Investigation of Fully Grouted Roof Bolts Installed Under In Situ Conditions

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ABSTRACT

The The National Institute for Occupational Safety ane Health (NIOSH) Pittsburgh Research Laboratory (PRL) is continuing to investigate the behavior of fully grouted roof bolts in the weak roof rock of the Safety Research Coal Mine (SRCM). This paper describes the results of three studies:

- A series of 24 pull tests of bolts installed fully grouted and overcored to leave 12 inches of grouted bolt. The tests compared the pull-out performance of offset-head roof bolts with that of standard 5/8-inch bolts;
- A second series of 24 tests that compared the pull-out loads obtained by bolts installed with 1 ft of resin (a Short Encapsulation Pull Test or SEPT) to that of fully grouted bolts overcored to leave only 12 inches of grouted bolt, and;
- An investigation into the pressures generated during the installation of fully grouted resin bolts.

All of the bolts installed and pulled were overcored and removed from the roof after the pull tests to allow inspection of the resin.

The first study found that there was no significant difference in pullout load between the offset-head bolts and the standard bolts. The second study, comparing the SEPT bolts and the partially-overcored fully grouted bolts, indicated that SEPT can significantly underestimate bolt anchorage grip factor, suggesting that the SEPT is a conservative measure of actual bolt performance.

Significant loss of resin to cracks in the roof was observed in the bolts overcored in the SRCM. The third study explored one possible explanation for the resin loss, high pressures generated during bolt installation. These tests employed bolts installed in strain gauged steel tubes. The results confirmed that significant pressures (greater than 4,000 psi) can be generated during bolt installation. The results of the pressure tests, combined with the observations of resin loss in bolts installed in the SRCM, suggest that under some circumstances resin loss and under-encapsulation could take place and lead to degraded bolt performance.

Glove fingering was observed in all recovered bolts to various degrees. The limited comparative data suggested that the effect of glove fingering ranged from slight to moderate. Complete mixing of the resin was observed on all of the 40 bolts recovered (28 fully grouted and 12 SEPT). Australian and U.S. resins were compared and the Australian resins were observed to have much smaller catalyst compartment areas and lower resin viscosities. These differences are suggested as potential explanations for occasional resin mixing problems noted in Australian resin bolt installations.

INTRODUCTION

Despite 30 years of experience with their use, resin grouted roof bolts remain a major research topic in the U.S. and around the world. Some issues of recent interest are:

- Grip factor (anchorage capacity) in weak rock
- Measurement of resin bolt performance
- Importance of resin mixing
- Significance of glove fingering

NIOSH recently developed a procedure to standardize the use of the Short Encapsulation Pull Test (SEPT) (Mark, et al., 2002) in the U.S. The test can be used as an index to identify when anchorage problems might occur, primarily through the comparison of regularly performed SEPTs. However, the question remains concerning how well a SEPT can actually reflect the real conditions at the top of a fully grouted resin bolt. Specifically, is the performance of a SEPT different from that of a fully grouted resin bolt given the differences in mixing conditions and resin confinement?

Other issues of recent interest were resin mixing and glove fingering. Recently Campbell and Mould (2003) identified frequent occurrences of both poor mixing and glove fingering in mines in New Zealand, both in newly installed bolts and in bolts installed as long as 12 years ago, indicating a long-standing problem. The poor mixing and glove fingering were found to take place regardless of geologic conditions, installation practice and resin manufacturer. More recently Mould, Campbell and MacGregor (2004) began looking at solutions to the mixing and gloving problems. They looked at a number of bolt modifications which seemed to reduce the incidence of both poor mixing and glove fingering, and they began to examine the possibility that modifying the design of the resin cartridges used in New Zealand might mitigate the problems.

Pettibone (1987) reported on a number of bolt installations using resin from three manufacturers. All bolts were inspected, but only a few were pulled. The occurrence of glove fingering was variable, common with one resin and uncommon with the other two. Pettibone could not detect any detrimental effect due to glove fingering on fully grouted roof bolts, even when 50% of a bolt was gloved. However, the technique he used to identify poor bolts was pull tests of fully grouted bolts. Fully grouted resin bolts will almost always pull to the yield strength of the steel, even when the installation is poor and the grip factor might otherwise be considered unacceptable.

One solution recently proposed to the problem of glove fingering and poor resin mixing is the use of offset head bolts (Campoli and Adams, 2003). Mould, et al., (2004) mentioned this as one of the more successful methods for improving bolt performance. Campoli and Shapkoff (2004) performed 1 ft short encapsulation tests on three standard bolts and three offset head bolts. However, all six bolts failed through yielding of the steel, so although all of the bolts performed well, the results of the comparison were inconclusive.

This NIOSH study was originally designed to evaluate the SEPT and offset head bolts. The SEPT procedure followed was the one described by Mark, et al. (2002). Both the SEPT and the offset head bolts were compared by measuring the bolt pull strength and comparing this to a fully grouted bolt overcored to within the short encapsulation length (12 inches) of the top of the bolt. This latter bolt configuration was referred to as the "Standard" bolt to distinguish it from the SEPT and offset head bolts. All three bolt treatments were conducted using 4 ft long, 5/8-inch, Grade 60 bolts. All of the bolts were overcored and recovered so that the resin condition could be observed and evaluated.

Because all of the bolts were recovered, this provided the opportunity to evaluate the degree of resin mixing and glove fingering and their effect on the resin grip factor (anchorage strength). Evaluations of the degree of resin mixing and glove fingering of the bolts are included in the report. No attempt was made in this study to influence the occurrence of or to determine the factors which might influence the occurrence of glove fingering or poor resin mixing.

Early in the course of the two comparative tests it was observed that resin was being injected into the roof rock during every bolt installation. The resin cartridges used provided a 55 inch equivalent length of resin and were installed in a 48 inch hole. Resin returns should have been seen during every bolt installation (except SEPT installations). Instead, typically 30 to 50% of the resin from each bolt was lost into either pre-existing cracks or into fractures created during the installation of the bolts. A recent study conducted in New Zealand (Campbell and Mould, 2003) reported the measurement of significant pressures in test bolt installations conducted in the laboratory using resins available in Australia. A decision was made to conduct a series of tests to determine the pressure generated during bolt installation using resins available in the U.S. A series of bolt installations were conducted in the SRCM, installing bolts in a steel pipe inserted in a hole previously drilled in the roof. These tests obtained results similar to tests reported by ., et al. (1999) where three sizes of bolts were installed in 1-inch inside diameter pipes using two different viscosity resins. A 0.25-inch-diameter hole in each pipe was used to simulate fractures. The tests measured bolter thrust rather than resin pressure, but the thrust values reported suggested high insertion pressures, and the thrust magnitudes increased as the bolt diameter increased and the annulus decreased. The Campoli, et al. (1999) tests measured resin losses of between 35 and 60 pct, depending upon bolt diameter and resin viscosity.

