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REPORT OF INVESTIGATIONS/1989

Relationships Between Annulus Thickness and the Integrity of Resin-Grouted Roof Bolts

By Bryan F. Ulrich, William J. Wuest,
and Raymond M. Stateham

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lb	pound
in	inch	lb/in	pound per inch
in^2	square inch	pct	percent
in/s	inch per second	s	second

RELATIONSHIPS BETWEEN ANNULUS THICKNESS AND THE INTEGRITY OF RESIN-GROUTED ROOF BOLTS

By Bryan F. Ulrich,[1] William J. Wuest,[2] and Raymond M. Stateham[3]

ABSTRACT

If resin-grouted roof bolts are not installed correctly, mine roof reinforcement can be affected, and roof falls can result. A bolt installation variable that is readily controlled by the mine operator is annulus thickness. The objective of this U. S. Bureau of Mines investigation was to study the effect of annulus thickness variations on the integrity of 3/4-in-diam resin-grouted bolts. Forged-head test bolts, 2 and 1 ft long, were installed in concrete blocks that had been drilled with 1-, 1-1/8-, 1-1/4-, 1-3/8-, and 1-1/2-in-diam bits. Standard pull tests were performed; then the concrete was broken away from the bolts so that grout mix quality could be inspected. It was found that the optimum annulus thickness is 1/8-in (1-in-diam drill hole), and as annulus thickness increases from the optimum, there is a corresponding decrease in grout mix quality, effective grout ratio, and axial stiffness.

[1]Mining engineer (now with Knight Piesold and Co., Denver, CO).
[2]Mining engineer.
[3]Supervisory geophysicist (retired).
Denver Research Center, U.S. Bureau of Mines, Denver, CO.

INTRODUCTION

The use of resin-grouted bolting systems to help stabilize underground mine workings has become an accepted practice throughout the world mining community. Grouted roof bolts were first developed and field tested in the Federal Republic of Germany and France about 1969-70. Presently, some of the other countries using resin-grouted bolts for ground control are Australia, Brazil, South Africa, the Soviet Union, and the United States. In addition, Great Britain, India, and the People's Republic of China have used grouted bolts on an experimental basis. Now more than ever, because global supplies of underground resources continue to be important to their way of life, it is essential that current, high-technology analysis of parameters affecting ground control is available.

From when bolting supplies are manufactured to when mine roof and ribs are reinforced with them, many things can happen to decrease bolt integrity. The miner needs to thoroughly understand this problem because, in some cases, lowered bolt integrity has resulted in catastrophic loss of life and capital equipment. Events detrimental to bolt integrity can be classified under four major categories: (1) manufacturing defects, (2) damage during transport,(3) improper storage procedures, and (4) inaccurate bolt-installation technique.

Examples of bolt-installation parameters are bolt strength, diameter, and length, grout type, penetration rate during bolt insertion, spin time during resin-catalyst mixing, rotational speed of drill head, type of drill, and drill-hole pattern, length, and diameter (annulus thickness). This U. S. Bureau of Mines investigation examines the effect of altering annulus thickness on the integrity of resin-grouted bolts.

Since the advent of grouted roof bolts, many public and private groups have, directly and indirectly, studied how to achieve maximum bolt reinforcement performance (*1-7*).[4] For this Bureau investigation bolts, which were installed with various annulus thicknesses, were not only subjected to axial-tensile tests, but were also broken away from the installation medium to be inspected. Photographic evidence of the steel-grout system is provided to confirm research results.

DISCUSSION OF TESTS

Two tests were necessary for this investigation. The first was conducted to gather preliminary results. Once this was achieved, a second test was conducted to verify and more clearly establish the results of the first.

For both tests, drill holes were made with an electric, rotary-percussive drill that was equipped with auger bits, and bolts were inserted and spun with a handheld, pneumatic drill that conformed to the grout manufacturer's recommendation of at least 100 rotations per minute. Other pertinent grout manufacturer recommendations are as follows: (1) bolts must be of steel concrete reinforcing bar with standard or mill rolled threadbar type deformation, (2) during installation, rotate the bolt as it is being pushed through the grout cartridge, (3) penetration rate while rotating the bolt should be 2 to 4 in/s, (4) after the bolt has reached the bottom of the drill hole, rotation should continue for an additional 10 to 15 s, depending on the gel time, (5) drill-hole length should be 1 in longer than bolt length, and (6) drill-hole diameter for a 3/4-in-diam bolt should be 1 or 1-1/8 in. Because bolt installation specifications vary, always follow the recommendations of the site-specific manufacturer.

Unwanted variables were eliminated by using a controlled laboratory procedure. Variations in installation procedures were held to a minimum and all test grout had the same expiration date.

TEST 1

Procedures

For this test, twenty-five 3/4-in-diam, 2-ft-long, type 40 steel-rebar bolts were installed in a block of concrete with a full column of grout according to the grout manufacturer's recommendations. Drill-hole length was held constant at 25 in. Water-based, polyester-resin grout with a 90-s gel time was used to assure proper spinning could be achieved. Drill-hole diameters of 1, 1-1/8, 1-1/4, 1-3/8, and 1-1/2 in were used. After the bolts were installed, the grout was allowed to cure, pull tests were conducted, and the concrete was broken away to inspect the installation. In determining results, emphasis was placed on grout mix quality.

Results

Every test bolt exceeded the standard pull-test criterion of less than 0.2-in deflection at 17,600-lb tensile load (table 1). However, grout mix quality differed greatly between the drill-hole sizes.

