FIELD PERFORMANCE TESTING OF FULLY GROUTED ROOF BOLTS

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ABSTRACT

More than 80% of U.S. roof bolts are fully-grouted, but about 1500 roof falls are reported each year. Anchorage failure of a fully grouted bolt can occur when the roof is active near the top of the hole. This paper reports on an extensive series of short-encapsulation pull tests (in which the bolts are installed with only 1 ft of resin) that were conducted in the National Institute for Occupational Safety and Health (NIOSH) Mine Safety Research Laboratory and operating mines in WV and PA. The tests confirmed that poor anchorage can be encountered under some weak rock conditions. Suggestions for improving anchorage are included.

BACKGROUND

Roof bolts have been the primary roof supports in U.S. coal mines since the late 1950's. Fully grouted resin bolts were introduced about a decade later. A survey conducted by NIOSH in 1999 (Dolinar and Bhatt, 2000) found that the coal mining industry used about 85 million roof bolts. Of these, approximately 80% were fully grouted. Figure 1 shows the historical trends in roof bolt usage in the U.S. For many years, the most common fully grouted bolt installation was a 19 mm (0.75 in) bolt in a 25 mm (1 in) hole. In recent years, however, 16 mm (5/8 in) bolts have become more popular. The 1999 survey found that about 80% of all fully grouted bolts were the smaller diameter.

The installed cost of roof bolts has been estimated at more than $500 million annually (Campoli, 2001). Yet MSHA statistics show that nearly 1500 non-injury roof falls are reported each year (Pappas et al, 2000). The big majority of these falls extend higher than the anchorage horizon of the bolts. Each of these large roof collapses represents a failure of the roof bolting system.

FAILURES OF FULLY GROUTED BOLTS

Fully grouted bolts are loaded by movement of the rock. As illustrated in figure 2, the movement may be vertical sag, shear along a bedding plane, or dilation of a roof layer buckled by horizontal stress (Signer, 2000; Fabjanczyk and Tarrant, 1992). The movements cause tensile forces in the bolt, usually combined with bending stresses.

Depending on where the roof movements are concentrated, the bolts can fail in one of three ways, as shown in figure 3 (Serbousek and Signer, 1987; Mark, 2000):[1]

1. The head or the plate can fail;
2. The rod may break, either in tension, or a combination of tension and bending; or
3. The anchorage may fail.

The anchorage can fail when roof movement occurs near the top of the hole, as shown in figure 3c. If the load applied to the bolt exceeds the strength of the grout anchor, the top of the bolt will be pulled out of the hole. If the bolt had been suspending weak or failed lower roof from intact upper rock, a roof fall can follow.

Roof falls can sometimes provide clues as to the type of bolt failure that took place. If broken bolts can be seen, the anchorage was probably adequate, and the problem may have been that the capacity of the bolts was inadequate to resist the loads applied by the roof (as in figure 3b). But if the tops of resin bolts can be seen protruding from the top of the muck pile after a fall, then inadequate anchorage should be suspected (figure 3c and figure 4).

ANCHORAGE MECHANICS OF FULLY GROUTED BOLTS

A fully grouted bolt anchors itself by frictional interlock between the resin and the rock. The performance of a fullygrouted bolt is determined by the load-transfer mechanisms between the rock, the grout, and the bolt. Signer (1990) provides an excellent discussion of load transfer mechanisms. Good load transfer exists when very high loads develop in the bolt in response to small ground movements, and these loads are rapidly dissipated away from the zone of roof movement.

[1] In addition, the roof bolts may be intact, but the support system can fail if the *bolts are too short*, allowing the roof to fail above them; or the *bolts fail to provide adequate skin control*, allowing loose rock to create a hazard.