SITE DESCRIPTION

The generalized lithology of the roof rock at the site is shown in Figure 1. The lithology shown is a composite from a corehole located about 15 ft from the site and from a small diameter hole drilled at the test site and examined using a video camera. The immediate roof at the SRCM consists of a series of weak, predominately carbonaceous, shales and coals to the top of the bolting horizon. The estimated CMRR for the bolting horizon (4 ft) is 35. The study site was mined in the mid-1990's and was chosen because the weak roof rock gave a greater probability of bolt failure due to anchorage than to steel yield.

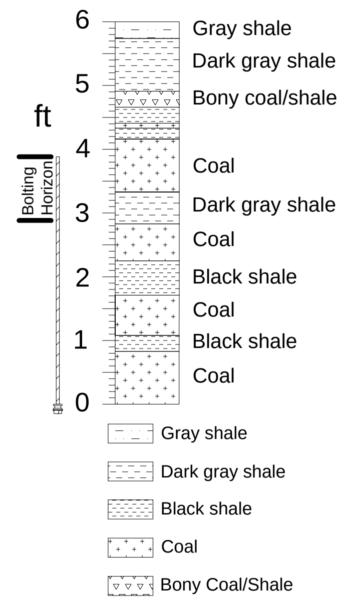

Figure 1. Roof lithology at the bolt installation site, showing typical bolting horizon.

The bolting horizons for the SEPT, standard and offset head bolts (the latter two after overcoring) all extended from 34.5 to 46.75 inches above the roof line (this is slightly more than 12 inches because the length of the bolts varied by about 0.25 inch). The anchorage length for each bolt was 12 inches and consisted of about 6.5 inches of coal on top and 5.5 inches of carbonaceous shale below, although the depths of the coal and shale varied slightly across the study site.

GENERAL TEST PROCEDURES

Both the comparison tests and the installation pressure measurements were conducted at the Safety Research Coal Mine (SRCM) using a single boom roof bolting machine. All bolts installed were 5/8-inch Grade 60 resin bolts, except for a few ¾-inch bolts used in bolt installation pressure tests.

The pull tests were instrumented with a string pot potentiometer to measure bolt displacement, and a pressure transducer and calibrated load cell to measure the pull load. Strain gauges were mounted on the outside of the 1 inch inside diameter schedule 40 pipe used to simulate roof bolt holes, to measure bolt installation pressures. A datalogger and a laptop computer were used to collect and display the data during the tests. The pull equipment, including reaction fixture, pull claw, 20 ton hydraulic ram and 1-inch thread bar, is shown in Figure 2. The bolts were loaded using a hand pump.

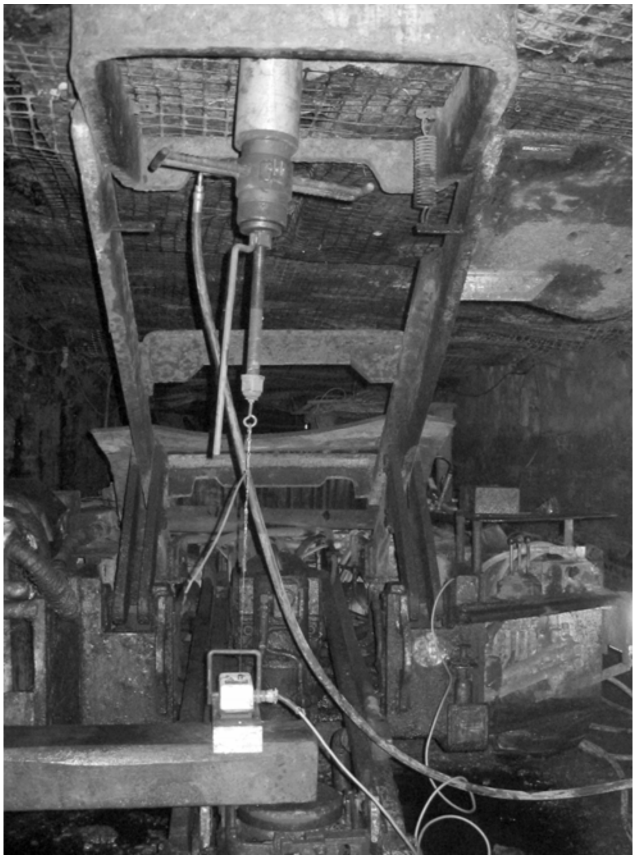

Figure 2. Pull test equipment showing reaction fixture, 20 ton hydraulic ram, 1-inch thread bar and string pot displacement sensor.

Offset Head versus Standard Bolt Performance Comparison Procedure

Both the offset head and standard bolts were installed and pulled using the same procedure. The only difference intentionally introduced was in the bolt types. The resin used in the installations was the resin recommended for use with offset head bolts. The resin for the first 15 bolts (8 offset head and 7 standard) tested came from the same box of resin. When that box of 20 cartridges ran out, a box of similar, but slightly faster setting resin was used. In order to reduce the effects of resin in general and from the change of resin in particular, bolts were usually tested in pairs, one offset head and one standard, and the same resin used for both bolts in a pair.

Several steps were required to install, pull and recover the bolts. The sequence, consisting of 6 separate operations, is shown in Figure 3.

1. A 1-inch diameter bolt hole with 1-inch overdrill was drilled using dry vacuum drilling with carbide tipped bits (Figure 3a).
2. A short NX diamond core bit with a pilot centralizer was used to drill a shallow (1 to 2 inch) NX (3-inch diameter) hole centralized on the bolt hole. This short pilot hole was also dry drilled. Dry drilling did not damage the core bit because of the soft roof and brief drilling period (Figure 3b).
3. The bolt was then installed without a roof bolt plate. Bolts were nominally 4 ft in length, but that length included the bolt head which, along with the pull collar, had to be subtracted from the drilled depth. The actual bolt lengths in the roof were between 46.5 and 46.75 inches, depending upon bolt length. With the 1-inch overdrill, hole depths were between 47.5 and 47.75 inches (Figure 3c).
4. A starter core barrel, and later a 4 ft NX core barrel were then run to overcore the bolt (Figure 4) to within 12 inches of the top of the bolt, leaving 12 inches of grouted bolt to pull (Figure 3d).
5. The test fixtures were then installed and the bolt pulled (Figure 3e), either to anchorage failure (preferred) or to bolt yield, which took place in only a few cases (Table 1).
6. The 4 ft core barrel was then run again to core the bolt out of the hole for inspection (Figure 3f).

