2 in, a T-value of 7.59 was obtained compared to a Z-value of ± 1.895. This indicated that the two data sets were not from the same population, and that the presence of the button embedded 2 in made a difference in the behavior of the samples. Further analysis of the data showed an obvious difference between test results from samples with no buttons and samples where the buttons were embedded 4 and 6 in. Consequently, T-tests were not conducted. In addition, there was a major difference in the results between the 2-in embedment samples and the 4- and 6-in embedment samples. However, results from the 4- and 6-in embedment samples were nearly identical. To verify this, a T-test was conducted on the two sets of data, and a T-value of 0.95 was obtained; the Z-value for these sets of data was ± 1.895, indicating that the two sets of data were from the same population and that increasing the embedment length from 4 to 6 in did not increase the maximum load-carrying capacity of the samples.

The load-displacement curves for samples with buttons were quite different from the curve representing conventional cables (fig. 5). The failure mechanics of the button-cable samples are complex. Initially, resistance to pullout was caused by mechanical interlock along the grout-cable interface. However, once slippage began, resistance to pullout was the result of a combination of friction along the grout-cable interface and a compressive force applied against the grout column by the steel button. In the samples where the buttons were embedded 2 in, the compressive load on the grout resulted in a short section of grout being fractured and pushed out of the pipe (fig. 6). Once this occurred, loads decreased rapidly. The buttons embedded 4 and 6 in also compressed the grout and moved along the grout column, as seen in a cross section of a pull-test sample in figure 7; however, the grout column above the button was not pushed from the pipe. Consequently, loads increased as displacement continued (fig. 5). Referring to figure 5, this type of load-displacement behavior suggests a soft support system in that the maximum loads are achieved at high degrees of displacement.

Test data on cables containing buttons indicated that buttons were effective in increasing the load-carrying capacity of these supports; provided a soft, yieldable support; and should be embedded at least 4 in from a failure plane. The location of the button within the grout column was an important key to their success. However, ensuring that the buttons are placed properly could be a difficult task, and consequently, this could be a major disadvantage to their use. Another disadvantage of using buttons is that the cable must be precut to the lengths used in the mine so that the buttons can be placed on

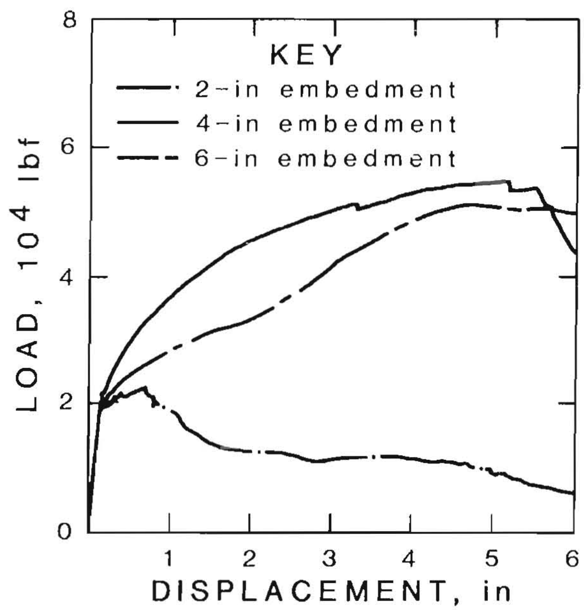

Figure 5.—Average 28-day load-displacement curves for test series 9A, 9B, and 9C.