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

TABLE 1.–Annulus-thickness investigation data

Test and bolt number	Drill hole diameter, in	Yield point, 10^3 lb	Deflection at yield, 10^{-3} in	Axial stiffness, 10^3 lb/in	Postbreakout grout-column length, in	Length quality mix, in	EGR, pct
1:							
11	1	21	97	NA	NA	NA	NA
21	1	23	165	NA	NA	NA	NA
31	1	20	108	NA	NA	NA	NA
41	1	20	122	NA	NA	NA	NA
51	1	26	141	NA	NA	NA	NA
13	1-1/8	24	128	NA	NA	NA	NA
14	1-1/8	22	97	NA	NA	NA	NA
15	1-1/8	23	121	NA	NA	NA	NA
16	1-1/8	25	104	NA	NA	NA	NA
17	1-1/8	26	158	NA	NA	NA	NA
22	1-1/4	21	48	NA	NA	NA	NA
23	1-1/4	21	155	NA	NA	NA	NA
24	1-1/4	21	140	NA	NA	NA	NA
25	1-1/4	27	155	NA	NA	NA	NA
26	1-1/4	23	95	NA	NA	NA	NA
32	1-3/8	25	156	NA	NA	NA	NA
33	1-3/8	18	82	NA	NA	NA	NA
34	1-3/8	21	136	NA	NA	NA	NA
36	1-3/8	26	106	NA	NA	NA	NA
37	1-3/8	27	144	NA	NA	NA	NA
42	1-1/2	26	98	NA	NA	NA	NA
44	1-1/2	24	117	NA	NA	NA	NA
45	1-1/2	20	76	NA	NA	NA	NA
46	1-1/2	29	102	NA	NA	NA	NA
47	1-1/2	26	123	NA	NA	NA	NA
2:							
1A3	1	18	320	56.3	10.5	10.5	88
1A4	1	21	257	81.7	6.5	6.5	54
1A16	1	26	308	84.4	9.0	9.0	75
1A17	1	24	275	64.5	8.0	8.0	67
1A21	1	20	285	70.2	12.0	12.0	100
1B2	1	24	337	71.2	10.5	10.5	88
1B4	1	23	291	79.0	8.0	8.0	67
1B5	1	27	310	87.1	11.0	11.0	92
1B17	1	18	322	55.9	9.0	9.0	75
1B21	1	24	203	118.2	6.0	6.0	50
2A1	1	22	230	95.7	11.5	11.5	96
2A2	1	19	345	55.1	8.5	8.5	71
2A3	1	21	225	93.3	10.0	10.0	83
2A4	1	21	290	72.4	11.0	11.0	92
2A21	1	24	342	70.2	11.5	11.5	96
2B2	1	27	368	73.4	8.0	8.0	67
2B4	1	21	314	66.9	11.0	11.0	92
2B6	1	24	326	73.6	10.5	10.5	88
2B7	1	20	225	88.9	11.5	11.5	96
2B10	1	26	457	56.9	7.0	7.0	58
2B11	1	25	373	67.0	10.5	10.5	88
2B14	1	19	200	95.0	8.0	8.0	67
2B15	1	19	325	58.5	9.0	9.0	75
2B16	1	18	231	77.9	7.5	7.5	63
2B17	1	20	230	87.0	9.0	9.0	75
2B18	1	22	274	80.3	6.5	6.5	54
2B19	1	22	264	83.3	9.0	9.0	75
2B20	1	25	313	79.9	10.0	10.0	83
2B21	1	21	280	75.0	6.0	6.0	50
2B22	1	17	312	54.5	8.0	8.0	67
2B23	1	19	295	64.4	9.0	9.0	75
2B24	1	21	295	71.2	10.0	10.0	83
2B25	1	21	280	75.0	11.5	11.5	96

See explanatory notes at end of table.