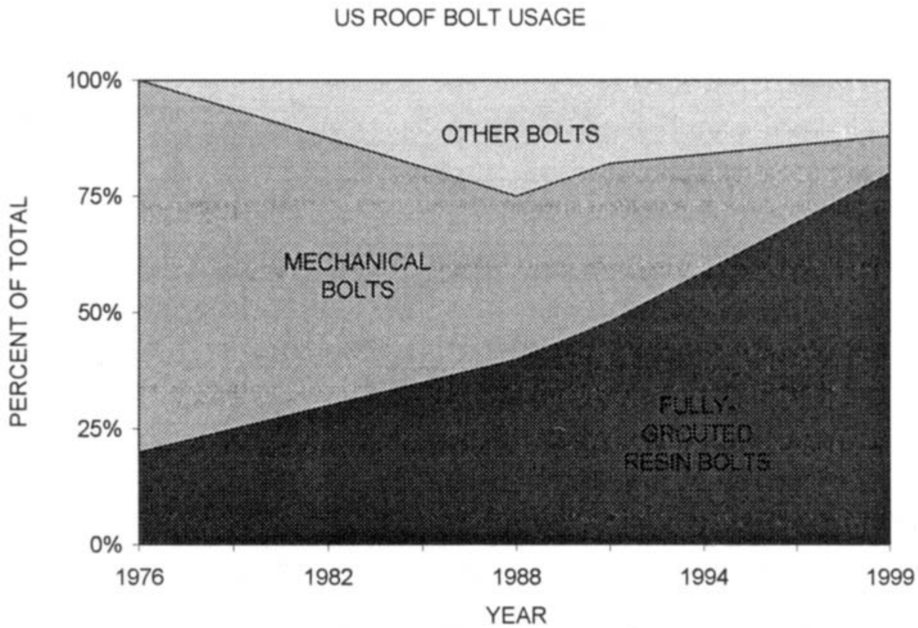

Figure 1. Trends in U.S. roof bolt usage (source: Dolinar and Bhatt, 2000).

The effectiveness of the interlock is measured by the "Grip Factor,"[2] which is defined as *the bolt's resistance to pullout per inch of bolt length*. The Grip Factor must be determined by loading the upper portion of the grouted bolt. This is accomplished with short encapsulation pull tests (SEPT), in which only the top 300 mm (12 in) of the bolt is grouted (figure 5). The Grip Factor (tons/in) is calculated as:

Grip Factor = Maximum SEPT Load (tonnes (tons))/(300 mm(12 in))

Figure 6 illustrates the effect of the Grip Factor on bolt performance. Within the anchorage zone (the upper portion of the bolt), the bolt's available resistance to loading from rock movement may be considerably less than its nominal yield strength. The length of the anchor (L_{Anch}, in mm or inches) is the bolt's yield load (Y, in tonnes or tons) divided by the Grip Factor (GF):

$$L_{Anch} = Y / GF \quad (1)$$

Obviously, a bolt with a larger Grip Factor will have more available resistance, as shown in figure 6b. In fact, the "Full Resistance Length" (L_{FR}) of a fully grouted bolt, which is the zone in which the force available to resist rock movement is at least equal to the yield strength of the bolt, is the total bolt length L minus the length of the anchor:

$$L_{FR} = L - L_{anch} \quad (2)$$

SEPT have been used since the earliest days of resin bolts (Franklin and Woodfield, 1971). They are widely employed

[2] In the literature, what this paper calls the "Grip Factor" has also been referred to as the "Bond Factor" or the "Anchorage Factor."