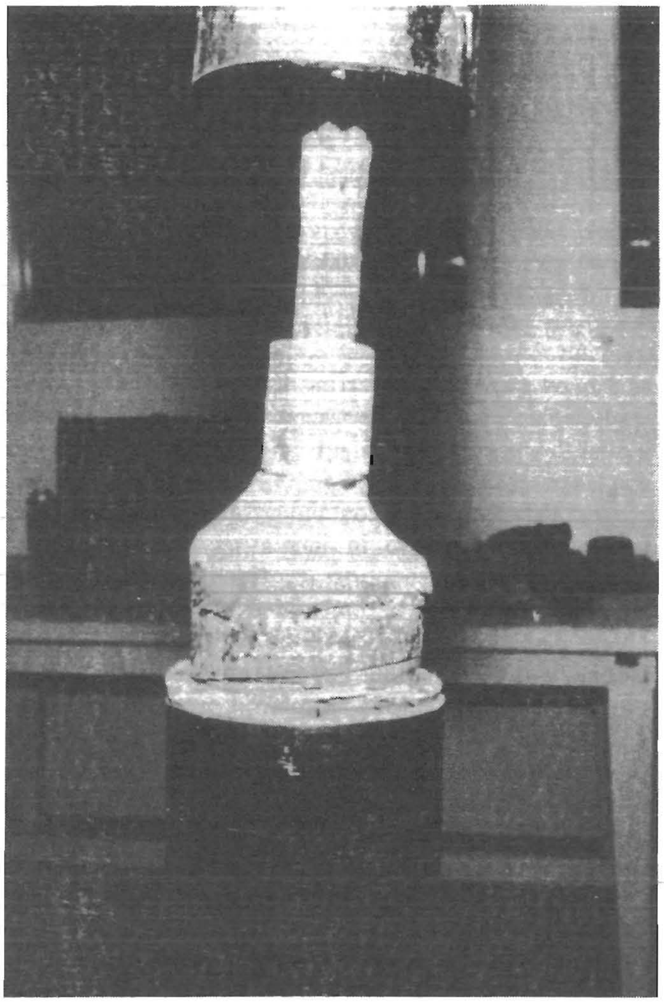

Figure 6.—Pull-test sample with steel button embedded 2 in.

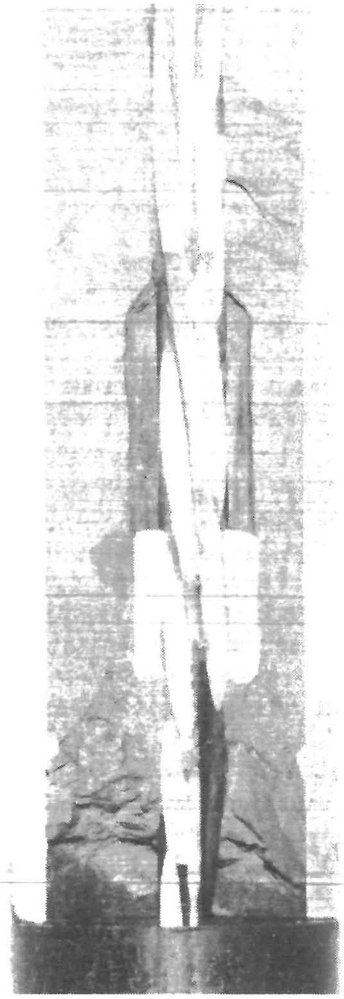

Figure 7.—Cross section of pull-test sample with steel button embedded 6 in.

them. The cable must then be handled in separate pieces rather than in a continuous coil. The cost of the buttons varies from \$0.50 to \$0.75 per button.

SINGLE BIRDCAGE CABLE

The tight fit of the seven wires of a conventional 0.625-in-diam cable limits the surface area of the cable that comes in contact with the grout to approximately 2.62 in^2/in of embedment. It is at this grout-cable interface that resistance to pullout is developed. Recently, a manufacturer in Australia developed a technique for separating the seven wires of a conventional cable and then recombining them to form an open cable with a series of nodes and antinodes spaced at approximately 7-in intervals along the cable (fig. 8). This configuration is called a birdcage and can begin or end at any point along the length of the cable.

When grout is placed around the birdcage cable, the wires of the cable tend to form reinforced nodes that behave as anchors along the length of cable. The even spacing of the nodes helps to eliminate the guesswork as to where to place reinforcing anchors. The location of these nodes with respect to the junction of the pipes in the pull-test assembly, or in the case of rock, to failure planes, could influence the behavior of the support system. For this reason, two test series (10A and 10B in table 1) were planned for the single birdcage cables. In series 10A, the center of an antinode was located at the junction of the pipes (fig. 9). In series 10B, a node was located at the junction of the pipes. No breather tubes or chemical additives in the grout were included.

Figure 10 shows the average load-displacement curve for the 28-day samples of birdcage and conventional cables (series 1). The behavior of the birdcage samples was quite different from behavior of the conventional cable samples

