

TRENDS IN ROOF BOLT APPLICATION

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ABSTRACT

The roof bolt system of a mine, if properly selected and installed, can allow for better roof control and reduce the potential for roof falls. Because of this potential to reduce roof falls and improve ground control conditions, the National Institute for Occupational Safety and Health (NIOSH) has an interest in the types of roof bolts that are used by the coal industry. Further, NIOSH has conducted research into how various support parameters can affect the number of roof falls that occur, including support type. Today, the five main types of roof bolts installed in U.S. coal mines are mechanical anchor bolts, point-anchor or resin-assisted mechanical anchor bolts, torque-tension bolts, combination bolts, and fully grouted resin rebar. This paper describes each support in detail. Because of the importance of resin in the functioning of the majority of bolts installed, resin grouts are also discussed. Further, trends in the types of roof bolts used are reviewed. Over the last 10 years, the significant trend has been the large reduction in the relative number of mechanical anchor bolts that are installed. These bolts have been replaced mainly by the resin-grouted rebar system. Data are also presented to show the impact of these changes in bolting on the number of roof falls.

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INTRODUCTION

Roof bolting in coal mines was initiated on a significant level only after World War II. At that time, the technological factor that drove the change from timber support to roof bolts was the increased mechanization in the mining industry, while the introduction of carbide-tipped drill bits made the drilling of bolt holes on a production basis feasible [Thomas 1950, 1954]. The change to roof bolts accelerated during 1949 after the steel shortage caused by the war had eased. Before 1949, only a few coal operations had experimented with roof bolting. By May 1949, there were more than 200 mines, mostly coal operations, that were installing roof bolts. Roof bolts supported over 14 million ft² of roof, using an estimated 800,000 to 1 million roof bolts. By the end of 1949, more than 430 coal mines used roof bolts.

Most of the bolts used a slot and wedge anchor, but some mines were already experimenting with expansion-shell or mechanical anchor bolts [Thomas et al. 1949]. The slot and wedge bolts had a threaded section at the head of the bolt and were tensioned by a nut tightened against a bearing plate. Because of the superior anchorage, the mechanical anchor bolts eventually replaced the slot and wedge bolts as the main roof support.

Even in the early days of roof bolting, it was recognized that a support in full contact with the rock along its entire length would be useful in dealing with rock shear forces, especially along hanging walls of hard-rock mines [Thomas 1954]. For the coal industry, the full contact support in the form of a fully

grouted rebar was introduced in the late 1960s to early 1970s. This rebar bolt now is the predominant support used by the coal industry. Resin-assisted mechanical anchor or specialty bolts that combined the superior resin anchor with the tension of a mechanical anchor bolt were introduced in the late 1980s. Today, the five main types of roof bolts used in the U.S. coal industry are fully grouted resin rebar, mechanical anchor bolts, resin-assisted mechanical anchor bolts, torque-tension bolts, and combination bolts.

The type of bolt can be important for roof control because each support has characteristics that determine how the bolt will support the roof. The main characteristics that differentiate supports are whether the bolt is pretensioned and whether the anchorage length is full or point contact. How the bolt will interact with the site-specific rock mass properties and stress conditions and stabilize the roof must be considered when selecting a support [Mark 2000; Deere et al. 1970; Scott 1989]. The design of the support system must also consider other support properties, including anchorage capacity, anchorage load distribution, axial stiffness and toughness, shear resistance, shear stiffness, and shear toughness [Karabin et al. 1980].

This paper discusses the recent trends in the types of bolts used and the impact on roof control as the type of reinforcement has changed. The main types of bolts used today are described, and resin grouts used to anchor most of the rock bolt systems are discussed.

TRENDS

To evaluate roof bolt usage and trends in U.S. coal mines, the National Institute for Occupational Safety and Health (NIOSH) collected information from all known U.S. roof bolt manufacturers. Figure 1 shows the results of this study for 1999. However, the data were not complete in every instance, and the data are for all bolt usage, not just coal mines. Therefore, the results shown in figure 1 should be considered estimates. In the figure, five bolt types are indicated:

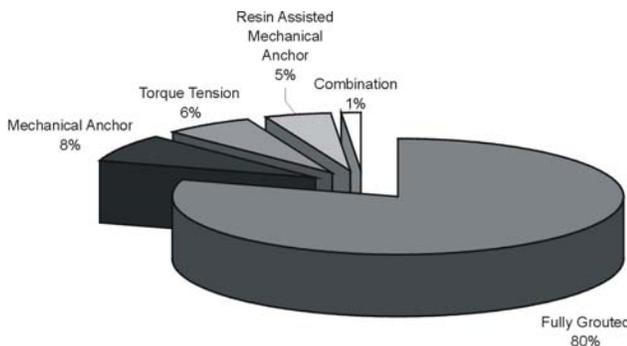


Figure 1.—Percentage of bolt types used in U.S. underground coal mines in 1999.

mechanical anchor, resin-assisted mechanical anchor, torque-tension, combination, and fully grouted resin rebar bolts. Although this figure does not break down bolt usage by commodity, based on coal production, the coal industry uses an estimated 80% to 85% of the reinforcement. Therefore, the percentages of the different types of bolts used are probably very representative of the distribution of the type of bolts used in coal mines. In 1999, approximately 100 million bolts were used in the U.S. mining industry.