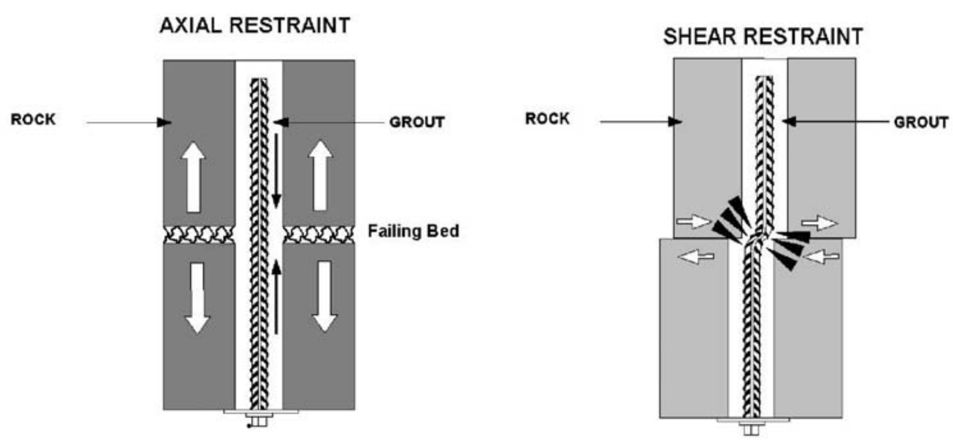

Figure 2. Loads in fully grouted roof bolts caused by roof movements. A) Tension resulting from bed dilation or bed separation; B) Tension and bending caused by slip on a bedding plane.

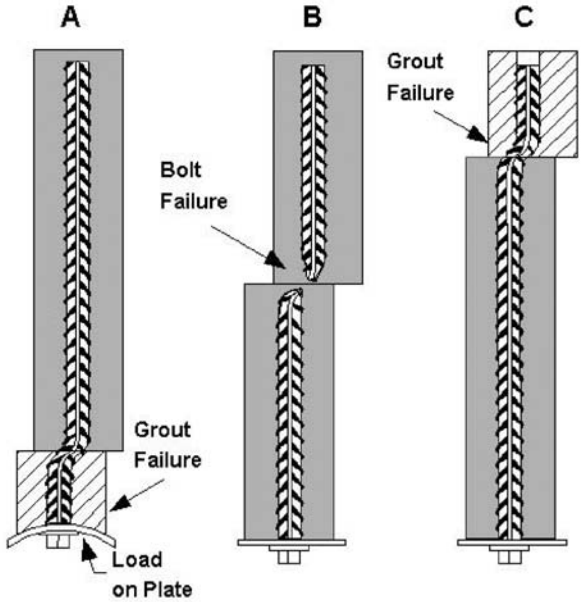

Figure 3. Failure mechanisms of a fully grouted roof bolt. (A) Roof movement near head; (B) Roof movement in central portion; (C) Roof movement in anchorage zone.

internationally today, and are even required in the UK (Health and Safety Executive, 1996). In the US, Karabin and Debevec (1976) reported some valuable results obtained from SEPT, and recommended that "pull tests of approximately one ft of grouted length should be made from time to time, to ensure that the resin used is of good quality."[3]

Table 1 gives typical anchorage factors and anchorage obtained from the literature. Short encapsulation tests are apparently rather rare in the US, and the only available published data was obtained from Peng (1998). Although the Australian (Yearby, 1991) and UK (Bigby, 1997) data probably applies to slightly larger bolts, there does seem to be a clear difference. The implication is that in weak rock in the U.S., the top 500 mm (20 in) of a fully grouted bolt may not be providing significant reinforcement to the rock. In such conditions, the "effective length" of the bolt may be considerably less than its nominal length.

[3]Standard pull tests cannot be used on bolts that are fully grouted for their entire length. Such a test only measures the strength of the rod, because the pulling forces seldom extend more than 450-600 mm (18-24 in) up the resin column [Serbousek and Signer 1987; Signer, 1990; Tadolini and Dyni, 1991].

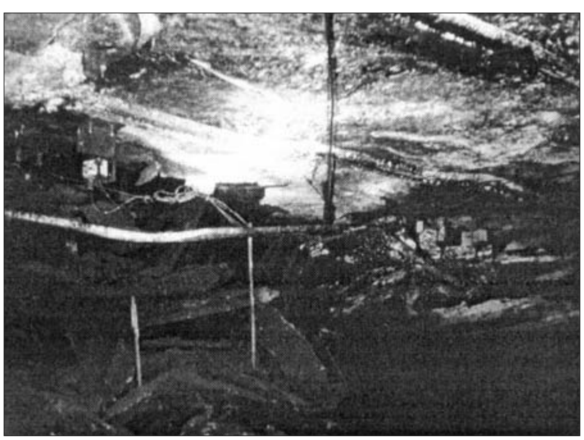

Figure 4. Photograph showing fully grouted bolts pulled from their holes in a roof fall.