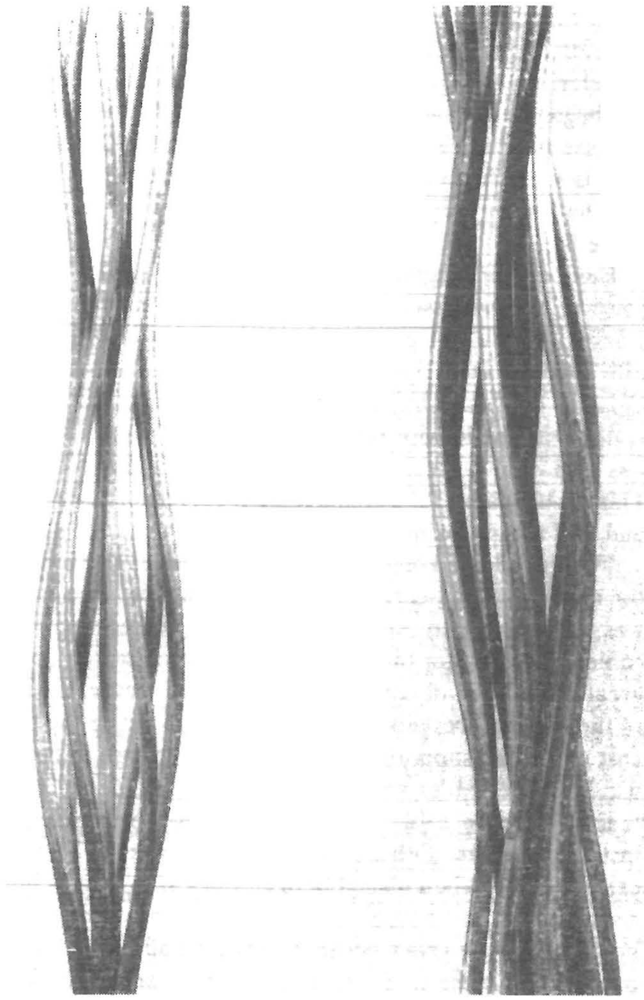

Figure 8.—Single and double birdcage cables.

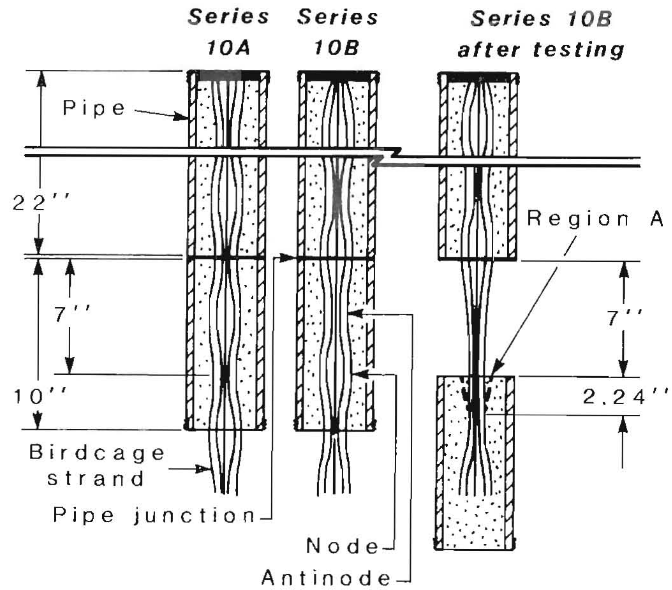

Figure 9.—Location of birdcage cables in pull-test apparatus.

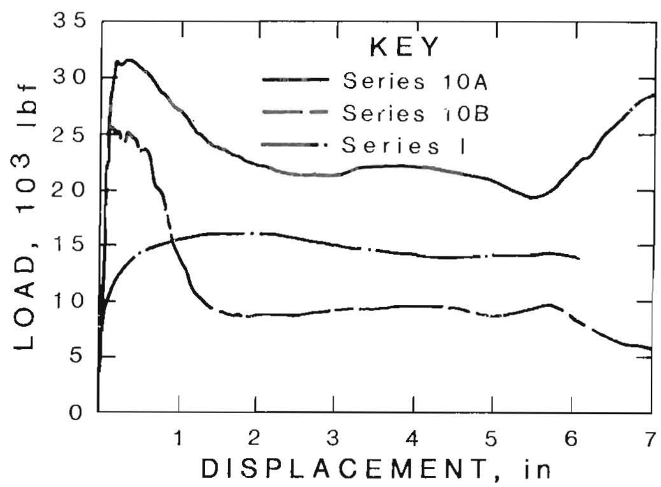

Figure 10.—Average 28-day load-displacement curves for test series 1, 10A, and 10B.

because (1) the maximum loads were much higher, and (2) the resistance to pullout cycled through increasing and decreasing loads up to 7 in of displacement, which is the approximate spacing of the nodes.

As the pipes in series 10A (fig. 9) were pulled apart during testing, the wires of the birdcage cable in the 10-in pipe began to slip through the grout column, following the narrow meandering holes in the grout formed around each wire. Resistance to pullout occurred along the grout-wire interface. The wires forming the node began to deform toward the center of the bulb as they were forced through the narrow opening in the grout column near the junction of the pipes; this deformation of the wires placed the grout in compression and increased the pullout resistance of the cable. The load on the cable increased until displacement reached approximately 0.5 in, at which point the load began to decrease (fig. 10) and then to maintain a residual load-carrying capacity of approximately 23,000 lbf. When approximately 5.5 in of displacement had occurred, loads began to increase rapidly once again. The tests were stopped at a displacement of 7 in. The failure sequence just described was quite different from that of conventional cables because the nodes on the birdcage cable acted as anchors and resisted pullout. However, the curves (fig. 10) indicate birdcage cable supports would be a stiffer system than conventional cable supports because birdcage cables allow less displacement before achieving maximum loads.