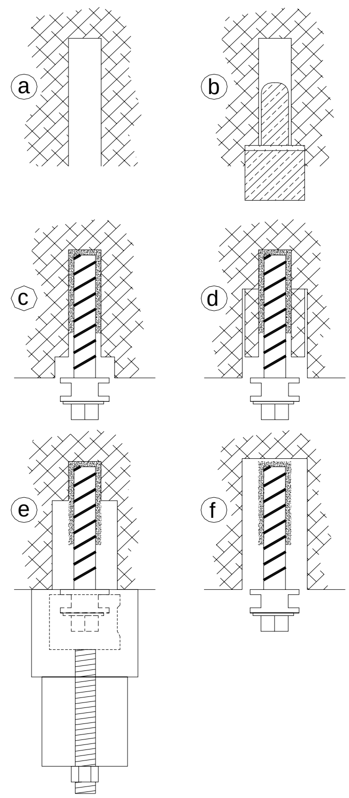

Figure 3. Bolt installation, pull test and overcoring procedure for offset head and standard bolts. (a) 1-inch bolt hole. (b) Overcore starter hole drilled using a pilot bit. (c) Bolt installation, without roof bolt plate. (d) Bolt overcored to within 12-inches of the top of the bolt using an NX (3-inch OD) bit. (e) Bolt pull tested. (f) Bolt overcored and removed from the roof for inspection. Drawings not to scale. SEPT bolt testing procedure similar, except the bolts were installed using a 12 inch equivalent resin length, step d was eliminated and the entire length of the bolt was overcored in step f.

Figure 4. Bolt overcoring equipment; NX core barrel, EW drill rod, water swivel and hex steel adaptors.

The bolt holes were drilled using dry vacuum drilling and a 1-inch bit. Initially hole diameters were measured using a caliper, but after they were found to be very consistent (from 25 to 26 mm in diameter), the frequency of the measurements was reduced. Holes were drilled between 47.5 and 47.75 inches in depth, depending upon bolt length. The required depth was the total bolt length less the head length and the height of the pull collar (the top of which was set flush with the roof line), plus 1 inch for the overdrill.

Bolts were installed along with a 43.25-inch by 0.9-inch resin cartridge, giving an equivalent resin length of 55 inches in a nominal 1-inch hole, with the 1 inch overdrill. Without resin loss to the roof rock, this would have been sufficient resin to ensure resin return in every bolt installation. Instead no resin returns were observed in any installation. Measured hole diameters generally ranged from 25 to 26 mm, close to the nominal size. Examination of the length of resin on the overcored bolts showed that an average of 44% of the volume of each resin cartridge was lost through injection of the resin into the roof rock (standard deviation 5%).

Table 1 – Offset Head versus Standard Bolt Data

Bolt ID	Max Load (tons)	Cause of bolt failure	Glove fingering[1,2]	Measured resin length (in)[3]	Resin loss (Pct)	Resin set time (min)
OFFSET HEAD BOLTS						
5	7.1	Anchorage	M	27.9	49%	34
6	6.1	Anchorage	S	26.8	51%	48
8	7.5	Anchorage	N/A	30.8	44%	31
10	10.5	Yield	L	26.9	50%	31
12	7.9	Anchorage	S	31.3	43%	21
13	8.5	Anchorage	M	29.5	46%	28
20	8.8	Anchorage	S	30.6	44%	22
24	6.5	Anchorage	L	31.8	42%	22
29	6.5	Anchorage	L	37.6	32%	22
32	6.2	Anchorage	L	33.4	39%	30
34	8.9	Anchorage	L	32.7	40%	25
39	6.1	Anchorage	L	26.5	51%	32
Average:	7.5			30.5	44%	29
Std Dev:	1.4			3.3	6%	8
STANDARD BOLTS						
4	10.6	Yield	M	30.1	44%	82
7	8.9	Anchorage	S	29.2	46%	26
9	6.0	Anchorage	L	28.5	48%	35
11	10.3	Yield?	L	30.8	44%	24
14	10.6	Yield?	M	31.1	43%	20
19	9.4	Anchorage	L	37.9	31%	43
23	8.5	Anchorage	L	31.8	42%	21
26	10.7	Yield	M	37.2	32%	23
30	7.7	Anchorage	N/A	N/A[4]	N/A	23
31	7.5	Anchorage	L	31.4	43%	117
35	6.2	Anchorage	L	32.3	41%	24
38	10.3	Yield?	L	29.0	47%	33
Average:	8.9			31.8	42%	39
Std Dev:	1.7			3.1	5%	30

All bolts: 5/8-inch, Grade 60, nominal 4 ft length. Holes overdrilled 1".
Resin cartridges 43.25" x 0.9", holes nominally fully grouted
All bolts pulled with 12" resin column.

[1]Estimated by area of film at resin surface. **L**ow<33%, **M**ed=33-66%, **S**evere>66%

[2]An offset head bolt, categorized **S** was dropped from the data for lack of a corresponding standard bolt, but used in estimating the glove fingering effect. Pull 3.2 tons

[3]Does not include resin in 1" overdrilled hole.

[4]Not overcored.

Bolt installations were accompanied by slow rotation as the bolts were inserted using the roof bolting machine. Insertion of the bolt was stopped when the top of the pull collar reached the roof line and the bolt was then spun for 6 seconds. This time was based upon the resin manufacturer's recommendation of 30 to 50 revolutions for adequate mixing and the measured maximum bolter table speed of 510 rpm, giving 50 revolutions of the bolt. However, later measurements of bolter rotational speed recorded using a torque, thrust and rpm measuring instrument indicated that it took about 2 seconds for the bolter to reach maximum speed, so the actual number of rotations was estimated to be 40. Since this was still within the manufacturer's recommendation and all bolts were spun the same length of time, spin time was not believed to have biased the test results. Bolts were held by the bolter for at least 1 minute and frequently longer for convenience. Hold times were assumed to not introduce any bias into the test results.