Fully grouted resin rebar comprises about 80% of these bolts. For the grouted rebar, approximately 80% are 0.625-in-diam #5 rebar, and nearly all of the remaining are 0.75-in-diam #6 rebar. Mechanical anchor bolts comprise about 8% of the supports, while torque-tension bolts represent 6% of the supports. Resin-assisted mechanical anchor bolts are approximately 5% and combination bolts about 1% of the market.

Surveys on bolt usage were also conducted in 1988 and 1991 [Scott 1989]. Table 1 shows a comparison between the percentages of each bolt type for these years and 1999. An estimate of the distribution of bolt types for 1976 is also given in the table. In that year, 80% of the bolts used were

mechanical anchor and 20% resin-grouted rebar [Karabin et al. 1980]. From 1976 to 1991 and from 1991 to 1999, there was a substantial shift away from mechanical anchor bolts to fully grouted resin rebar. For resin-assisted mechanical anchor bolts, there was also a small decrease in the percentage used from 1991. In the 1991 survey, no distinction was made between torque-tension and combination bolts; the two systems were classified as point-anchor tension rebar. However, the combined usage of these two systems was about the same for 1988 and 1999, with a slight drop in the percentage used for 1991.

Table 1.—Bolt usage in U.S. mines by type

Bolt type	Percent			
	1976	1988	1991	1999
Mechanical anchor	80	35.3	34.1	8
Fully grouted	20	40	48.2	80
Torque-tension	—	3.5	4.6	6
Resin-assisted mechanical anchor	—	14.1	11.5	5
Combination	—	3.5	—	1
Other ¹	—	3.6	1.5	—
Total ²	100.0	100.0	100.0	100.0

¹Includes both torque-tension and combination bolts.

²Data may not add to totals shown because of independent rounding.

In general, resin-grouted rebar, despite being a passive support, may be considered a superior system to the mechanical anchor bolt because of the anchorage capacity and load transfer capabilities. Therefore, with the significant shift toward resin bolts, a corresponding improvement in roof stability might be expected that could be traced over the last 10 or even 25 years. The number of reportable roof falls that occurs each year can be used to evaluate whether a significant improvement has occurred. Table 2 shows the number of reportable roof falls, the number of mines, and the tons mined from 1989 to 1998 for longwall and room-and-pillar mining. To better compare the data for each year, the roof fall rate based on production is also shown. Figure 2 shows the roof fall rate per million tons of coal from 1989 to 1998 for both longwall and room-and-pillar mining.

For room-and-pillar mining, the roof fall rate trend from 1989 to 1998 can be evaluated by fitting a linear regression to the data. The results indicate that the coefficient of determination is <0.1, while the slope of the line is not significantly greater than zero. Essentially, there has been no change in the roof fall rate for the last 10 years in room-and-pillar mines. For 1975 and 1976, the roof fall rate per million tons was 5.667 and 6.841, respectively. Compared to the rates for 1997 and 1998 (7.067 and 7.011, respectively), there certainly has not been any decrease in the fall rate over 25 years.

For longwall mining, there was a decrease of about 1.6 roof falls per million tons, or a reduction of about 50% in the roof fall rate between 1988 and 1998. However, other factors such as face width, seam height, and number of gate road entries have caused much of this change by reducing the amount of development mining. Over this period, there was a 26%

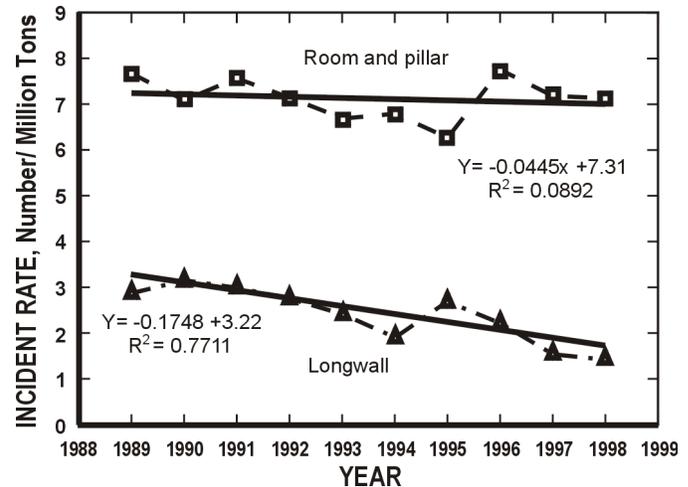


Figure 2.—Incident rate for reportable roof falls based on production from 1988 to 1998 for both longwall and room-and-pillar operations, including a regression analysis.

increase in panel width and a 7% increase in seam height [Merritt 1991; Fiscor 1999]. Further, the number of entries for a gate road has been reduced from 3.5 in 1990 to 3.1 in 1999, a decrease of 11%. Therefore, the increased panel width and seam height and the decrease in the gate road entries could account for nearly all of the decrease in the roof fall rate. In 1990, about 26% of the production from a longwall was from development [Bhatt 1994]. In 1999, an estimated 15% to 18% of production came from development. Essentially, the change in roof support has had a minimal effect on the roof fall rate in longwall mines.