Because the configuration of the birdcage cables is different from that of conventional cables, shear stress developed along the lengths of these cables was not used to compare performance. Instead, loads per unit length of embedment were used. Table 4 shows statistical data for series 1 and 10A samples based on 10-in embedment lengths. Data for series 1 samples were obtained from part 1.

Table 4.—Average 28-day test results from five samples each in series 1, 10A, and 10B

(Based on 10-in embedment lengths)

Statistic	Test series		
	1	10A	10B
Mean load . . . . lbf . .	19,820	33,960	25,760
Standard deviation	1,352	2,551	2,260
Max. load . . . . lbf . .	20,000	37,400	27,600
Min. load . . . . lbf . .	17,200	30,400	23,000
Coefficient of variation . . . . pct . .	7.1	7.5	8.9

The average maximum load for the samples in series 10A was 33,960 lbf or a 79-pct increase in capacity over conventional cables (series 1). A T-test was not conducted on these data because the difference in maximum load-carrying capacity was so great.

Samples from series 10B were made with a node at the junction of the pipe. The mean maximum load for these samples was 36 pct greater than for samples from series 1, but was 24 pct less than samples from series 10A. A T-test conducted on series 10A and 10B data sets showed a T-value of 5.38 compared to a Z-value of ± 1.860, indicating that the two data sets were not from the sample population and that the location of the node did make a difference in the maximum loads carried by the samples.

The load-displacement curves for the 28-day birdcage samples from series 10A and 10B (fig. 10) are similar in shape; however, as seen in table 4, the average maximum load achieved by the series 10B samples was lower than the average load of series 10A samples. The reason for this can be explained by studying the behavior of the strand as displacement takes place. Referring to figure 9, as the loads increased and displacement occurred with samples from series 10B, there was a loss of the grout column in region A because the wires in this region were deflected toward the center, crushing the grout and forcing it out of the pipe at the free surface. Consequently, there was a reduction in pullout resistance. The depth to which grout was lost in region A averaged approximately 2.24 in. Therefore, the length of the grout column was reduced by approximately 22.4 pct at the same time there was a loss of friction resistance to pullout. This phenomenon did not occur with series 10A samples. As stated previously, the average difference in maximum load-carrying capacity between series 10A and 10B samples was 24 pct (table 4), nearly the same percentage as loss from the grout column in series 10B samples.

Referring to figure 10, the load for series 10B samples began to increase again at approximately 5 in, but the increase was much smaller than for series 10A samples. This is most likely because the length of the grout column had been reduced at a critical location (region A in figure 9).

Embedment lengths longer than 10 in were not tested; however, it was assumed that as embedment length increases, the loss of grout near the junction of the pipes will become less significant to the total load-carrying capacity of these supports and that the location of the node or antinode with respect to a failure plane will be a less important aspect of the behavior of birdcage cables. This should cause load-displacement curves for series 10A and 10B to approximate one another.

Tests conducted on single birdcage samples showed that the maximum load-carrying capacity of the birdcage cables was between 71 to 30 pct greater than for conventional cables. The cost for birdcage cable is approximately 35 pct greater than that of conventional cables; however, the cost of the cable represents only about 10 to 15 pct of the total cost of a cable support. Therefore, the increase in cost to use birdcage cables would be about 3.5 to 5.2 pct. This makes birdcage cable bolts cost effective, depending on installation costs. Other important advantages of birdcage cables are (1) when placed in drill holes at or near a horizontal angle, the entire surface area of the cable should be covered with grout because only a small area of a few outer wires at the nodes will rest on the wall of the hole; (2) birdcage cables are not as sensitive to grease, rust, mud, etc., being on the wires as are conventional cables because the failure mechanism is different; and (3) birdcage cables do not contribute to grout bleeding (see part 1 of this report). Major disadvantages are that the cables must be made to specific lengths, and, therefore, cannot be handled as a continuous coil, and that these cables are more difficult than conventional cables to push into a drill hole.

DOUBLE BIRDCAGE CABLE

As with single birdcage cables, it was assumed that the location of the nodes and antinodes with respect to the junction of the pipes would affect the load-displacement behavior of double birdcage cables. Consequently, two test series were run on double birdcage samples (series 11A and 11B), and the results were compared with results from tests on double conventional cables (series 7). For series 9A, each cable was placed so that an antinode was positioned at the junction of the pipes, and for series 9B, a node was positioned at the junction of the pipes. Table 5 lists the basic statistics for the 28-day pull-test samples for these series as well as for series 7.