Because the bolts were being overcored and the alignment of the NX core barrel with the bolt was critical to prevent drilling through the resin and bolt (which sometimes still happened in the early tests), the bolting machine was not moved until a bolt was pulled and cored out of the roof. This made it very time consuming to let the resin cure for long periods before conducting the pull tests. In past work NIOSH has typically opted for a minimum curing time of 1 hour before pulling bolts. In this test series the curing time was as long as 117 minutes, but in most tests a minimum time of 20 minutes was considered acceptable and the average curing time was 34 minutes. Curing times for both the offset head and standard bolts were similar. The average for the offset head bolts was 29 minutes and for the standard bolts 39 minutes (excluding two standard bolts given unusually long curing times the standard bolt average was also 29 minutes).

In order to reduce the effects of geologic anomalies on the test results, bolts were initially installed in pairs, with a coin toss deciding the first bolt of a pair to be installed. The first 11 bolts were installed using this procedure. A bolter malfunction prevented the completion of the last bolt pair. The remaining 13 bolts (including a makeup bolt for the one not installed earlier) were installed in groups of three, Standard, Offset head and SEPT bolt, so that the standard bolt statistics could be used in both sets of comparisons. All bolts (including SEPT bolts to be discussed later) were installed within a roughly 10 ft by 7 ft area of roof (Figure 5). Bolt hole locations were chosen for ease of positioning the roof bolting machine rather than for randomization of location, but the effect of the bolt placement technique used was, to a great extent, to randomize the placement of the bolts.

SEPT versus Overcored Standard Bolt Performance Comparison Procedure

The procedure for the SEPT versus overcored fully grouted bolt comparison was similar to that of the offset head versus standard bolts. The standard bolts were installed and pulled using the procedure described in the previous section and both the SEPT and overcored bolts were anchored at the same roof horizon. However, the procedure for installing and testing SEPT bolts was slightly different. Because it was not necessary to overcore the bolts to obtain a 12 inch length of grouted bolt, the following changes were made to the procedure described in the previous section. Steps 1, 2 and 3 (bolt installation), were conducted as before, but step 5 (bolt pulling), was then performed next. Steps 4 and 6, overcoring the bolt, were then combined into one operation.

Figure 5. Bolt installation site in NIOSH Safety Research Coal Mine (SRCM), showing the 3 inch diameter holes from overcored bolts and several previously pulled bolts which were not removed from the roof

The installation procedure for both the SEPT and standard bolts was the same as for the offset head comparison. All bolts were rotated slowly during insertion, and when the bolt reached the proper depth it was spun at full bolter rotation speed (510 rpm) for 6 seconds. This is estimated to have produced 40 mixing revolutions. All bolts were held stationary for a minimum of one minute, and frequently the hold time was extended beyond one minute. Bolts were tested after a minimum of 20 minutes. The average times were 41 minutes for the SEPT bolts and 43 minutes for the standard bolts. Excluding two standard bolts and one SEPT bolt tested after long set times, the averages were 28 and 32 minutes.

As was the case in the offset head versus standard bolt tests, resin was lost in every standard bolt installation. The average resin loss for the standard bolts used in the SEPT versus standard bolt comparison was 40% (standard deviation 6%). Some resin was also lost from the SEPT bolts, which complicated the test results. The bolts were examined and the raw pull loads were corrected for the lost resin, as will be discussed in the RESULTS section.

Installation Pressure Measurement Tests

The pressure developed during installation of a fully grouted resin bolt was measured by installing bolts in strain gauged 1-inch steel pipes (Figure 6) using the single boom roof bolting machine. One inch Schedule 40 pipe has a nominal 1.049 inch inside diameter, which is only slightly larger than the diameter of a 1 inch roof bolt hole. The pipes were cut to a length of 49 inches to allow the insertion of 4 ft resin bolts with a 1 inch overdrill.

The pipes were instrumented with circumferential strain gauges and the gauges were calibrated by pressuring the pipes with oil to 2,500 psig and recording the pressure and the strain readings[1]. The gauges were installed at approximately 2, 8, 14 and 20 inches from the top of the pipe. The calibration curves were also compared to a calculated strain versus internal pressure relationship determined from thick wall cylinder theory (Cook and Young, 1985). The

[1]An earlier series of pressure measurements were made using ports drilled in the pipe, oil-filled tubing and pressure transducers. The results of these tests were inconsistent and the measured pressures were low, probably because void space at the port had to be filled before pressure was transmitted to the pressure transducer.

empirical calibration curves obtained from the laboratory agreed to within a few percent with the theoretical values, but the empirical strain/pressure calibration curves were used to convert the measured strain to pressure.

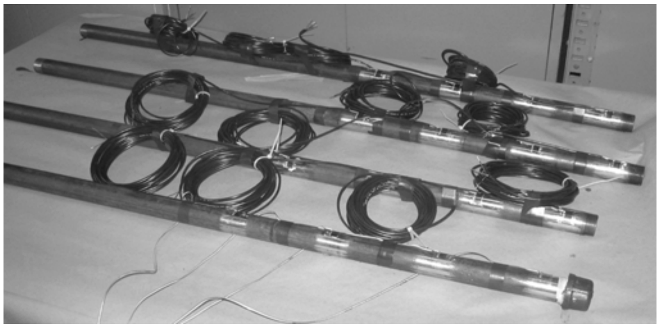

Figure 6. Four strain gauged 1-inch Schedule 40 pipes for measuring bolt insertion pressure. The end caps have not yet been put on three of the pipes in the photo.

Four bolts were installed, three 5/8 inch bolts and one ¾ inch bolt. In all four cases the resin used was from the same box of cartridges used for the pull tests. The resin cartridges used provided a 48.75 inch equivalent resin length in the pipe and for 1 inch of overdrill length.

The pipes were inserted into a 4 ft deep, 3-inch-diameter corehole previously drilled in the SRCM roof. A test fixture, held in place by two mechanical bolts installed in the roof, was used to clamp each pipe in place to prevent its rotation during the bolt installation.

The strain gauge wires were connected to a datalogger and strain readings were recorded at 0.1 second intervals during the installation process. Since the strain gauges were not temperature compensated the strain readings taken just before bolt installation were used to zero the gauges. The pressure readings obtained were also probably slightly greater than the actual pressure because of heat generated by the resin. The magnitude of the temperature error was estimated from pre-test strain readings to be about 100 psi, which was not considered significant when compared to pressures of 5,000 psig or greater.

The bolts were installed in the same manner as the bolts installed in the two comparison tests. The resin cartridges installed insured resin return in the steel pipe. Bolts were slowly rotated during installation, and the bolts were pushed into the roof at the maximum speed of the bolter head, an estimated 5 inches/sec. The bolts were to be pushed to within about ½ inch of the roof, spun for 6 seconds and then pushed to contact the pipe.