Therefore, despite the significant change from mechanical bolts to fully grouted rebar, there has been little change in the roof fall rate. This does not mean that the roof bolt type does not influence roof stability. There is documented evidence for specific cases where mines have changed bolt type and increased roof stability [Karabin and Hoch 1980; Peacock 1986; Stankus 1991]. However, there are many other aspects to the design of a roof support system other than the support type, and in many situations roof falls may have been prevented only with the addition of supplemental support. Further, the fully grouted bolts might have allowed mining under more difficult roof conditions, and therefore an increase in the roof fall rate could be expected that is balanced by the use of the fully grouted bolt. Also, a general analysis of all U.S. coal mines indicates that a number of factors may have changed, including the number of mines, roof conditions, and the accuracy of reporting roof falls. Further, there are reasons for changing the roof support other than for ground control, including different requirements for checking installation quality. Lastly, the mechanical anchor bolt has been replaced by a fully grouted resin bolt system using a #5 rebar in a 1-in-diam hole, and this may not be the optimum resin rebar system from a support standpoint. A more detailed discussion of the potential problems with the #5 rebar system compared to a #6 rebar bolt is presented below.

Table 2.—Roof fall rate per million tons mined for room-and-pillar and longwall mines

Year	Room-and-pillar				Longwall			
	Roof falls	Mines	Tons, million	Rate, falls per million tons	Roof falls	Mines	Tons, million	Rate, falls per million tons
1989	1,945	1,669	253	7.7	397	70	134	3.0
1990	1,875	1,659	266	7.0	470	76	154	3.1
1991	1,898	1,482	249	7.6	472	76	155	3.1
1992	1,726	1,338	242	7.1	452	77	161	2.8
1993	1,418	1,197	212	6.7	335	75	136	2.5
1994	1,496	1,136	221	6.8	348	71	175	2.0
1995	1,333	979	209	6.4	501	70	187	2.7
1996	1,653	874	214	7.7	460	66	197	2.3
1997	1,569	883	222	7.1	307	57	198	1.6
1998	1,528	828	218	7.0	285	55	201	1.4

Besides the bolt type, information was also obtained on the lengths of bolts installed. For the resin-grouted rebar lengths, 30% were under 4 ft, 47% were 4 ft, 13% were 5 ft, 8% were 6 ft, and 2% were >6 ft. The average bolt length for fully grouted rebar was 4.2 ft; for the mechanical anchor bolt, 4.1 ft; for the resin-assisted mechanical anchor bolt, 5 ft; and for the

torque-tension bolt, 5.4 ft. It seems that the torque-tension and resin-assisted mechanical anchor bolts systems may be used in more difficult roof conditions where an increased length is also required to control the roof. However, no data from other years are available for comparison.

ROOF BOLTS

The five main types of roof bolts used in U.S. coal mines can be classified by two criteria: (1) anchorage length and (2) whether the support is installed with pretension [Scott 1989; Peng 1998]. Both criteria affect how the support actually functions in supporting the rock. From an anchorage standpoint, the bolts are either point- or full-contact anchors. For a point-anchor system, the anchorage lengths are usually <2 ft and include the mechanical anchor and resin-assisted mechanical anchor bolt. With the full-contact supports like the fully grouted rebar system, most, if not all, of the support is in contact with the rock. Besides anchorage, the full-contact provides reinforcement through resistance to rock movement. The full-contact support includes the fully grouted and torque-tension bolts. Although the combination bolts are only partially grouted, the anchor section can be considered a full contact support.

The other criterion is whether the system is installed with tension and therefore applies an active force to the rock. The tensioned support systems include the mechanical anchor and point-anchor bolts, which rely to a large extent on the active forces developed from bolt tensioning to provide reinforcement to the roof. The fully grouted rebar bolt is a nontensioned system. Both the combination and torque-tension bolts are active supports, yet have a full-contact anchor along a portion of their length. Therefore, along the anchorage portion, these supports resist movement similar to fully grouted rebar, with an active component to clamp the roof similar to the point-anchor systems.

MECHANICAL ANCHOR BOLTS

At one time, mechanical anchor bolts were the main roof support used in the coal industry. One advantage of mechanical anchor bolts is quick installation (usually <10 sec). Today, however, the mechanical bolt has been to a large extent displaced by other support systems, primarily fully grouted rebar. Mechanical anchor bolts consist of a smooth headed bar with a threaded anchor end. A mechanical shell anchor attached to the threaded end of the bolt is used to anchor the system. As the bolt is torqued, the force drives a plug against the outer shell, which expands and is set with a radial force against the rock (figure 3). Once the anchor is set, the bolt is then tensioned. Bolt torque is required to set the anchor and provide an active force to the rock for reinforcement.