CAUSES OF POOR RESIN BOLT ANCHORAGE

The two most likely causes of poor anchorage are *weak rock* and *poor installation*.

Weak Rock: Table 1 shows that weaker rock requires a longer

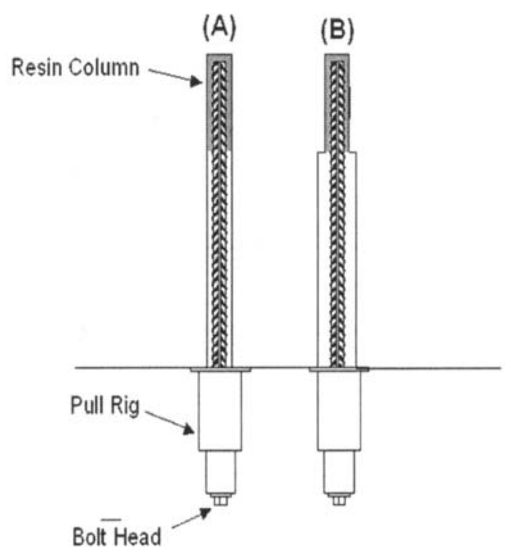

Figure 5. The Short Encapsulation Pull Test. (A) Normal hole; (B) Reamed hole.

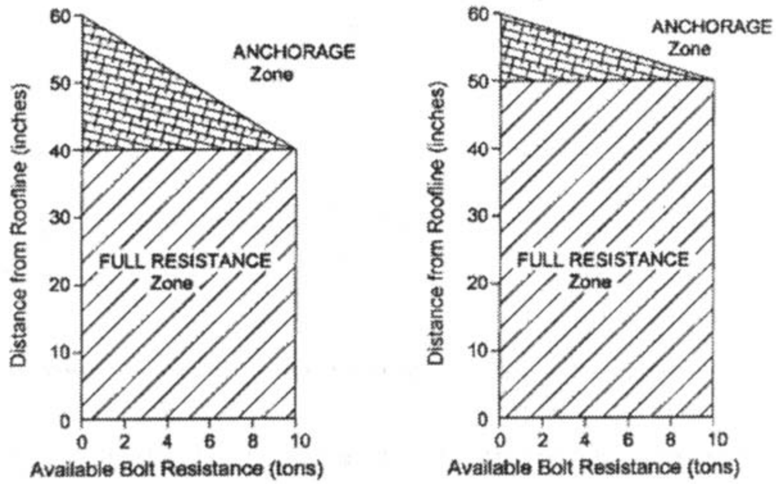

Figure 6. Effect of the Grip Factor on the resistance available from 10-ton roof bolts to react against roof loads. (A) Grip Factor = 0.5 tons/ch; (B) Grip Factor = 1.0 tons/in.

grouted length to achieve the same anchorage as strong rock. In very weak rock, Grip Factors can be so low that 1.8 m (6-ft) bolts have been pulled from the rock at 12 tonnes (14 tons) even though they were fully grouted for their entire length (Rico et al. 1997)!

Perhaps the most extensive study of resin bolt anchorage in the U.S. was conducted by the former U.S. Bureau of Mines in the mid-80's [Cincilla 1986]. More than 1000 pull tests were conducted at 11 underground coal mines throughout the U.S. The tests involved anchorage lengths of 300-1,200 mm (12-48 in). The anchorage length was considered adequate when 90% of the tested bolts reached the yield load of the steel. The study found that coal and shale roofs required an average of *790 mm (31 in)* of grouted length to meet this criterion. Sandstone required 450 mm (18 in) on average, and limestone needed just 300 mm (12 in).

Poor Installation Quality: The Troubleshooting Guide for Roof Support Systems (TGRSS) computer program (Mazzoni et al., 1996) identifies a number of factors that can result in poor anchorage with fully grouted bolts. These include:

• *Defective grout* can result from improper storage (too hot, too cold, too wet, or shelf life exceeded), or (rarely) from manufacturing problems.