Table 5.—Average 28-day test results from series 7, 11A, and 11B

(Based on 10-in embedment lengths)

Statistic	Series		
	7	11A	11B
Number of samples	5	5	4
Mean maximum load . . . . . lbf	41,000	77,300	79,750
Standard deviation	5,761	9,698	6,348
Max. load . . . . . lbf	49,600	90,000	87,750
Min. load . . . . . lbf	36,000	63,000	72,250
Coefficient of variation . . . . pct	14.1	12.5	8.0

The results in table 5 show a significant difference between double conventional and double birdcage cables. The mean maximum loads for series 11A and 11B samples increased 88.5 and 94.5 pct, respectively, over conventional double cables. A T-test was not conducted on the data from series 7 and 11A or 11B because the differences in average maximum loads were so great. Figure 11 shows average 28-day load-displacement curves for double conventional and double birdcage samples. The three curves are strikingly different. The location of the nodes and antinodes with respect to the junction of the pipes has made a significant difference (fig. 10). Pull-test samples

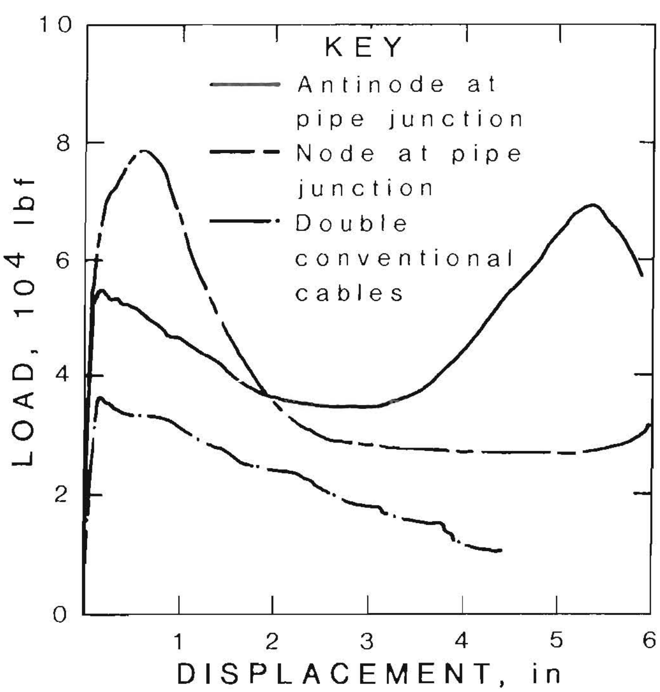

Figure 11.—Average 28-day load-displacement curves for test series 7, 11A, and 11B.

with an antinode at the junction of the pipes (series 11A) showed high initial loading, then a load reduction followed by a second significant increase in load. In a similar manner, samples from series 11B also showed high initial loads followed by a reduction; however, loads did not increase rapidly again. Also, maximum loads in series 11A occurred when displacements were greater than 5 in, whereas average maximum loads for series 11B occurred before 1 in of displacement. Samples from series 11B showed a loss of grout in region A, and it was assumed that this loss was responsible for the lack of increase in load at a displacement of 5 in or greater.

As with single birdcage cables, when double birdcage cables are placed in drill holes at or near a horizontal angle, grout should cover almost 100 pct of the surface area of the cable because only a small area of a few outer wires at the nodes will rest on the wall of the hole. Double birdcage cables are not as sensitive to grease, rust, mud, etc., on the wires as are conventional cables because the failure mechanism is different. In addition, birdcage cables do not contribute to grout bleeding. Based on these results, double birdcage cables appear attractive as a replacement for conventional cables.

SINGLE EPOXY-COATED CABLE

The surface condition of a conventional cable has a great influence on its shear resistance. For example, grease on the cable will reduce the shear resistance of the system because grease does not permit a good bond between the cable and the grout. On the other hand, a light coating of rust on the surface of a cable will increase shear resistance because there is an increase in friction between the cable and the grout.

Recently, an epoxy-coated cable was marketed for use in prestressed concrete members to provide corrosion resistance (fig. 12). The coated cable, however, did not provide enough shear resistance against pullout, so the manufacturer adopted a method of embedding silica grit in the outer surface of the coating to provide this resistance. Shear resistance can be altered by varying the size and concentration of the grit.[5] Bureau engineers concluded that this type of cable could be used for long-term supports or where corrosion may be a problem.

A series of test samples was made using neat cement grout and a single epoxy-coated cable with embedded grit (series 12, table 1). The 0.6-in-diam cable contained seven wires. The epoxy coating was approximately 0.03 in thick over the crowns of the outside wires, thus making the outside diameter of the coated cable approximately 0.66 in.

[5]Dorsten, D., F. H. Frederick, and H. K. Preston. Epoxy Coated Seven-Wire Strand for Prestressed Concrete. Prestressed Concr. Inst. J., v. 29, No. 4, July-Aug. 1984, pp. 1-11.