The tension can be up to the yield of the steel or the anchorage capacity of the system. However, the anchor must be able to support high bolt loads with minimal displacement. Therefore, the anchor is critical to the functioning and capacity of this system. In general, there are two types of mechanical shell anchors: a standard and a bail anchor [Karabin et al. 1976]. The standard anchor has fixed leaves and makes only point contact with the rock. Because of this point contact, this anchor is usually better in stronger rock. The bail or free leaf anchor allows for almost total shell contact along the borehole wall and is therefore usually better in softer rock. However, because of variations in design of the shell anchors,

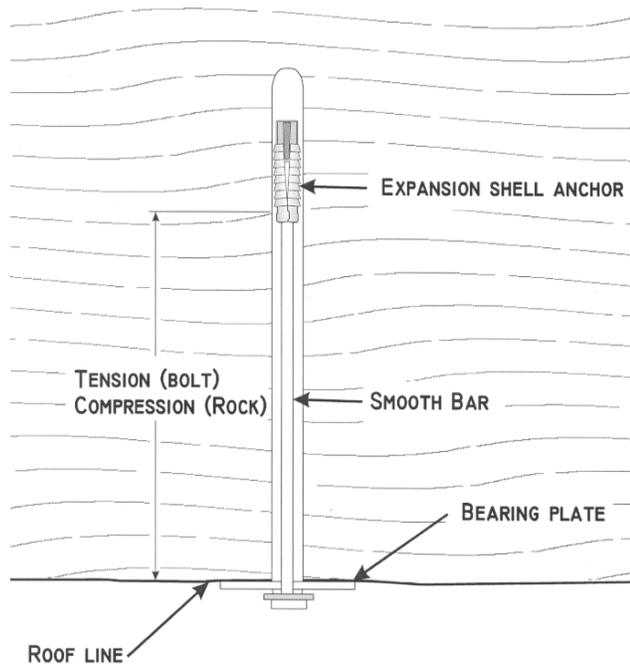


Figure 3.—Mechanical anchored bolt installed in roof.

underground testing is necessary to establish the best system for a particular rock.

Anchorage capacities up to 25,000 lb have been achieved, although the rock strength will always control the anchorage capacity. Therefore, the rock limits the amount of tension that can be applied by the mechanical anchor bolt and, in part, whether this load will be sustained or bleed off. Over time, the tension may be reduced because of creep or failure of the rock around the anchor and relaxation of the anchor threads. Therefore, the mechanical anchor bolt system has usually been installed in stronger roof rock or at least where the anchor is placed in a good-quality rock.

RESIN-ASSISTED MECHANICAL ANCHOR BOLT

Resin-assisted mechanical anchor bolts are essentially mechanical anchor bolts that have been transformed with the addition of a resin plug. Today, they are often called point-anchor bolts. These systems can be installed almost as fast as the mechanical anchor systems. Because they have greater anchor stability and less tension bleedoff than can be achieved with only the mechanical anchor, these bolts are used where ground control conditions are less favorable.

Although there are several varieties of resin-assisted mechanical anchor bolts, in general, the system consists of a headed bar (either deformed or smooth) with a threaded end for attachment of the mechanical shell anchor (figure 4). The mechanical anchor shells are designed with resin passages to allow for the flow of the resin around and below the anchor. The resin anchorage is usually established by a short cartridge

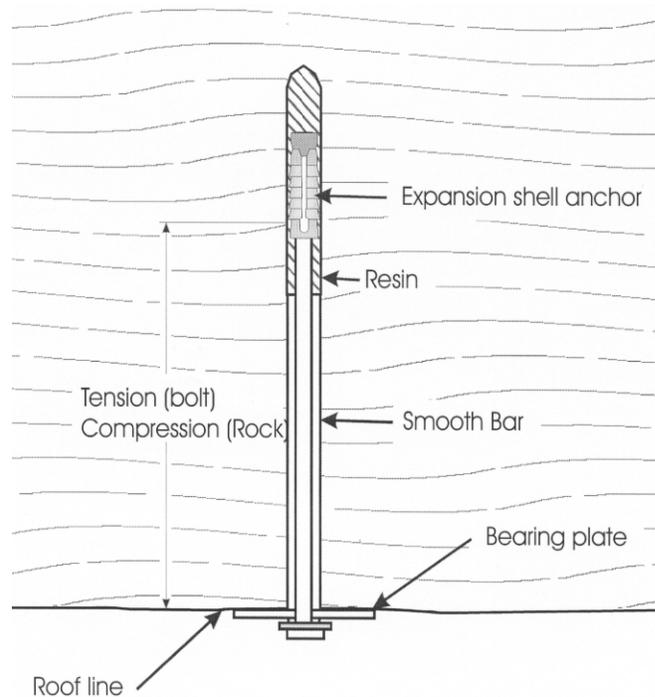


Figure 4.—Resin-assisted mechanism anchor bolt installed in roof.