TABLE 1.–Annulus-thickness investigation data–Continued

Test and bolt number	Drill hole diameter, in	Yield point, 10^3 lb	Deflection at yield, 10^{-3} in	Axial stiffness, 10^3 lb/in	Postbreakout grout-column length, in	Length quality mix, in	EGR, pct
2:							
1A6	1-1/4	16	328	48.8	7.5	7.5	63
1A7	1-1/4	22	269	81.8	10.5	7.0	58
1A8	1-1/4	8	99	80.8	2.0	1.0	8
1A9	1-1/4	18	207	87.0	9.5	7.5	63
1A18	1-1/4	16	248	64.5	9.5	4.0	33
1B7	1-1/4	23	266	86.5	9.0	9.0	75
1B8	1-1/4	6	110	54.6	10.5	8.5	71
1B9	1-1/4	20	402	47.6	10.0	8.5	71
2A10	1-1/4	21	367	57.2	10.0	10.0	83
2A23	1-1/4	20	375	53.3	11.0	9.0	75
3A2	1-1/4	24	319	75.2	11.0	11.0	92
3A3	1-1/4	26	358	72.6	10.0	10.0	83
3A5	1-1/4	24	295	81.4	7.5	7.5	63
3A6	1-1/4	21	291	72.2	8.5	8.5	71
3A8	1-1/4	26	448	58.0	9.0	9.0	75
3A9	1-1/4	26	332	80.8	10.0	10.0	83
3A10	1-1/4	26	300	86.7	11.0	11.0	92
3A11	1-1/4	26	549	47.4	8.5	8.5	71
3A12	1-1/4	25	308	81.2	7.5	7.5	63
3A15	1-1/4	26	309	84.1	10.0	10.0	83
3A16	1-1/4	19	335	56.7	9.5	7.0	58
3A17	1-1/4	24	478	50.2	10.0	8.0	67
3A18	1-1/4	25	523	47.8	10.5	10.5	88
3A20	1-1/4	25	336	75.1	11.0	8.0	67
3A21	1-1/4	18	119	90.5	10.5	9.5	79
3A24	1-1/4	19	309	61.5	11.0	8.5	71
1A11	1-1/2	22	347	63.4	11.0	8.0	67
1A12	1-1/2	13	301	43.2	10.5	10.5	88
1A13	1-1/2	22	90	22.2	10.0	8.0	67
1A14	1-1/2	19	242	78.5	6.0	5.0	42
1A15	1-1/2	5	42	119.1	12.0	7.0	58
1A20	1-1/2	2	41	48.8	12.0	7.0	58
1A25	1-1/2	12	206	58.3	8.5	5.0	42
1B12	1-1/2	28	484	57.9	10.5	10.5	88
1B15	1-1/2	18	176	102.3	12.0	11.0	92
1B19	1-1/2	4	140	28.6	9.0	2.0	17
1B20	1-1/2	11	371	29.7	10.0	8.0	67
1B25	1-1/2	3	26	115.4	12.0	4.0	33
2A13	1-1/2	16	231	69.3	12.0	10.0	83
2A14	1-1/2	26	371	70.1	9.0	6.0	50
2A19	1-1/2	16	351	45.6	12.0	10.5	88
2A25	1-1/2	18	392	45.9	12.0	10.0	83
3B1	1-1/2	18	306	58.8	12.0	11.0	92
3B2	1-1/2	3	58	51.7	4.0	4.0	33
3B3	1-1/2	4	79	50.6	2.5	1.5	13
3B4	1-1/2	6	73	82.2	10.5	8.5	71
3B5	1-1/2	4	54	74.1	10.5	3.0	25
3B7	1-1/2	10	300	53.3	10.0	8.5	71
3B10	1-1/2	5	85	58.8	9.5	5.0	42
3B11	1-1/2	18	227	79.3	11.0	10.0	83
3B13	1-1/2	12	313	38.3	9.5	7.5	63
3B14	1-1/2	8	214	37.4	5.5	5.0	42
3B15	1-1/2	12	185	64.9	7.5	3.0	25
3B16	1-1/2	13	190	68.4	10.0	7.0	58
3B17	1-1/2	13	215	60.5	8.0	8.0	67
3B19	1-1/2	8	206	38.8	9.5	4.0	33
3B24	1-1/2	10	207	48.3	9.5	8.0	67
3B25	1-1/2	11	293	37.5	12.0	7.5	63

EGR Effective grout ratio.
NA Not available.

Bolts installed in 1-in-diam holes consistently had properly mixed grout. The resin and catalyst were homogeneously mixed along the entire length of the bolt and the plastic wrapper was completely shredded. The color of the grout was medium-gray, and it was not easily broken with a hammer. A sample of these bolts is shown in figure 1.

Bolts installed in the 1-1/8-, 1-1/4-, 1-3/8-, and 1-1/2-in-diam holes had varied degrees of grout mixing. Generally, the quality of mixing decreased as hole diameter increased. Many bolts showed obvious signs of improper mixing. Figure 2 shows five test bolts that have partially mixed grout columns caused by failure of the catalyst to disseminate properly. Figure 3 shows a test bolt that has large pieces of plastic wrapper that have not been shredded.

Some bolts with hole diameters greater than 1 in had proper mixing at the collar end of the bolt only. This can be caused by eccentric spin due to nonrigid fittings on bolting equipment. Toward the back end of these bolts, eccentric spin is resisted by the viscous grout, and a poor mix results. This effect has also been observed by Gerdeen (*2*).

Since all bolts passed the standard pull-test criterion, it is clear that the pull test is not a good measuring tool for grout-mix quality determination. The pull test will only measure anchorage capacity of a short length of grout column. It has been observed that in limestone, depending on the stiffness of grout, pull-test load will dissipate to 0 lb at a distance of about 20 in from the collar of the bolt (*2*). This distance is known as load-transfer length, and is related to the physical properties of the steel, grout, and rock. If a resin-grouted bolt installed in typical coal-mine roof rock has a grout-column length greater than load-transfer length, pull test results will not measure grout mix quality. To test quality of the grout mix, bolts should be installed with a grout-column length less than the load-transfer length. Test 2 was conducted in this manner.