RESULTS

Offset Head versus Standard Bolts

Table 1 shows the results of the offset head versus standard bolt tests. The average pull strength of the 12 offset head bolts was 7.5 tons, with a 1.4 ton standard deviation. The average pull strength of the 12 standard bolts was 8.9 tons with a 1.7-ton standard deviation. These results suggest that there is no significant difference between the performance of offset head and standard roof bolts

Observation of the resin in the overcored bolts also indicated that adequate mixing took place in all bolts of both types (Figure 7). The resin from all bolts recovered appeared hard, with no indication of unmixed resin. Four bolts not shown in Tables 1 and 2 were installed and only spun for one second; or an estimated two revolutions. In those four cases the average offset head bolt pull load was 1.3 tons and the average standard bolt pull load was 2.5 tons. All four bolts showed indications that unmixed resin had been washed off the bolts by the drilling water during overcoring. Some of the remaining resin was solid, but crumbly. This appeared to be an indication of partially mixed resin. Neither resin loss due to washing of the bolts or crumbly resin was observed in the case of bolts spun for 6 seconds.

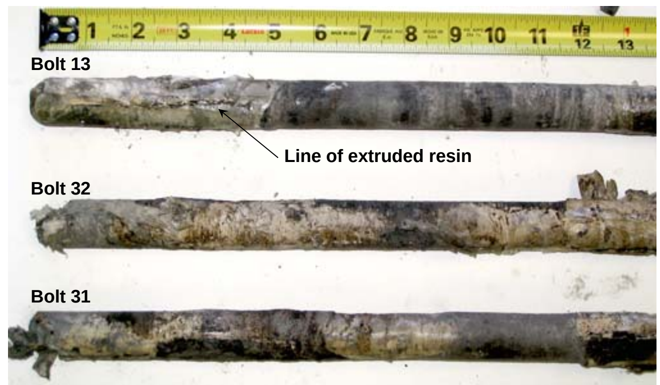

Figure 7. Bolting horizons of bolts 13, 32 and 31, showing typical good resin mixing and partial glove fingering. Bolt 13 shows a line of resin extruded into the coal. Bolts 13 and 32 are offset head bolts. Bolt 31 is a standard bolt. Bolt tops at left.

Since all resin on the test bolts had been fully mixed, it was not possible to evaluate resin color as an indicator of resin mixing, but it was noted that the resin color was frequently affected by the lithology the resin was mixed in and by the dust present in the holes and mixed into the resin; so it appeared that resin color would not be a good indicator of resin mixing in mixed roof lithologies.

Glove fingering was observed on every bolt, both offset head and standard bolts, to various degrees. In order to quantify the effect of glove fingering a visual evaluation of each bolt was performed and the bolts categorized into light, moderate and severe glove fingering groups, based upon the percentage of cartridge polyester film visible on the outside surface of the resin (Figure 7). The pull strengths of the lightly and severely gloved offset head bolts were then compared to look for a glove fingering effect. Ten offset head bolts were categorized as lightly or severely glove fingered (four severely and 6 lightly). The average pull capacity for the lightly glove fingered bolts was 7.4 tons (standard deviation 1.8 tons), while the average for the severely glove fingered bolts was 6.5 tons (standard deviation 2.4 tons). However, one of the four severely glove fingered bolts pulled to 3.2 tons, three standard deviations below the mean of the offset head bolts in Table 1. This bolt was not included in Table 1. If this outlier bolt is eliminated from the set of severely glove fingered bolts the mean and standard deviation become 7.6 and 1.4 tons, respectively. If the outlier bolt is included in the data, the results suggest a moderate reduction in bolt strength due to glove fingering. If this bolt is rejected from the data, the data suggest that there is no glove fingering effect. In any case no strong conclusions can be drawn from the glove fingering results. There were not enough severely glove fingered standard bolts to perform this comparison on the standard bolts recovered.

Of the 8 standard bolts categorized as either lightly or severely glove fingered, only one was categorized as severe.

Almost every overcored bolt showed evidence of resin extrusion into coal cleat or induced fractures. The extruded resin frequently formed wavy lines about 1/8-inch wide and about 1/8-inch deep (Figure 7) which remained on the bolts after overcoring. The resin could either be soft or well mixed and hardened, typically the latter. These observations are in agreement with those made by Campbell and Mould (2003), who reported resin injection similar to that shown in Figure 7. In two cases resin remaining on the bolts was extruded into the fractures at least ½-inch (Figure 8). In those cases the resin was well mixed and hard. During one bolt installation resin was observed falling out of an adjacent NX cored hole (3-inch-diameter). The holes were approximately 4 to 5 inches apart, center-to-center, indicating that resin had been extruded a distance of 2 or 3 inches through coal cleat or vertical fractures. The extruded resin was not recovered, so the exact quantity of resin extruded and its degree of mixing could not be determined.

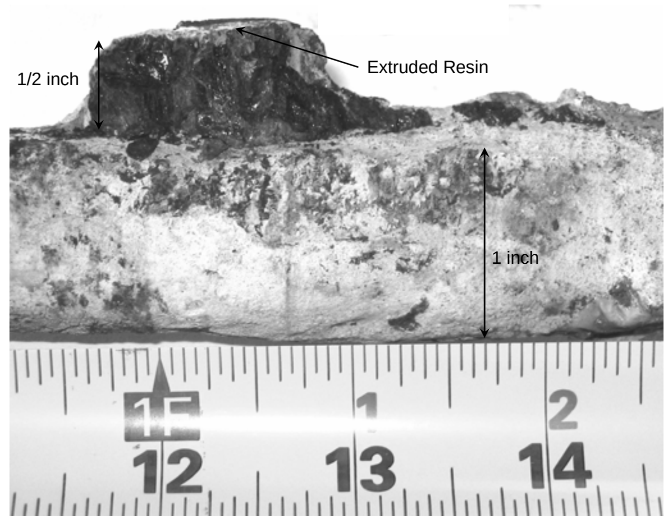

Figure 8. Resin extruded into vertical fractures or opened coal cleat. Long wavy lines of resin extruded less than 0.1-inch were typical. The more deeply (up to ½ inch) extruded resin was unusual. Note that the extruded resin was thoroughly mixed.