of fast-setting resin with an anchor length of 1 to 2 ft. Mixing of the resin is achieved primarily by inserting the bolt and anchor through the cartridge. Compression washers and shells are also used with some systems to compress the resin and may result in improved anchorage [Stankus 1991]. The mechanical anchor allows for the immediate tensioning of the bolt, while the resin stabilizes the anchorage capacity. Often, the bolt tension is set at 70% or more of the yield of the bolts with torque loads up to 250 to 300 ft-lbf depending on the strength of the bolt. However, the amount of tension that can be applied is still limited by the rock strength. With the resin anchor, the tension bleedoff should be less than with a mechanical anchor system, although some bleedoff can still occur because of resin creep and anchor thread relaxation.

FULLY GROUTED REBAR BOLTS

The fully grouted bolt is now the main support used in U.S. coal mines, with about 80% of the market. The system consists of a headed rebar anchored with a full-length column of resin obtained from a cartridge (figure 5). The system is usually considered nontensioned, although plate loads of several thousand pounds may develop during installation [Karabin et al. 1976]. There are also special techniques that will allow for even higher installed loads [Tadolini et al. 1991]. The system works because of superior anchorage and stiffness that develops as a result of the full bolt length resin anchor. Pull tests show that it usually takes less than 2-ft length of a resin anchor to achieve

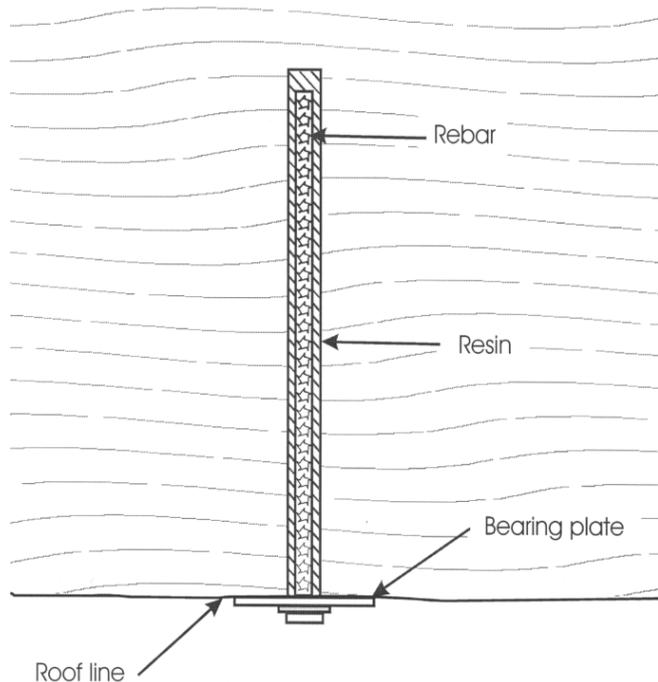


Figure 5.—Fully grouted resin rebar installed in roof.

the capacity of the support, although the "anchorage factor" depends on the rock strength and other installation parameters [Mark 2000]. The high stiffness is accomplished due to the full contact grout anchor and the ability of the resin grout annulus to quickly transfer the loads developed in the system back into the rock. Because of the superior bolt stiffness, significant resistance to the rock movement will be developed both axially and laterally. Loads developed along the bolt where roof separations occur will be quickly transferred back into the rock and the movement resisted and limited at these points.

Because the system works as a result of the load transfer that develops between the support and the rock, the annulus thickness of the resin grout, the distance between the bolt and the rock, is important to the proper installation and functioning of the system. The optimum system annulus as determined from experimental investigations was found to be about 0.125 in [Karabin 1976; Gerdeen et al. 1977]. Therefore, the optimum system for a 1-in hole is developed by using a 0.75-in-diam #6 rebar. Using an annulus smaller than 0.125 in has been limited by practical considerations, such as the thrust capacity of the bolter, the variation in the rebar diameters, and the potential resin loss [Campoli et al. 1999]. However, systems are now available that allow for only a 0.0625-in annulus that have overcome some of these problems, including controlling the rebar diameter [Tadolini 1998]. Testing has shown that effective load transfer and anchorage capacities can be achieved with this smaller annulus. Further, the installation forces, although higher with the smaller annulus, should be within the capacity of most roof bolt machines. There are two aspects to the performance of the system based on the resin annulus size, the bolt installation, and load transfer along the

bolt. Both will be impacted negatively by a larger annulus. Of the rebar systems, the #5 rebar installed in a 1-in-diam hole is by far the most widely used bolt. However, the annulus for this system is 0.1875 in, which is larger than the optimum annulus thickness.