• *Improper mixing* can occur if the proper spin time is not followed. Underspinning can result in inadequate mixing, while overspinning can destroy the partially cured resin. Improper mixing can also occur with long bolts where the top of the hole has less time to mix before the bottom sets up. The temperature of the resin at the time of installation can also affect the cure time.

• *Improper holes* can be too long, too short, too large, or too smooth. The proper grout cartridge must also be matched to the hole and the bolt being installed.

· *Finger gloving* occurs when the plastic cartridge wrapper remains intact around the hardened resin. It is more likely if the bolt is not rotated as it is inserted in the hole (Pettibone, 1987).

Other possible causes of poor anchorage that have been identified are:

Hole annulus: Numerous tests over the years have found that optimum difference between the diameter of the bolt and the diameter of the hole is no greater than 6 mm (0.25 in), giving an annulus of about 3 mm (0.125 in) (Fairhurst and Singh, 1974; Karabin and Debevic, 1976; Ulrich et al., 1989). For example, a 3mm (0.125 in) annulus is obtained by a 19 mm (0.75 in) bolt in a 25 mm (1 in) hole. Larger holes can result in poor resin mixing, a greater likelihood of "finger-gloving," and reduced load transfer capability. One Australian study found that the load transfer improved more than 50% when the annulus was reduced from 4.5 to 2.5 mm (0.35 to 0.1 in) (Fabjanczyk and Tarrant, 1992). Smaller holes, on the other hand, can cause

Table 1.—Grip factors for fully grouted resin bolts

Rock type	Country	Grip Factor, tons/in (N/mm)	Length for 10 tons of anchorage, in (mm)	Reference
Coal, shale	Australia	0.7-2.1 300-900	4-12 100-300	Yearby, 1991
Hard sandstone, limestone	Australia	2.3-5.8 1000-2500	1.4-3.6 35-90	Yearby, 1991
Minimum allowable[1]	U.K.	1.1 400 N/mm	8.9 210	H&S Exec., 1997
Soft rock	U.S.A.	0.5 220	20 500	Peng, 1998
Strong rock	U.S.A.	2 870	5 125	Peng, 1998

[1]Over at least 50% of the bolt length.

insertion problems and magnify the effects of resin losses or oversized holes (Campoli et al., 1999). However, one recent U.S. study found that annuli ranging from 2.5-6.5 mm (0.1-0.25 in) all provided acceptable results in strong rock (Tadolini, 1998), indicating that annulus may be most important in soft rock. Ulrich et al. (1989) found no significant difference in the mean anchorage strength between annuluses of 3 and 6 mm (0.125 and 0.25 in), but the standard deviation was much higher for the wider annulus.

Hole and bolt profile: Because resin grout acts to transfer load by mechanical interlock, and not by adhesion, rifled holes and rougher bolt profiles result in better load transfer (Karabin and Debevic, 1976; Haas, 1981; Aziz et al., 1999). Reportedly, wet drilled or water-flushed holes can also improve load transfer (Siddall and Gale, 1992). One study found that the pullout load of standard rebar was seven times that of a smooth rod (Fabjanczyk and Tarrant, 1992).

Resin characteristics: Tests in the UK in the late 1980's demonstrated that the compressive strength of resin was important to the performance of grouted roof bolts (British Coal Technical Department, 1992), and current UK regulations require resin strength to exceed 80 MPa (11,000 psi). A strength test was recently added to the U.S. ASTM standards for resin. However, an extensive series of laboratory "push tests" found little correlation between shear stress and resin strengths in the 20-60 MPa (3,000-6,000 psi) range (Fabjanczyk and Tarrant, 1992).

DEVELOPMENT OF A US STANDARD SHORT ENCAPSULATION PULL TEST

The primary goal of this study was to develop SEPT procedures that could be widely used in US mines. The test focuses primarily on No. 5 Gr. 60 and No. 6 rebar, which together constitute the great majority of US roof bolt installations. It is designed to be a simple "green/yellow" test where:

• Green means that a 300 mm (12-in) encapsulation length achieves the yield strength of the rebar (at least 8 tonnes (9 tons) for No. 5 Gr. 60 and No. 6 Gr. 40 rebar; and about 12 tonnes (13 tons) for No. 6 Gr. 60 rebar), and;

• Yellow means that the anchorage obtained from 300 mm (12 in) of encapsulation is less than the yield strength of the rebar.