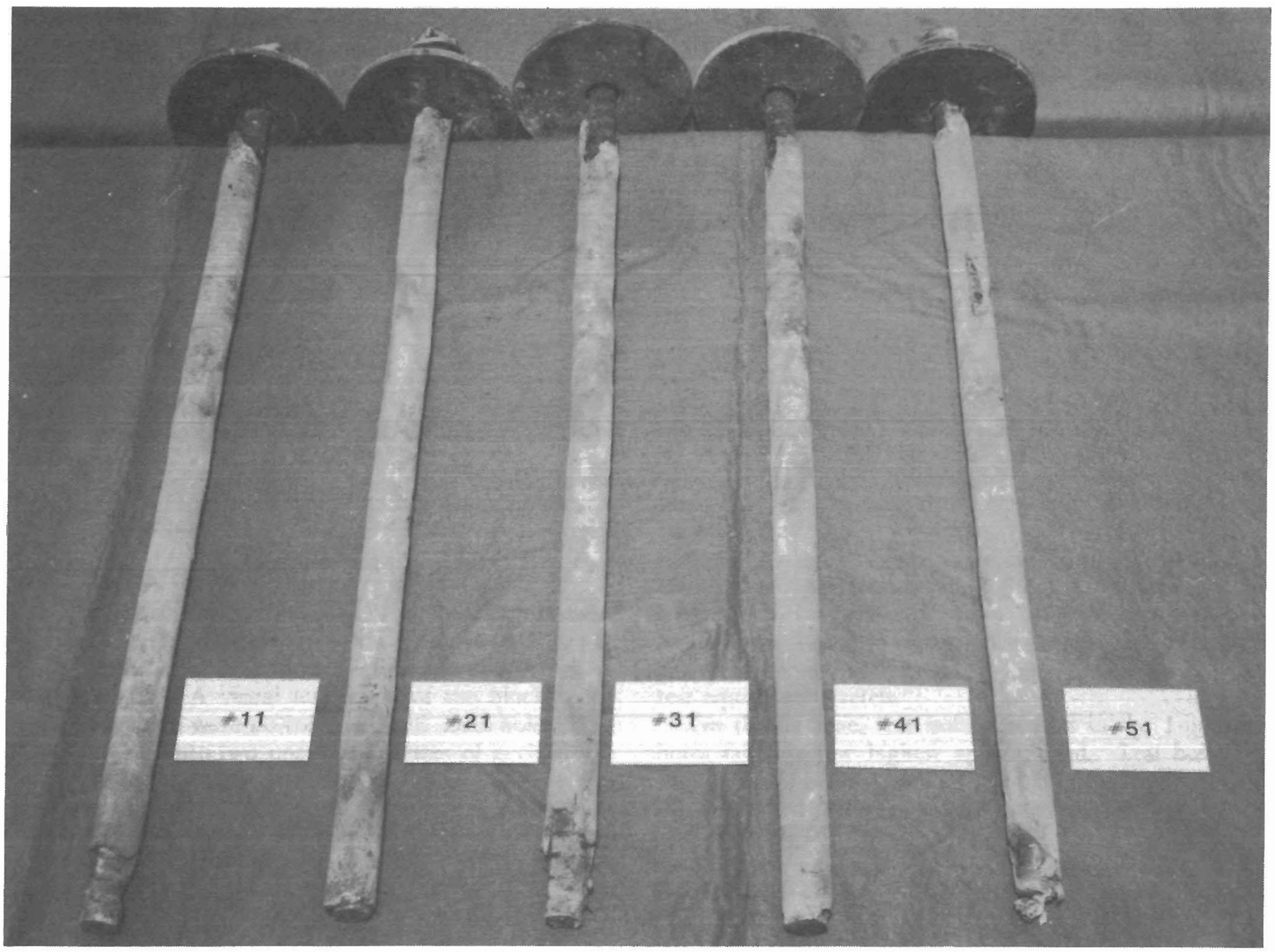

Figure 1.–Bolts from 1-in-diam holes, test 1.