Even though fully grouted bolts are a passive system, the bearing plates are a necessary part of the support system. Without a bearing plate, a fully grouted bolt can still function and resist rock movement. However, surface control is lost where the bearing plate is the first support element in controlling surface or skin failure. About 98% of all ground fall injuries are from the failure of the surface of the roof or rib, and the plate helps protect the workers from injury due to failure of the skin of the roof. Further, loads of over 20,000 lb have been measured at the bearing plates, which indicates that the plates can add significantly to the roof support [Tadolini et al. 1986]. The plate will help the bolt resist roof movement in the lower 2 ft of the roof and is therefore an important element in roof reinforcement.

TORQUE-TENSION BOLT

A torque-tension bolt is essentially a resin-grouted rebar system that is pretensioned on installation. This system consists of a rebar with a threaded end at the head of the bolt. A nut with a torque-delay mechanism is used to torque and tension the bolt, with a resin column used to anchor the bolt (figure 6). With a full-column anchor, two different speeds of resin are used. In the upper portion of the anchor, there is a fast-setting resin; in the lower portion, a slower setting resin. The bolt is inserted, then rotated in the resin, when the upper fast resin sets, a torque-delay mechanism on the nut breaks and the nut is rotated up against the plate, tensioning the system. The applied load is distributed over the lower portion of the bolt containing the slow-set resin. When the slower resin sets, the system will resist rock movement with the stiffness of a fully grouted bolt and will further reinforce the lower roof with an active clamping force. A variation of this system is to leave the lower portion of the bolt ungrouted. If the grout column is sufficiently long, this upper part of the system will reinforce the roof similar to a full-grouted rebar, with the lower portion of the roof reinforced by the clamping action of the applied force. However, the lower portion of the bolt will have much less stiffness than the full-grout column and therefore less resistance to rock movement. In general, the fully grouted torque-tension system combines both the active force of the resin-assisted mechanical anchor bolts and the superior anchorage and stiffness of the resin rebar systems.

COMBINATION BOLTS

A combination bolt consists of a rebar anchor usually 3 to 4 ft long connected with a coupler to a smooth headed bar (figure 7). The rebar section is anchored in the hole with a

resin cartridge. A shear pin in the coupler allows the resin to be mixed and set before the lower smooth headed bar is torqued and the system tensioned. Essentially, the rebar is a full-column resin bolt that provides an anchor for the system and provides reinforcement to the roof. With the tensioning of the lower section of the system, a clamping force is applied to the rock. These systems are often up to 8 ft long, and because the system consists of at least two components joined by coupler, a support system much longer than the seam height can be installed with relative ease. However, the weakness of the system is the coupler. Although the coupler is designed to withstand axial forces up to bolt failure, coupler failure can occur when there is sufficient lateral roof movement that causes coupler failure by shear.

RESIN

Grout anchors used with coal mine supports are commonly made with a polyester resin and packaged in a cartridge form. These systems can be either water- or oil-based. The trend today is toward water-based resins due to market forces. In the cartridge there are three components, but only two are active. These three components are the resin and the catalyst, which are active, and an inert filler (figure 8). Usually, the filler comprises between 65% to 75%, the resin 20% to 30%, and the catalyst 2% to 3% of the system [Eaton 1993]. However, in the United States some of the resin systems can have up to 85% filler. The resin consists of a polyester polymer solid with a liquid styrene monomer, while the catalyst is benzoyl peroxide. The filler is usually a limestone and acts not only to fill the

hole, but also to help form the mechanical interlock between the rock, bolt, and grout. The cartridge is formed with mylar packaging and is set up with two compartments to keep the resin and catalyst apart. The packaging is torn and the system mixed during insertion and rotation of the bolt during installation.

Two important functional parameters of the resins are the mix time and the set or gel time. The mix time is usually between 3 to 10 sec and is limited by the gel point. However,

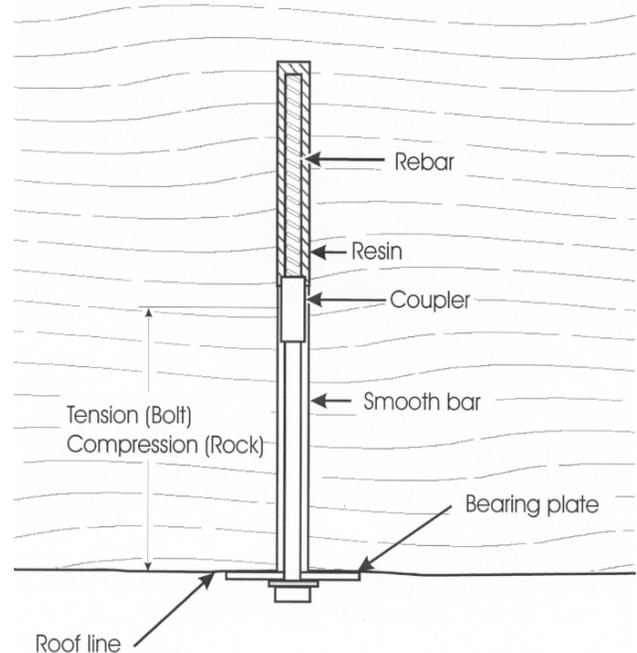


Figure 7.—Combination bolt installed in roof.