The test is also designed to be quick and simple, and to require a minimum of specialized equipment. A detailed description of the test procedure has been provided elsewhere (Mark et al., 2002).

While simple in concept, international procedures for SEPT have differed in a number of details:

• Encapsulation length: The international consensus seems to be that at least 300 mm (12 in) of the bolt should be grouted to minimize the effect of the zones of poor mixing at the top and the bottom of the resin (Fabjanczyk et al., 1998). Shorter and longer lengths have sometimes been used, however.

• Hole depth: In the US, production roof bolt holes are often overdrilled by 25 mm (1 in) (Mazzoni et al, 1996). The overdrill presumably provides a space for the resin cartridge wrapping, clips, etc, while also providing a margin of error against underdrilling. When conducting a SEPT, however, it is important that correct encapsulation length be obtained, and overdrilling might result in a miscalculation of the amount of resin used.

• Hole Reaming: One method to ensure the correct encapsulation length is to ream the lower portion of the hole to a larger diameter (figure 5b). Then only the upper, unreamed portion of the hole is effectively grouted. This method is employed internationally, though an unreamed test is also allowed in the UK under certain conditions (Health and Safety Executive, 1996; Wittenberg and Ruppel, 2000). Reamed holes also make it possible to pull the bolt completely out, so that the resin anchor can be viewed.

A series of 56 bolts were pulled in the NIOSH Safety Research Coal Mine (SRCM) at Bruceton to help develop the test. Both No. 5 and No. 6 bolts were tested in 300 mm (1-in) holes, and the effects of hole depth and hole reaming were evaluated.

The tests were conducted at the ends of a dead-end entry and adjacent crosscut. Two coreholes were drilled to determine the most suitable horizon for performing the tests. The first consistent horizon of sufficient thickness that was not coaly was a weak claystone about 1.70 m (5.5 ft) above the roofline. The long bolts and a relatively low mine roof made it necessary to bend the bolts to install them. This may have had some effect upon resin mixing, since it may have made the bolts crooked. Since the bends were several feet below the bolting horizon and since none of the bolts reached yield, the bends are not believed to have had an effect on the bolt strength.

In order to insure consistent drilling depths, the steels were marked and checked each day and all drilling was performed by the same drill steels. Because the horizons drilled were so soft, bit wear was found to be minimal during the tests. Bit diameters were measured regularly, and no significant change in bit diameter was noted.

The resin used was a 1 minute resin from the same manufacturing date and lot (January 2002). Cartridges were made up on the day of the test, with a manufacturer's clip at the bottom of the cartridge and a tie wrap at the top. The tie wraps used were all of the same size. The speed of the bolting machine was determined to be 500 rpm and the resin manufacturer's recommendation for 30 to 50 revolutions was followed, by setting the spin time at 6 seconds, thus giving 50 revolutions for each bolt installation. Hold times were standardized at 54 seconds.

BRUCETON MINE PULL TEST RESULTS

Figure 7 shows a typical load deformation curve for a short encapsulation pull test in which the anchorage fails (and the rod does not yield). Initially the load deformation curve is linear. However, as the resin along the lower portion of the anchor begins to fail, the load deformation curve deviates from a straight line. As the applied load approaches and exceeds the peak anchor capacity, the anchor begins to slip. After the peak the anchor still carries on average about 70 pct of the peak load over 38-50 mm (1.5-2.0 in) of deformation.

The results of the tests are summarized in Table 2. In the "Hole Depth" column, "E" refers to holes drilled to the exact depth required to accommodate the bolt (taking into account the bolt plate and pull collar), while "O" refers to holes overdrilled 1-in deeper. The resin cartridge lengths were adjusted to account for the different hole volumes. "Hole Preparation" includes "R" for holes that were reamed with a 34 mm (1 3/8 in) bit up to the anchorage horizon, and "S" for standard holes. Details of the individual tests can be found in Mark et al. (2002).