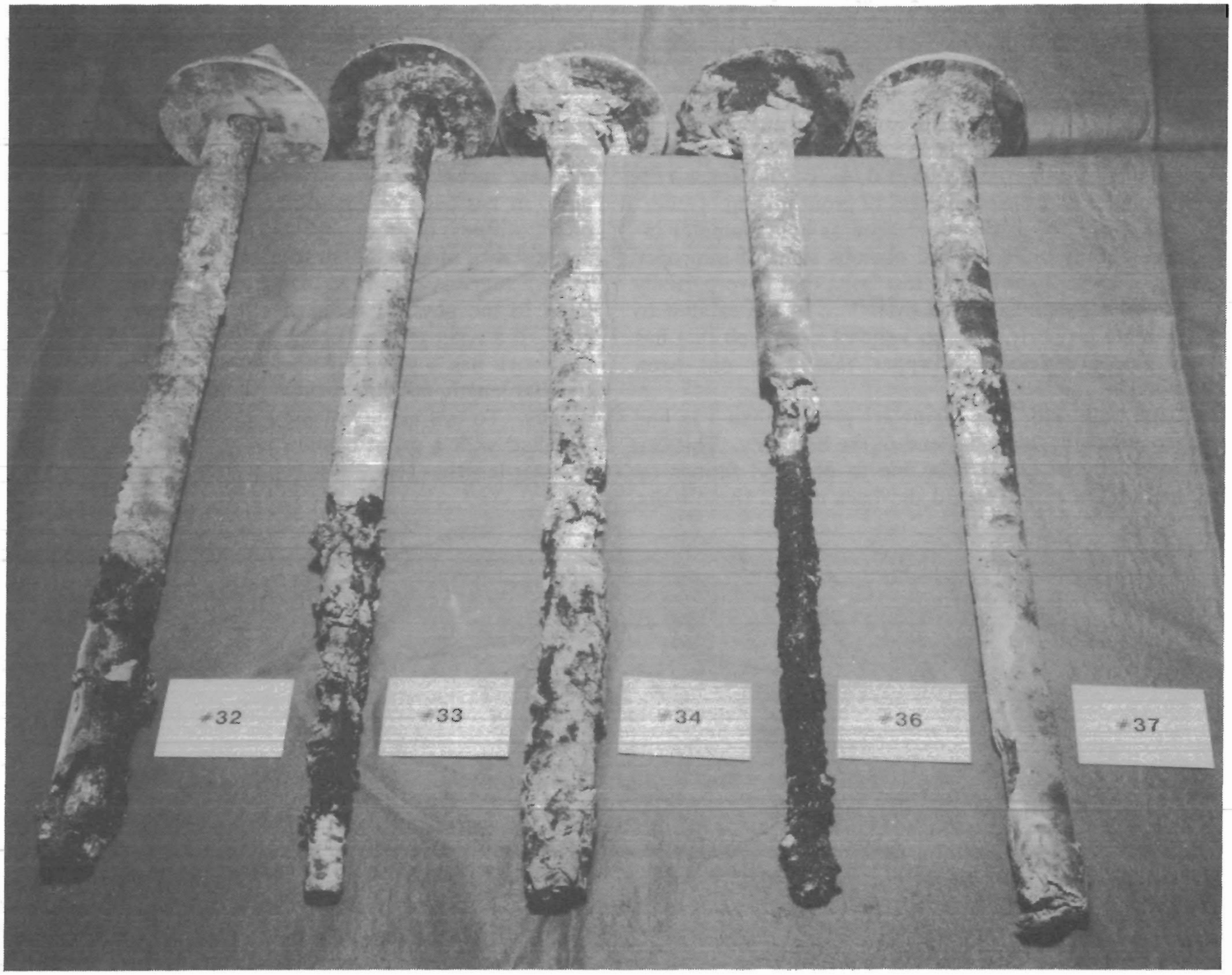

Figure 2.–Bolts from 1-3/8-in-diam holes, test 1.

Figure 3.–Bolt from 1-1/2-in-diam hole showing sleeving.

TEST 2

Procedures

For this test, three cubic blocks were constructed by pouring concrete into wooden forms which were 30 in per side. The blocks were left to cure; then the wooden forms were removed. A visual inspection of the blocks confirmed that there were no voids present. Drill holes 13-in deep were put into two opposite surfaces of each block, yielding six total drilling surfaces.

One-hundred-fifty drill holes were put into the concrete blocks utilizing two different size patterns. The first pattern, used for three of the drilling surfaces, was a random one. Twenty-five holes with three different diameters (1-, 1-1/4-, and 1-1/2-in) were placed in each surface. For the second pattern, used on the remaining three faces, 25 holes of the same diameter (1-, 1-1/4-, or 1-1/2-in) were placed in each surface.

After being drilled, the holes were cleaned with a borehole brush, flushed with water, and allowed to dry. Diameter and length of each hole were measured to ensure proper dimensions, and the holes were inspected to ensure they had no voids and cracks.

Twelve-in, full-column, polyester resin-grouted bolts were installed in the cubic blocks according to the grout manufacturer's recommendations. As in test 1, the grout had a 90-s gel time, was water-based, and was allowed to cure before the pull tests were conducted.

Standard bearing plates were not installed. To provide a bearing surface for the hydraulic ram of the pull-test equipment, a reusable bearing plate in the shape of a large flat washer was placed in between the concrete block and the hydraulic ram.

During a pull test, roof bolts are subjected to an axial-tensile load which is increased in 1,000-lb increments while the distance (deflection) that the bolthead travels away from the concrete block is measured. The bolts were loaded until yield occurred.

Following completion of the pull tests, the concrete was carefully broken away from the roof bolts with a pneumatic jack hammer so that grout mix quality could be inspected.

Fifty-nine test bolts were not included in the results and analysis because manufacturer recommendations could not be adhered to during installation.

Results

Load-versus-deformation graphs were made from the collected data. Thirty-three 1-, twenty-six 1-1/4-, and thirty-two 1-1/2-in-diam-drill-hole test bolts were analyzed (table 1).

For the purpose of test 2, failure occurs at yield point. Yield point is the load at which the resin-grouted bolt no longer behaves elastically when submitted to an axial-tensile load. The load-versus-deformation graphs were not corrected for deflection due to roof-bolt stretch or pull-test equipment stretch.

On the average, test bolts installed in the 1-in-diam holes failed at the highest applied load. Test bolts installed in 1-1/4-in-diam holes failed at lower applied loads. Bolts installed in 1-1/2-in-diam holes failed at the lowest applied loads of all others (table 2).

TABLE 2.–Test 2 pull-test results

Drill hole diam, in	Annulus thickness, in	Annular area, in^2	Yield point, 10^3 lb		Deflection at yield, 10^{-3} in		Axial stiffness, 10^3 lb/in	
			Mean	SD	Mean	SD	Mean	SD
1	1/8	0.34	21.8	2.8	294	54	76.0	14.1
1-1/4 . .	1/4	.78	21.2	5.3	321	106	68.6	14.9
1-1/2 . .	3/8	1.32	11.8	7.0	213	121	59.4	23.0

SD Standard deviation.

Analysis

Mean stiffness is highest for the test bolts with 1-in-diam drill holes, and is defined here as

$$Km = \frac{\frac{L_1}{D_1} + \frac{L_2}{D_2} + \frac{L_3}{D_3} + \cdots \frac{L_n}{D_n}}{n}$$

where Km = mean stiffness,

L = yield point load,

D = deflection at yield,

and n = total number of test bolts (for each bolt set with common drill-hole diameter).

Due to data scatter (see standard deviations of mean axial-stiffness values, table 2), linear regression analysis of axial stiffness versus drill-hole diameter does not demonstrate a high degree of correlation. But, when "mean" axial stiffness versus hole diameter is plotted, a definite trend exists (fig. 4). As drill-hole diameter increases, mean axial stiffness decreases. Linear regression analysis of this function reveals that r^2, the standard coefficient of correlation, is 0.991. For perfect linearity, r^2 = 1.000. Because of the likelihood that individual test results will deviate from the trend, figure 4 should not be used to predict bolt stiffness. However, this trend confirms the general decline in grout mix quality with increased drill-hole diameter that was noted during visual inspection.