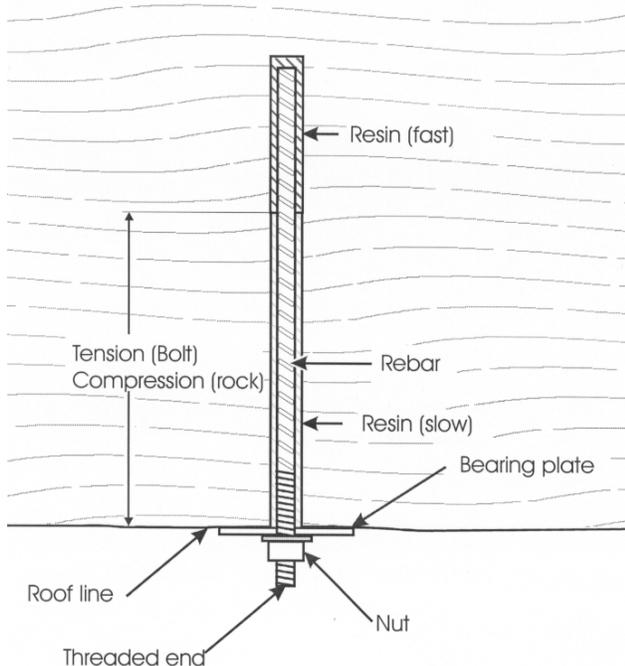


Figure 6.—Torque-tensioned bolt installed in roof.

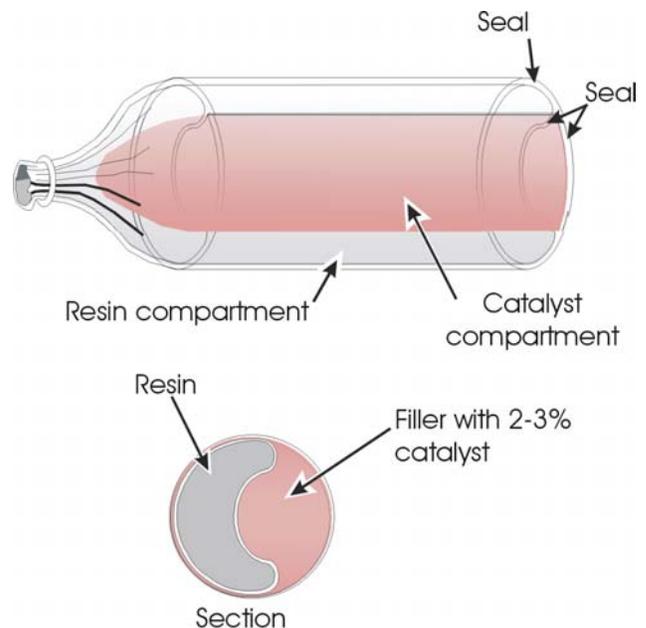


Figure 8.—Resin cartridge used to develop anchorage for roof bolts.

proper mixing of the resin is based on a certain number of rotations of the bolt that will occur during installation prior to the gel point of the resin. The gel time is controlled by inhibitors added to the resin and is the time required for the resin catalyst to change from a liquid to a solid; it will usually vary from 5 sec to 1 hr or more. The gel time must be long enough to allow for the installation of the support, but it is affected by the rock, bolt, and resin cartridge temperature. The resin systems come with manufacturer-recommended installation procedures, which, if not followed properly, could result in a substandard anchor. Also, the annulus thickness will affect how well the resin is mixed and therefore the anchor performance.

Strength and stiffness of the resin may affect the performance of the anchor system. A higher elastic modulus will allow for more efficient load transfer, while the higher strength will allow load transfer to take place over a more extended range of bolt

load. The U.K. mining industry uses resins with strengths of about 11,600 psi and an elastic modulus of 1.6 million psi. These resins are designed to maximize anchor performance. In the United Kingdom, it is believed that a resin grout should be as strong as the strata that are being supported. In the United States, lower strength resins are used, normally with a strength of about 5,000 psi. With these weaker and less stiff grouts, load transfer may not be as effective and the grouts can fail sooner, resulting in less overall load transfer. However, it is uncertain whether stronger, stiffer resins would have a significant impact on roof conditions in most mining situations. In many cases, the resins used in U.S. coal mines are developing adequate anchorage for load transfer and are able to withstand strata movement and failure. The American Society for Testing and Materials (ASTM) has also developed standards for resin testing, including strength and mix time [ASTM 1998].

#5 VERSUS #6 REBAR IN A 1-IN-DIAMETER HOLE

The optimum annulus thickness based on experimental evidence and practical considerations has been found to be 0.125 in [Karabin et al. 1976; Geredeen 1977; Campoli 1999]. In a 1-in hole, this annulus is achieved with a #6 rebar. However the annulus thickness for a #5 rebar is 0.1875 in, and there is 30% less steel in the hole with this system. How and to what degree the increase in annulus and decrease in steel affects the performance of the system merits attention, especially since the #5 rebar represents about 65% of support installed.