The average Grip Factor for all the tests was 250 N/mm (0.69 tons/in), which is well below the "Green" level of about 360 N/mm (1 ton/in). This result confirms that low grip factors can be encountered when the rock is extremely weak, even under optimum installation conditions. In general, the results were reasonably consistent, with the standard deviation on average being about one-fifth of the mean.

There was no statistically significant difference between the No. 5 and the No. 6 rebar in these tests, either in the mean Grip Factor or the standard deviation. Apparently, the difference in annulus did not affect these results.

Reaming the hole also had no statistically significant effect on the test result. Standard holes are more convenient, but reamed holes can be used if the additional information that can be obtained from

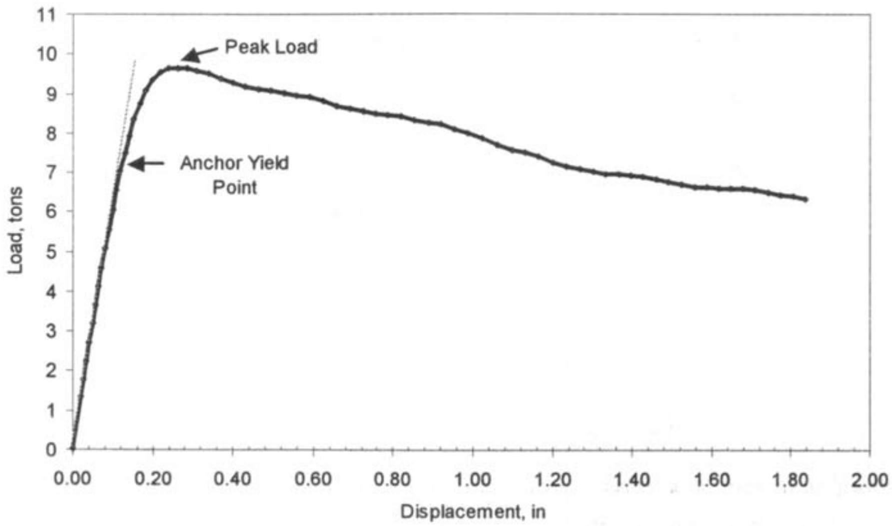

Figure 7. Load deformation curve for typical short encapsulation pull test.

visual inspection is desired.

The only statistically significant difference was between the exact depth and the overdrilled holes. Surprisingly, the exact depth holes achieved greater the anchorages, even though the visually inspected bolts showed that it was common for the top 12-50 mm (0.5-2 in) of their resin to pull away from them. It seemed that the upper portion of the resin was weak due to the presence of the bag and resin clips. In contrast, the overdrilled holes generally appeared to have solid resin, with no residue from the bag or clips to the top of the bolt. However, because the effect was relatively small (about 10%), overdrilled holes should normally be used, unless exact depth holes are the normal installation practice at the mine.

As part of the tests, 32 of the anchors were recovered by pulling the bolts completely out of the reamed holes. Figure 8 shows a typical anchor that was pulled from the roof. Each anchor was examined for evidence of the length of the installed grout column while the length of the grout still attached to the rebar was measured. This confirmed that the specified grout length was achieved during the installation. Usually 70-80% of the installed length of anchor was still attached to the rebar after being pulled from the roof. The other 50-100 mm (2 to 4 in) of the grout usually broke away from the lower portion of the anchor. This is the portion of the grout that failed during the pull test.

PRELIMINARY TESTS IN US COAL MINEs

Short Encapsulation Tests were conducted in two operating U.S. coal mines, one in West Virginia and one in Pennsylvania. The goal was to determine how widespread the problem of poor anchorage might be, and the mines were selected because they were encountering extremely weak roof conditions.

The tests were conducted early in the study, and the procedures differed in some respects from the final ones used in the Bruceton study. So while the results are not strictly comparable, they do provide some indication of the anchorage that can be encountered. The tests involved a variety of Nos.5 and 6 rebar types.