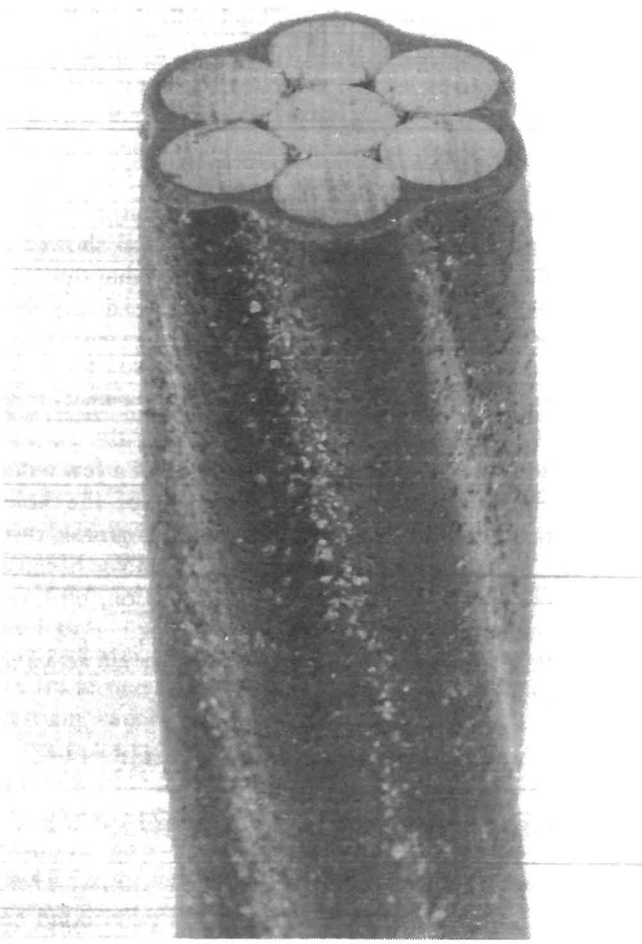

Figure 12.—Epoxy-coated cable.

Table 6 shows the results of the pull tests on single epoxy-coated cables (series 12), as well as for single bare cables (series 1). In conducting a T-test on results from series 1 and 12, a T-value of -5.26 was obtained compared to a Z-value of ±1.860. This indicated that the two data sets were not from the same population and that the epoxy coating on the cables from series 12 made a difference in the behavior of the samples. After 28 days of curing, the average shear strength for the epoxy-coated cables was 878 psi, or approximately 31 pct higher than shear strength for conventional bare cables. This means that, given the same length of cable, the epoxy-coated cable should have a greater load-carrying capacity if conditions were identical. Figure 13 shows one of the epoxy-coated cables cut in half longitudinally after being tested. This cable had actually been pulled through the grout for approximately 6 in, yet there was still excellent surface contact between the grout and the epoxy coating. The epoxy coating did not pull away from the cable. All of the slippage took place between the cable and the grout. Figure 14 shows the average 28-day load-displacement curves for both single conventional and single epoxy-coated cables. Both types of cables exhibited similar behavior in that they reached the maximum load within the first 2 in of displacement and then maintained a very high residual load-carrying capacity. However, the epoxy-coated cables showed a higher average load-carrying capacity.

DOUBLE EPOXY-COATED CABLE

Test series 13 involved two epoxy-coated cables. This series was conducted to determine if the load-displacement behavior of these cables was significantly different from the behavior of single epoxy-coated cables (series 12) as well as double conventional cables (series 7). By adding a second cable, the contact area between the cables and the grout was doubled compared to a single cable. Therefore, one would expect to obtain at least a 100-pct increase in the load-carrying capacity of the system and the same shear stress for an identical length of embedment. However, results in table 6 show an increase in shear stress of 266 psi for two epoxy-coated cables (series 13) over a single epoxy-coated cable (series 12). This is an increase of approximately 30 pct. By comparison, double conventional cables (series 1 and 7 table 2) showed an increase in shear stress of 170 psi, or 25 pct, over single conventional cables. Table 7 compares single and double conventional, birdcage, and epoxy-coated cables; these results suggest that cable bolt supports using double cables are far more efficient (that is, they have a greater maximum load-carrying capacity) than single cables. This conclusion is important because the use of double cables in each drill hole could give ground control engineers the option of increasing hole spacing, thereby requiring fewer holes for a given rock mass.

Table 6.—Average 28-day test results from series 1, 7, 12, and 13

Statistic	Test series			
	1	7	12	13
Number of samples	5	5	5	4
Mean shear stress ... psi	668	838	878	1,144
Standard deviation	23	121	85	41
Max. shear stress ... psi	692	1,019	1,012	1,191
Min. shear stress ... psi	640	783	786	1,100
Coefficient of variation ... pct	3.4	14.4	9.7	3.6

Table 7.—Comparison of single and double conventional, birdcage, and epoxy-coated cables

Type of cable	Conventional	Birdcage[1]	Birdcage[2]	Epoxy-coated
	SINGLE			
Test series	1	10A	10B	12
Av. max. load ...... lbf ..	19,820	33,960	25,760	27,875
Displacement at av. max load ..... in ..	1.78	0.27	0.30	2.08
	DOUBLE			
Test series	7	11A	11B	13
Av. max. load ...... lbf ..	41,080	77,300	79,750	57,550
Displacement at av. max load ..... in ..	0.11	4.74	0.60	1.95
Difference between av. max. load[3] .... lbf ..	21,260	43,340	53,990	29,675

[1]Antinode at junction of pipes.
[2]Node at junction of pipes.
[3]Differences are between single and double cables for each type listed.