Table 2. SEPT versus Overcored Bolt Data

Bolt Id	Max load (tons) Raw	Max load (tons) Corrected	Cause of bolt failure	Tested resin length (in)	Resin loss (pct)	Resin set time (min)
			SEPT BOLTS			
SC1	5.2	5.8	Anchorage	10.8	10%	188
SC3	5.1	5.9	Anchorage	10.3	14%	39
SC5	5.7	6.3	Anchorage	10.9	10%	34
SC7	4.5	5.4	Anchorage	10.0	17%	26
SC9	4.0	4.8	Anchorage	10.0	17%	35
21	4.2	6.6	Anchorage	7.6	36%	22
22	3.9	4.4	Anchorage	10.8	10%	26
27	4.0	4.4	Anchorage	11.0	8%	24
28	5.8	6.4	Anchorage	11.0	9%	22
33	3.0	3.4	Anchorage	10.5	12%	24
36	4.6	5.2	Anchorage	10.5	13%	27
37	5.8	7.4	Anchorage	9.4	22%	25
Average:	4.6	5.5		10.2	15%	41
Std Dev:	0.9	1.1		0.9	8%	47
			STANDARD BOLTS			
SC2	8.8	8.8	Anchorage	12	36%	51
SC4	7.5	7.5	Anchorage	12	38%	82
SC6	8.9	8.9	Anchorage	12	36%	48
SC8	5.5	5.5	Anchorage	12	45%	31
19	9.4	9.4	Anchorage	12	31%	43
23	8.5	8.5	Anchorage	12	42%	21
26	10.7	10.7	Yield	12	32%	23
30	7.7	7.7	Anchorage	12	N/A	23
31	7.5	7.5	Anchorage	12	43%	117
35	6.2	6.2	Anchorage	12	41%	24
38	10.3	10.3	Yield?	12	47%	33
40	9.9	9.9	Anchorage	12	48%	22
Average:	8.4	8.4		12	40%	43
Std Dev:	1.6	1.6		0	6%	29

All bolts: 5/8-inch, Grade 60, nominal 4 ft length. Holes overdrilled 1".
Standard resin cartridges 43.25" x0.9", holes nominally fully grouted
SEPT resin cartridge 10.25"x0.9". Holes overdrilled 1".
Resin loss did not affect Std tested resin lengths, but did affect SEPT tested length.

SEPT versus Overcored Standard Bolts

Table 2 shows the results of the SEPT versus Standard bolt tests. The average pull strength of the 12 SEPT bolts was 4.6 tons with a standard deviation of 0.9 ton. The average strength of the 12 Standard bolts was 8.4 tons with a standard deviation of 1.6 tons.

One explanation for the poor performance of the SEPT bolts was the loss of resin into the roof in the SEPT tests. This also took place in all of the standard bolts and in the offset head bolts, but did not effect the test results, since the grouted column always exceeded 12 inches and overcoring was conducted to reduce the effective resin length to the required 12 inches for testing. The resin cartridges for SEPT tests were carefully measured to give a 12 inch resin column. Any resin loss into the formation would reduce the actual resin column length to less than 12 inches. Inspection of the tested SEPT bolts suggested that some resin was lost from all of the SEPT bolts and large amounts of resin were lost from some. Further examination of the bolts also suggested that some resin was broken off of some bolts after testing due to vibration of the bolts during overcoring. This was confirmed by examining the standard and offset head bolts and observing that about one third of the fully grouted bolts had resin damage. Since the SEPT bolts were free over much of their length during overcoring, it was expected that a larger proportion of the SEPT bolts would sustain resin damage during overcoring.

The decision was made to correct the SEPT pull data for the reduced resin length, but the resin length during pull testing was assumed to include resin which broke off during overcoring, based upon resin traces remaining on the bolts. The test statistics were then computed using the Standard bolt statistics directly and adjusting the SEPT pull strengths to the estimated strength of a full 12-inch resin column. This increased the average SEPT bolt pull strength from 4.6 to 5.5 tons and changed the standard deviation of the strengths from 0.9 to 1.1 tons. This correction assumes that the anchorage strength is constant over the length of the resin.

Corrected for resin loss the pull strengths of the SEPT bolts were 5.5 tons compared to 8.4 tons for the overcored bolts. The difference between the pull strengths of the two samples is 35%; calculated on the overcored bolt average. The difference between the two groups of bolts appears to be far too large to be explained in any way except by assuming that the overcored bolts produced significantly higher pull strengths than SEPT bolts. This conclusion would also be reached assuming that all of the SEPT bolts had 12 inches of resin; an obviously erroneous assumption. Assuming no resin loss during overcoring, and that all the resin loss took place prior to testing would give results that would require assuming no difference between SEPT and overcored bolt performance, but all of the observations indicated that this was also an erroneous assumption. The data suggest that there is a significant difference between the SEPT pull strength and the overcored bolt pull strength and that the SEPT is highly conservative. That is, when a SEPT determined anchorage factor is found to be acceptable, it appears reasonable to assume that the anchorage factor for typical, properly installed bolts will be acceptable. However, when a decision is made that the SEPT determined anchorage factor is low, it cannot automatically be assumed that the anchorage factors for typical bolts are also low. This does not necessarily invalidate the SEPT test, which can still be used to indicate when a problem might exist and as an index to compare anchorage factors under conditions of changing roof lithology.

One possible explanation for the performance differences between the two tests (assuming that the corrections to SEPT pull strengths are accurate) is that the lack of confinement of the resin during the mixing and hardening process reduces the SEPT bolt anchorage strength compared to that of the fully grouted bolts. Pressures in the short SEPT resin column were probably much less than in the full resin columns. Another possibility is that during fully grouted bolt installations resin was being injected into existing or newly created cracks and hardening, thus improving the mechanical interlock. This could also happen during SEPT, but at the expense of the length of the effective resin column. The overcored SEPT bolts did not show any sign of resin extrusion. Several recovered standard bolts showed signs of hardened resin at distances up to 0.5 inch from the bolt hole wall (Figure 8) and many standard bolts showed long shallow lines of both hardened and unmixed resin injected into cracks in the rock to depths of no more than 0.1 inch. If the former explanation is correct, then SEPT would generally be expected to be conservative. If the latter is correct, the differences between the two test types might be more variable, depending more on differences in rock properties, in situ horizontal stress, and variations in installation procedure (causing differences in resin pressure during the installation).

The authors feel that additional work is warranted to confirm the difference between SEPT and overcored standard bolt pull tests. Future work should be conducted in a more homogeneous roof rock, without the mixed coal and shale lithology present at the NIOSH SRCM. Tests should also be conducted in the laboratory under controlled conditions to look at the effect of resin confinement on bolt strength. The preferable site would be a one with a uniform roof lithology with weak rock between 2 and 4 ft, allowing the use of 3 or 4 ft roof bolts.