Table 3 shows that the anchorage was “green” at 2 of the 5 sites, and borderline at a third. At the other two the anchorage factor was only 220 N/mm (0.6 tons/in).

IMPROVING ANCHORAGE OF FULLY GROUTED BOLTS

Once short encapsulation tests have confirmed that the anchorage is poor, there are some things that can be done. The first step is to *check the quality of the installation*. It is essential that roof bolt operators carefully follow the installation instructions provided by the resin manufacturer. The TGRSS program, which is available at the NIOSH Mining Website, contains some simple suggestions for testing the resin and the hole.

If the grout and the installation procedure are found to be adequate, then attention should shift to the hole and the bolt. *Rifled holes and rougher bolt profiles* should result in better anchorage. Unfortunately, special bits to drill rifled holes are easier to find

Table 2. Average test results by group ordered by hole depth

Bolt Size	Test Type	Hole Depth	Mean Maximum load (tons)	St. Dev., (tons)	Grip Factor (tons/in)
No. 6	R	E	9.7	1.4	0.81
No. 6	S	E	8.5	1.7	0.71
No. 5	R	E	7.8	1.1	0.65
No. 5	S	E	9.1	1.0	0.76
No. 6	R	O	7.6	1.4	0.63
No. 6	S	O	7.4	2.3	0.62
No. 5	R	O	7.5	2.0	0.62
No. 5	S	O	8.7	2.1	0.73

Table 3. Results from Underground Coal Mines.

State	Rock Type	Grip Factor (tons/in)	Green/Yellow
Pennsylvania site 1 @ 6ft	clay, claystone	0.87	Green
Pennsylvania site 1 @ 8ft	layered dark. gray shale	0.72	Yellow
Pennsylvania site 2 @ 6ft	dark gray fireclay	0.63	Yellow
West Virginia @ 6ft	dark gray shale	1.04	Green
West Virginia @ 1.5ft	thinly banded gray shale	0.83	Borderline

overseas than they are in the US.

Another possibility is to *reduce the hole annulus*. The simplest way to do this might be to substitute #6 rebar for #5, while keeping the hole size constant. In very severe conditions, the only way to *increase anchorage may be to increase both the hole diameter and the bar diameter*. This enlarges the area of the grout-rock contact surface, thereby increasing the total shear resistance [Karabin and Debevic, 1976; Rico et al. 1997].

CONCLUSIONS

Since its introduction more than 30 years ago, resin grouting has dramatically improved the effectiveness of roof bolting. One important advantage of fully grouted resin bolts over conventional mechanical ones is that resin anchorage generally does not degrade over time. Another is that resin bolts can provide significant support even when their anchorage is poor.

On the other hand, despite years of research, no practical and reliable method to routinely test resin bolt installations has ever been developed. It is very difficult to know whether resin bolts are performing as well as they could be–whether a mine is truly getting its money's worth in support and safety.

This paper has focused on the specific problem of poor anchorage. When anchorage is poor, roof movements near the top of the bolt (within the anchorage zone) can pull the bolt out of the upper portion of the hole at loads less than the yield strength of the rod. The two most likely causes of poor anchorage are weak rock and poor installation quality.

The short encapsulation pull test (SEPT) is a relatively simple technique to test resin bolt anchorage. Step-by-step procedures for conducting SEPT have been provided elsewhere (Mark et al., 2002). It is hoped that more widespread use of the SEPT will aid quality control, improve the effectiveness of resin bolts, and result in enhanced safety for US mineworkers.

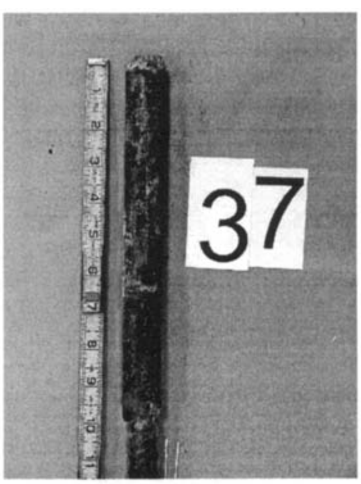

Figure 8. View of a short column grout anchor recovered from the roof.

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