When the standard deviations of yield point and deflection at yield are calculated, it is clear that test results are more consistent for bolts installed in the 1-in-diam drill holes and less consistent as drill-hole diameter increases (table 2).

The results of test 2 combined with the findings of Dunham (*1*) indicate that when using 3/4-in-diam roof bolts, a 1-in-diam drill hole should be used in order to achieve optimum grout mix quality.

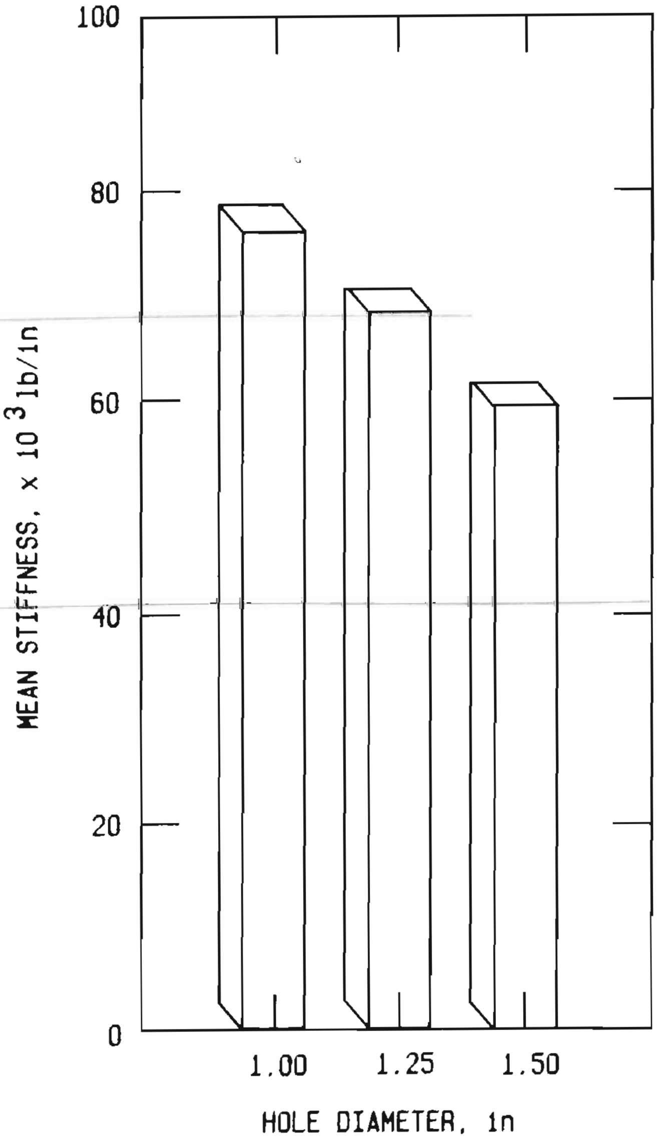

Figure 4.–Mean stiffness versus hole diameter.

Visual Examination of Bolts

Once broken away from the concrete blocks, the bolts were inspected. The grout from test bolts installed in 1-in-diam drill holes was well mixed and hard to break with a hammer (fig. 5). Although these bolts were installed with a full grout column, 2 to 3 in of grout at the collar end of the drill hole was missing. This grout could have been absent because the impact from the jack hammer during bolt breakout separated the partially debonded portion of the grout column from the bolt. Tadolini (*6*) and Yap (*7*) have observed similar roof-bolt behavior. Yap's findings, which provide a possible explanation of this event, maintain that when a resin-grouted bolt is subjected to a pull test, a decrease of bolt diameter, due to Poisson's effect in the steel, causes partial debonding at the steel-grout interface near the collar end of the bolt (fig. 6).

The grout from test bolts in the 1-1/4- and 1-1/2-in-diam drill holes was soft, black, and sticky. The remaining grout-column length was longer than that on bolts with 1-in-diam drill holes. Large pieces of plastic wrapper were present, especially in the grout from the set of bolts with 1-1/2-in-diam holes (figs. 7-8). The grout in the bottom 1 in of all tested drill-hole diameters was not mixed at all.