Installation Pressure Measurements

All four of the bolt installations produced high pressures in the pipes (Figure 9), with the maximum pressures for the 5/8 inch bolts ranging from 5,500 to 6,900 psig and a 9,900 psig maximum pressure for the ¾ inch bolt. If the bolts are assumed to behave like a piston with an area approximately equal to that of the bolt, the maximum pressures generated would have been 14,700 and 10,200 psig, respectively for 5/8 and ¾ inch bolts, given the 4,500 lbf maximum thrust developed by the single boom bolter. The difference may be assumed to be due to leakage of resin around the sides of the bolt during insertion. The leakage appears to have been significant for the 5/8 inch bolts, reducing the actual insertion pressure to less than half of the maximum possible pressure. The leakage for the ¾ inch bolts appeared to be much less and the maximum insertion pressure was just slightly less than the maximum possible pressure.

None of the four bolt installations went smoothly. The first bolt, a 5/8-inch bolt, buckled before being completely inserted. The second 5/8-inch bolt was spun for only 3 instead of 6 seconds, and the resin appeared to have fully set up at that time. The third bolt, a ¾ inch bolt, could not be completely inserted into the hole and was never spun at all. The fourth bolt was only spun for about a second before stalling the bolter. The difficulty of bolt insertion is partially explained by the higher thrust required to insert a bolt into a closed pipe, but this also suggests that in normal bolt installations the pressure is being reduced by extrusion of resin into the roof rock. The overcored bolts showed that large quantities of resin were lost in every bolt installation at the SRCM, so this mechanism for reducing the insertion pressures appeared to be at work at the SRCM. The difference in ease of bolt insertion

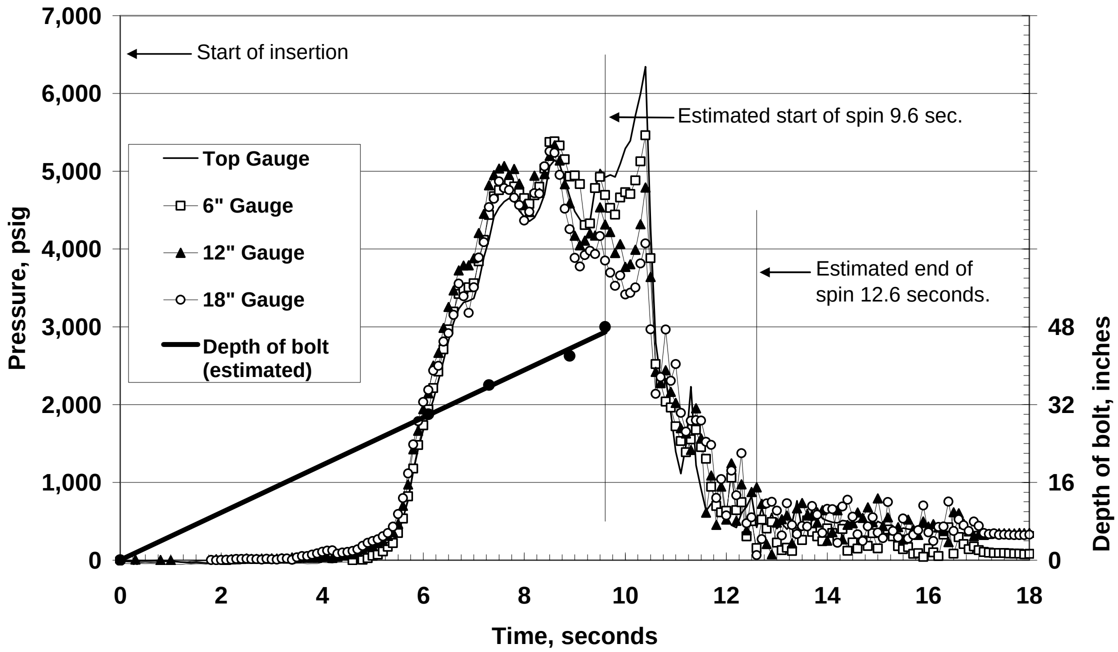

Figure 9 – Pressure at four locations in a schedule 40 1-inch pipe simulating a bolt hole during resin bolt installation. The straight line shows the position of the top of the bolt.

suggests that extrusion of resin significantly reduces the required installation thrust. Unfortunately, the bolter thrust was not measured during the project, precluding a comparison of normal installation thrust with the thrust required during the installation pressure measurement tests.

Tests were conducted during the following week to determine if the difficulty in bolt installation was increased by low temperatures at the time of the installation pressure tests. Several bolts were installed under three sets of conditions, the first was using resin warmed to room temperature, the second cold resin, and the third using cold resin, bolts and pipe. No quantitative measurements were made, but the installations were carefully observed. Although noticeably more thrust was required to install the bolts in cold resin, all bolts were installed without difficulty and all bolts were spun for 6 seconds. The tests were considered inconclusive, although they suggested that temperature had not played a significant role in the difficult bolt installations. This leaves the high thrust required to insert bolts in the pipes as the most likely reason for the installation difficulties. It suggests that either high installation pressures or resin extrusion are the normal conditions during resin bolt installation and that the high pressures recorded during the insertion pressure tests do represent pressures which could be reached in a sufficiently high strength rock.

Generally, all four strain gauges in each installation read similar pressures (Figure 9). Bolt pressures were generally low until about half of the length of the bolt was inserted in the pipe. The pressures in all gauges would then increase rapidly from a few hundred psig or less to around 4,000 to 5,000 psig. Although the travel of the bolter table was not measured during the tests, it was known to be about 5 inches/sec. The rate of pressure increase was found to be slightly lower below the top of the bolt than above it. The time at which this slight reduction in the rate of pressure increase took place allowed determination of when the bolt top passed each gauge. The estimated positions (large circles in Figure 9) agreed with estimates based upon the known speed of the bolter table. The data suggested that pressures would be slightly higher above the top of the bolt, but that pressures would continue to rise along the entire length of the bolt as long as bolter thrust was being applied. The exact pressure profile to be expected in a real bolt hole could, of course, be modified by extrusion of resin into the roof rock.

After the bolt was fully inserted and the bolt was spun the pressure rapidly dropped off. No attempt was made to determine the cause of the pressure reduction, but it was assumed that the primary cause was flow of resin around the bolt and out of the tube, assisted by the action of rotating the bolt.