As part of the analysis of pull-test data, a comparison was made between double conventional cables (series 7) and double epoxy-coated cables (series 13). The difference in the mean shear stresses (table 6) for samples from these series is 306 psi, indicating that the presence of the epoxy coating and the embedded grit (series 13) significantly increased the shear stress developed along the grout-strand interface. A T-test conducted on the two data sets showed a T-value of -4.26 compared to a Z-value of ± 1.895, which indicates that the two sets of data were not from the same population. Therefore, the epoxy-and-grit coating did influence the strength of the double cable samples.

Figure 15 shows the average load-displacement curves for both double conventional and epoxy-coated cable samples. The shapes of the curves are similar to one another in that, after reaching maximum loads, both curves drop rapidly; however, the curves for the samples with double epoxy-coated cables show much higher loads.

The manufacturer of the epoxy-coated cables had the product tested for chemical resistance, flexibility of the coating, abrasion resistance, and many other conditions, as required by the Federal Highway Administration,[6] and the cable passed.[7]

[6]Many of the conditions found during installation of cables in highway construction are also found in mining. Included are placement of cables in rock masses and soil embankments, exposure of cables to corrosive chemicals, flexing of the cables during installation, and abrasion of the cables when the rock mass being supported begins to move. Therefore, the results from tests required by the Federal Highway Administration to determine the capabilities of the cables are also applicable to mining.

[7]Work cited in footnote 5.

The high shear stress of the epoxy-coated cable coupled with its resistance to corrosion and its ability to reduce grout bleeding makes this type of cable very attractive for bolting when the support system is long term. The cost for epoxy-coated cable, however, is approximately twice that for conventional cable, and this factor must be considered when evaluating the use of this cable.

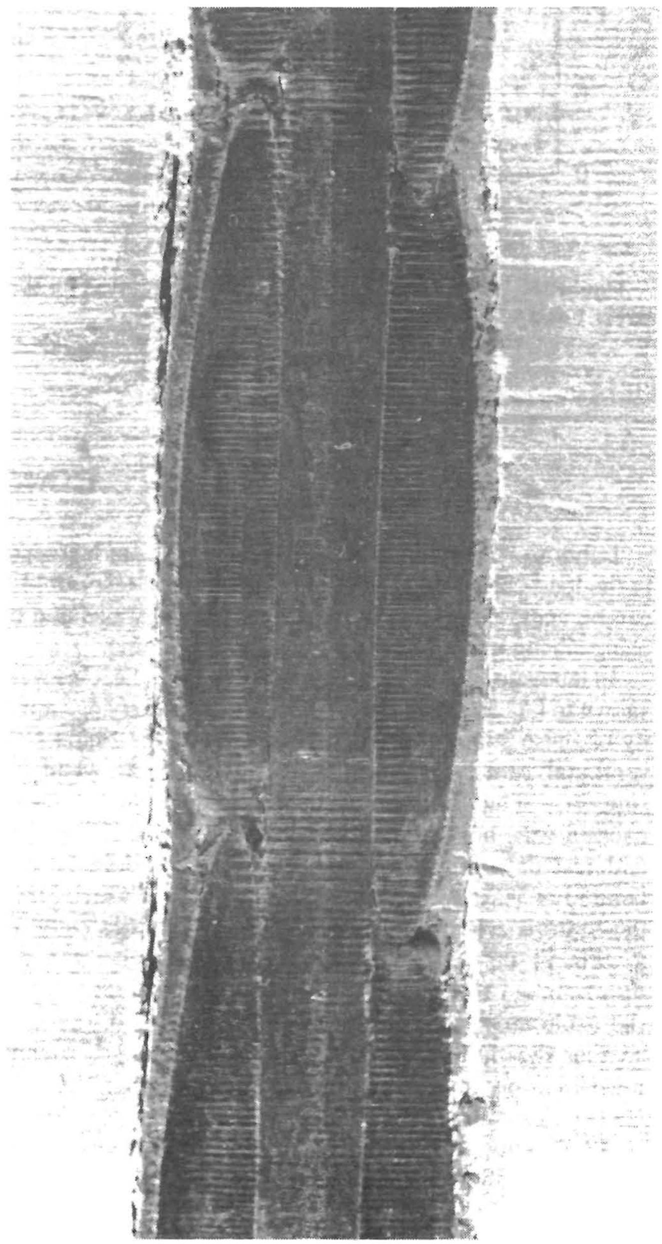

Figure 13.—Cross section of epoxy-coated pull-test sample after testing.