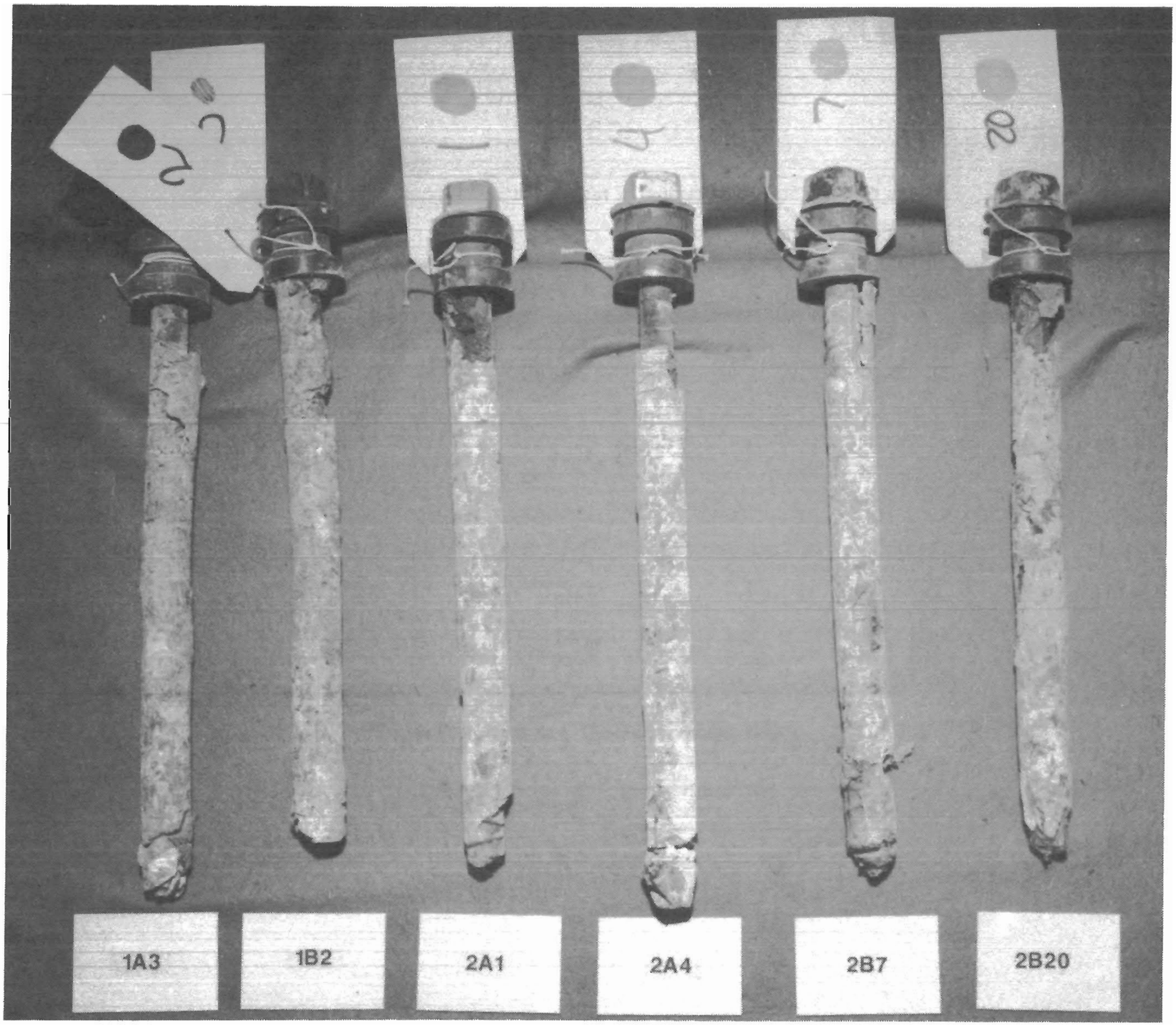

Figure 5.–Bolts from 1-in-diam holes, test 2.

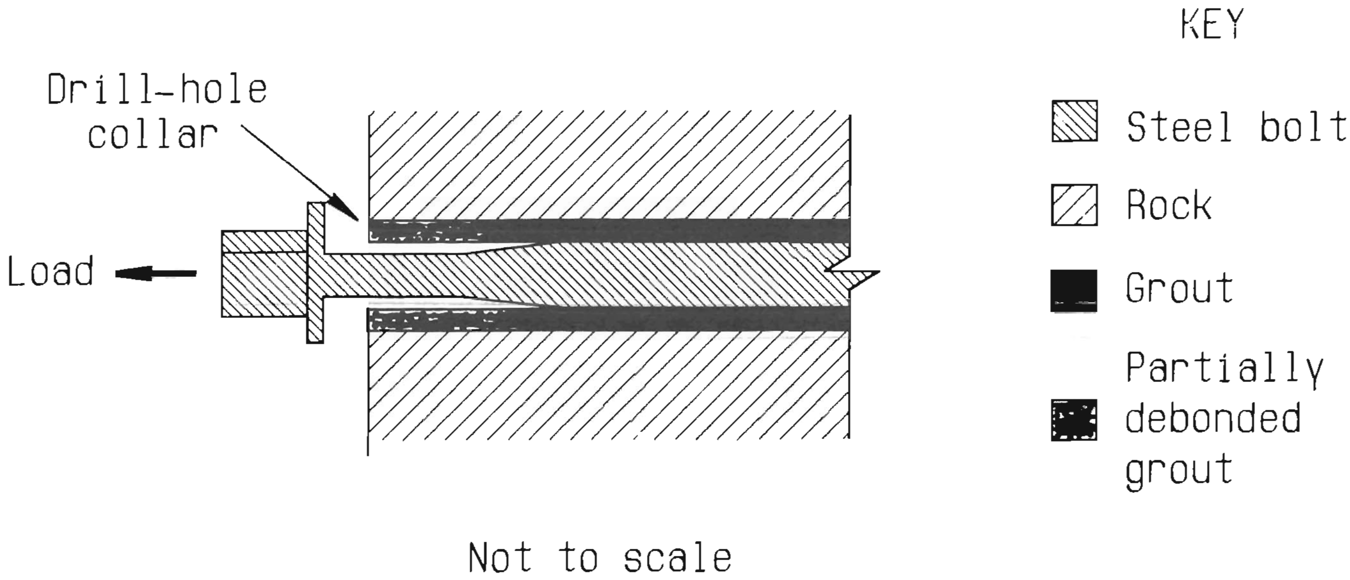

Figure 6.–Conditions at collar end of resin-grouted bolt when subjected to load.