OBSERVATIONS ON RESIN CARTRIDGE GEOMETRY

During this project the authors were able to observe the condition of the resin and degree of glove fingering taking place on 33 fully grouted resin bolts, installed using "best practice" methods, and 4 fully grouted bolts deliberately installed with short spin times. Because significant amounts of unmixed resin were not observed on any of the properly installed bolts, an effort was made to find an explanation for the difference between the performance observed during this study and that reported by Campbell and Mould (2003). More recently, Mould, et al. (2004), began testing resin cartridges with larger catalyst areas. The results of their work in this area have not yet been reported as of early 2005.

Discussions in early 2004 with representatives of the two U.S. resin manufacturers led to the suspicion that there might be significant differences between the resins used in the U.S. and Australia/New Zealand. U.S. resins appear to be of much higher viscosity, apparently contain much higher quantities of ground limestone, and the catalyst component takes up a larger percentage of the cartridge area.

As part of this study one of the resin cartridges from the SEPT tests was sectioned and cartridges from a major Australian manufacturer and the other major U.S. manufacturer were also obtained and sectioned. The relative areas of the catalyst compartments of all three cartridges were determined and are shown in Table 3. Because of the flexibility of the cartridges and the difficulty of making accurate area estimates the areas have been estimated to within 5%.

Table 3 – Resin cartridge catalyst relative area

Resin	Catalyst relative area (%)
US A	30-35
US B	40-45
Aust A	5-10

All cartridges approximately 0.9 inch diameter

Figure 10 shows photographs of the Australian cartridge and the U.S. cartridge with the smallest relative catalyst area. Superimposed on the photographs are circles representing the diameters of the typical holes the cartridges would be used in and the diameters of the typical bolts used in that hole. In the U.S. case a 5/8-inch bolt in a 1-inch hole was chosen. In the Australian case a 22-mm bolt with a 27-mm diameter hole is shown. In both cases the diameter shown includes the ribs on the bolt, since the diameter of the bolt at the ribs will control resin mixing. Figure 10 shows the worst possible positioning of bolt, resin cartridge and borehole for resin mixing.

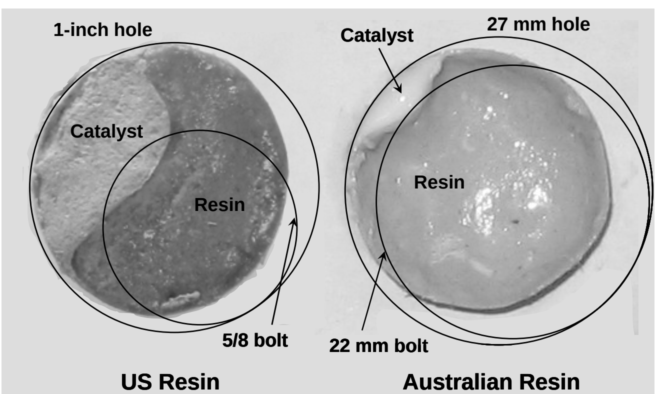

Figure 10 – Sections of typical U.S. and Australian resin cartridges, showing catalyst and resin compartments. Large circles are the diameter of a typical bolt hole. Small circles are the bolt diameter across the ribs. Cartridge diameters approximately 0.9 inch.

Figure 10 shows that it is highly unlikely that even a 5/8-inch bolt could run through a US resin cartridge without tearing the polyester film between the two compartments (Note that the two U.S. manufacturers included in Table 3 control the entire US roof bolt resin market.). In the Australian case tearing the film between the compartments appears possible, but does not appear to be as certain to take place as in the case of the U.S. resins.

Campbell and Mould (2003) reported that the resin along about 27% of the length of the bolts they investigated was unmixed and they noted that the catalyst compartment was often found flattened against the side of the borehole and remained unshredded. Figure 10 suggests a reason why this might have frequently taken place. The geometric observations and the data from this study together suggest that unshredded catalyst compartments should not be a cause of poor mixing of resin in U.S. mines.

CONCLUSIONS

The offset head versus standard 5/8 inch roof bolt pull tests suggest that there is no significant difference between the pullout performance of a standard 5/8 inch roof bolt and an offset head roof bolt of the same diameter and grade, when both are installed in the same manner.

The Short Encapsulation Pull Test (SEPT) versus overcored standard bolt pull tests indicated that there is a significant difference between the two; the results suggest that SEPTs are highly conservative. The SEPT test is still useful to confirm adequate anchorage and as index test to compare relative anchorage strengths.

Adequate resin mixing was observed on all of the bolts installed in this study. All bolts were spun for the same time period (6 seconds) and no unmixed resin was observed on any of the 45 tested bolts cored and removed from the roof. Several bolts, not included in the comparative studies, were installed using 1 second spin times, and in these cases poor bolt performance and partially unmixed resin were both anticipated and observed.

Glove fingering, of varying extent, was observed in almost all bolts installed in this study. Comparison of four slightly glove fingered offset head bolts to six severely glove fingered offset head bolts, based upon visual examination of the amount of polyester film visible at the surface of the resin, led to inconclusive results, but suggested that the effect of glove fingering ranged from slight to moderate. This comparison could not be conducted on standard bolts because of a lack of bolts which could be considered severely glove fingered.

The pressure tests suggested that significant pressures, up to 5,000 psig, may be generated in the resin during the installation of fully grouted resin bolts, unless extrusion of resin into the roof rock takes place. Physical examinations of bolts installed at the NIOSH Safety Research Coal Mine (SRCM) clearly showed that significant quantities of resin (averaging 44%, but up to 50%) were lost in weak rock through extrusion of resin into existing fractures or fractures created by the installation pressure. In weak roof rock resin loss of this magnitude could have a detrimental effect upon bolt performance and possibly upon mine roof conditions, especially where the lower portions of the bolts are left ungrouted by the resin loss. However, the SRCM tests also suggest that resin extrusion may be common and minor extrusion of resin, as long as sufficient resin is present to insure that bolts remain fully grouted, may not have a detrimental effect.

Finally, comparison of what are believed to be typical U.S. resin cartridges to typical Australian cartridges suggests that the large difference in the relative proportions of catalyst to resin between U.S. roof bolt resins (30-45% to 70-55%) and Australian (10% to 90%) resins may partly explain the relatively high incidence of poorly mixed resin reported by Campbell and Mould (2003). If this is the case, the problem of poor resin mixing may not be common in the U.S., since the manufacturers supplying most of the resin used in the U.S. make resin cartridges with large catalyst compartments, which are more likely to insure tearing of the wall between the two compartments and mixing of the two components.

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