One way to compensate for the decrease in bolt diameter is to increase the strength of the steel used for the #5 rebar. For many mines, the grade 60 #5 rebar replaced a grade 40 #6 rebar. Therefore, for the grade 60 #5 rebar the minimum yield load is 18,600 lbf compared to a grade 40 #6 rebar of 17,600 lbf. Essentially, both systems have about the same yield load. This increase in strength is accompanied by a loss of ductility in the steel. The elongation of the grade 60 rebar is 9% at failure and for the grade 40 rebar 12%. Further, the ultimate load for the #5 grade 60 rebar is 27,900 lbf, while the #6 grade 40 rebar is 30,800 lbf. The decrease in elongation and ultimate load results in a significant loss of toughness or the ability of the #5 rebar to absorb energy. Higher steel strengths such as grade 75, 90, and 100 are now used, while alloys can increase the elongation range of the steel. However, the general problem of replacing the bolt diameter with higher strength steels is still the loss of elongation and therefore toughness of the system.

Both axial and lateral stiffness of the system is affected by the annulus thickness. In tests conducted on 2-ft-long fully grouted bolts in a 1-in-hole, the axial stiffness for the #5 rebar was 142,000 lbf/in and for the #6 rebar 275,000 lbf/in [Bartels et al. 1985]. In testing these systems in shear (across the bolt axis), the shear stiffness for the #5 rebar was 30,200 lbf/in and for the #6 rebar 131,000 lbf/in. The results of these tests show

a significant decrease in the stiffness both axially and laterally of the #5 rebar system. The fully grouted bolt relies on the system stiffness to resist rock movement both axially and laterally. Therefore, a decrease in stiffness should impact the support's ability to provide roof reinforcement.

With the larger annulus, more installation problems could be expected mainly in the form of increased glove fingering. To prevent this from occurring, extra care may be required to ensure that the manufacturer's recommendations on spin and rotation are followed during installation. Glove fingering will affect the bond between the grout and the rock developed by mechanical interlock and therefore the load transfer between the support and the rock. Further, glove fingering will often occur at the end of the bolt; thus, the anchorage capacity will be reduced along a critical portion of the support system. Essentially, the effective length of the support is reduced because of inadequate anchorage at the end of the bolt. Unfortunately, a pull test on a full-column grouted bolt will not normally reveal this condition.

In many situations, the #5 rebar system seems to be an effective support. However, some situations may require the increased stiffness and load transfer of the more optimum #6 rebar system. Also, the effects of inadequate installation resulting from the larger annulus have not been documented. To date, as far as the authors know, there is no published information on a direct comparison of the two systems in an underground setting or even on any extensive laboratory studies of the #5 rebar system. Therefore, the performance of the #5 rebar system needs to be evaluated in detail to determine if there is any reduction in reinforcement capabilities over those of the more optimum #6 rebar in a 1-in-diam hole. This is especially important since the #5 system is by far the most widely used support system in U.S. coal mines.

SUMMARY AND CONCLUSIONS

Today, there are five main types of roof bolts used in U.S. coal mines: fully grouted resin rebar, mechanical anchor bolts, resin-assisted mechanical anchor bolts, torque-tension bolts, and combination bolts. The trends in bolt usage indicate that the fully grouted rebar is the most widely used support, representing nearly 80% of the market. Essentially, the fully grouted rebar has replaced the mechanical anchor bolt where mechanical anchor bolts are about 8% of the market. The fully grouted bolt system is generally regarded as a superior reinforcement system compared to the mechanical anchor bolt, and there are a number of documented cases where a change from the mechanical anchor to the fully grouted bolt has increased roof stability at individual mines. However, the trend away from the mechanical anchor bolt to the fully grouted bolt has not resulted in any noticeable change in the rate of reportable roof falls in U.S. coal mines. It is possible that the fully grouted bolt has allowed for mining under more difficult roof conditions, or roof conditions in general have become less favorable in the overall mine population. Under such conditions, a higher roof fall rate would be expected where the use

of the fully grouted bolt has actually offset this increase. However, such a change in the overall roof conditions, if it has occurred, might be difficult to document and prove. Further, there may be other reasons besides improved roof stability to change bolting systems, such as the different requirements to check the quality of the installation of each system. The torque-tension checks are more demanding for the mechanical anchor bolt than the installation checks for a fully grouted bolt.

For the fully grouted bolt, the #5 rebar is the most widely used and comprises nearly 65% of all support installed. However, this is not an optimum system when compared to a #6 rebar in a 1-in hole. Further, the strength and stiffness of resins used by the U.S. industry are generally less than those used in the United Kingdom and Australia. Therefore, how the #5 rebar and the property of the resins have impacted roof support performance is certainly open to discussion and further evaluation based on the reportable roof fall data. However, the selection of a specific bolt system to reinforce the roof is only one aspect of the design of primary roof support systems, although an important aspect for roof control.

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