In addition to visual inspection, the postbreakout grout-column length and grout-column length that was mixed correctly were measured for each test bolt (table 1). Mean effective grout ratio (EGR), which is the mean quality-mix length divided by installed grout-column length, was then calculated. Table 3 shows that mean EGR decreases as annular area increases. Linear-regression analysis of mean EGR and annular area reveals that there is a high degree of correlation between these two factors. The value of r^2 in this comparison is 0.999. As with axial stiffness, because of the likelihood that individual test results will deviate, this trend should not be used to predict EGR, but it confirms visual inspection results. Also, as drill-hole diameter increases the standard deviation of EGR increases. Thus, the chance of installing a roof bolt with quality grout mix is low for large diameter drill holes.

TABLE 3.–Test 2 postbreakout results

Drill hole diam, in	Annulus thickness, in	Annular area, in^2	Grout-column length, in Mean	Grout-column length, in SD	Length of quality mix, in Mean	Length of quality mix, in SD	EGR, pct
1	1/8	0.34	9.2	1.8	9.2	1.8	77
1-1/4 . .	1/4	.78	9.4	1.9	8.3	2.1	69
1-1/2 . .	3/8	1.32	9.7	2.4	7.0	2.8	58

EGR Effective grout ratio
SD Standard deviation

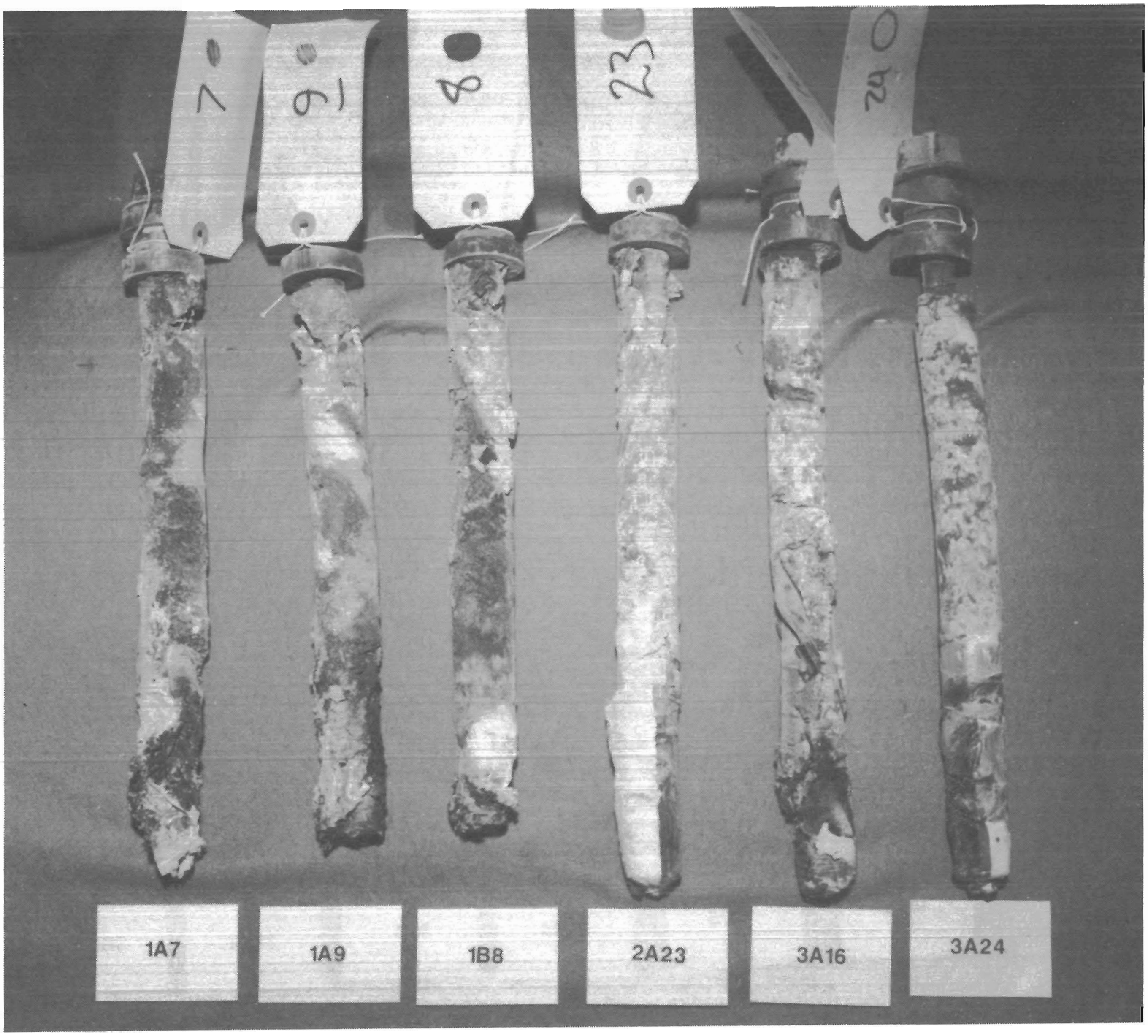

Figure 7.–Bolts from 1-1/4-in-diam holes, test 2.

Figure 8.–Bolts from 1-1/2-in-diam holes, test 2.

CONCLUSIONS

Resin-grouted roof bolt integrity is directly related to annulus thickness. The results of this investigation indicate that, for a 3/4-in diam roof bolt installed in competent rock, optimum annulus thickness is 1/8 in (1-in-diam drill hole). As annulus thickness increases from the optimum, grout mix quality, EGR, and axial stiffness will decrease.

When using a standard pull test to measure grouted bolt integrity, it is difficult to detect grout mix quality if grout-column length is greater than load-transfer length. From this investigation it appears that visual examination, although somewhat subjective, is better than the pull test for determining grout mix quality, even for short column lengths.

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