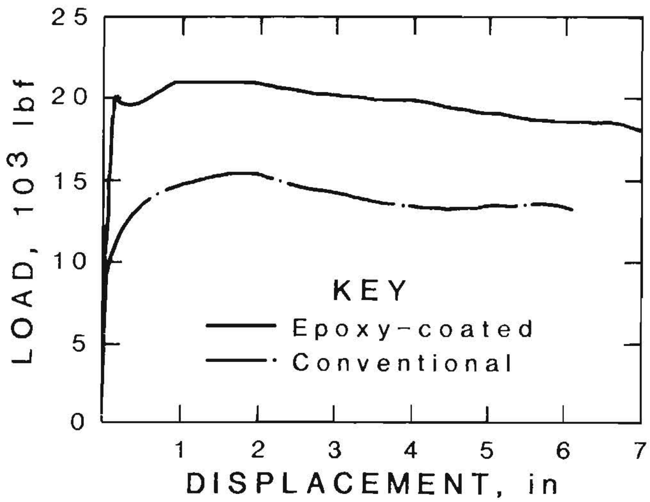

Figure 14.—Average 28-day load-displacement curves for test series 1 and 12.

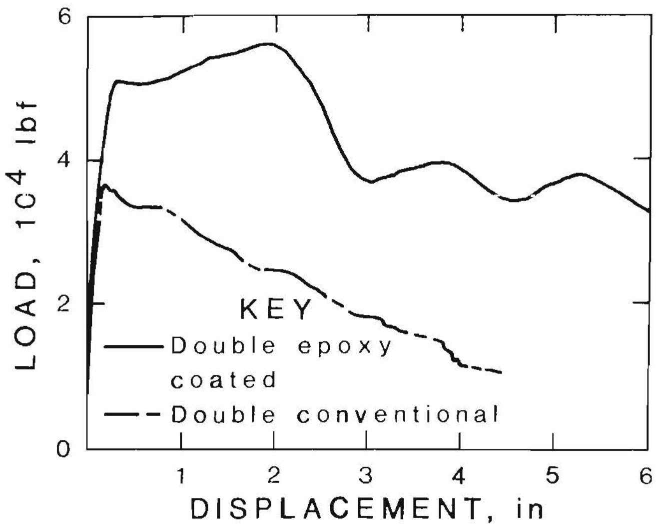

Figure 15.—Average 28-day load-displacement curves for test series 7 and 13.

CONCLUSIONS

Laboratory test results showed that significant increases in the load-carrying capacity of cable bolt pull-test samples can be achieved by modifying cable configurations and by using silicon grit embedded in an epoxy coating.

In laboratory tests, steel buttons attached to cables were shown to be effective in increasing the load-carrying capacity of these supports from 34 to 182 pct over single conventional cables. They also provided a soft, yieldable support. The location of the button within the grout column was, however, an important key to their success, and test data indicated that the buttons should be embedded at least 4 in from a failure plane. Ensuring that the buttons are placed properly along the cable could be a difficult task. Consequently, this could be a major disadvantage to their use. Another disadvantage is that the cable must be precut to the lengths used in the mine so that the buttons can be placed on them. The cable must then be handled in separate pieces rather than in a continuous coil.

Tests conducted on both single and double birdcage cables showed that the nodes acted as anchors and helped to increase the load-carrying capacity of these supports over conventional single and double cables. Other important advantages of birdcage cables are as follows:

1. When placed in drill holes at or near a horizontal angle, the entire surface area of the cable should be covered with grout because only a small area of a few outer wires at the nodes will rest on the wall of the hole.
2. Birdcage cables are not as sensitive to grease, rust, mud, etc., on the wires as are conventional cables because the failure mechanism is different.
3. Birdcage cables do not contribute to grout bleeding.

Major disadvantages are that the cables must be made to specific lengths and, therefore, cannot be handled in a continuous coil. These cables are also more difficult to push into a drill hole than conventional cables.

Results from tests with both single and double epoxy-coated cables indicated that they are more efficient (greater shear stress) than either single or double conventional cables. The increase in shear stress of the epoxy-coated cables coupled with their resistance to corrosion makes them very attractive for use where the support system is long term. In addition, epoxy-coated cables also reduce grout bleeding. The cost for the epoxy-coated cables, however, is approximately twice that of conventional cables, which must be considered when evaluating use of this cable.

Laboratory evaluation of various cable bolt configurations shows that it is important for ground control engineers to recognize and understand the impact of each type of cable bolt on a support system and to incorporate beneficial properties into a support system whenever possible.

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