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Rock Reinforcement Longevity

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ABSTRACT

Rock reinforcement has been in widespread use and generally has been accepted in underground mining and tunneling since the 1950s. The first rock reinforcement technologies employed were mechanical anchors such as split wedges or expansion shells with ⅝-inch-diameter steel bolts. Failures occurred in weak strata which provided poor anchorage or in ground with corrosive waters. Friction rock fixtures consisting of relatively thin-walled tubes have been in use for about 15 to 20 years. While generally performing adequately, longevity problems have developed from corrosion in water bearing ground. Longevity of rock reinforcement is much enhanced with grouted bolts. Portland-cement-grouted rock reinforcement has been in use since the mid-1950s, primarily in tunneling and other civil engineering underground construction. Tests of decades-old installations have revealed few problems except in ground with aggressive waters. Polyester-resin-grouted rock reinforcement was introduced in the United States to mining in the late 1960s and to tunneling in the early 1970s. Experience from 30 years of resin-grouted bolt installations and field tests have identified longevity problems associated with degradation of steel reinforcing bars, but in generally unusual situations. Improvements continue in resin chemistries, packaging, corrosion protection, grout quantities, and mixing and distribution in the drilled hole to achieve long-term performance. Specific case histories cited with resin- or Portland-cement-grouted rock reinforcement longevity or performance problems, upon close examination, reveal that the causes of the problems were quality control procedures being inadequate and not in accordance with good practice. Manufacturers' recommendations and engineering specifications, if followed in the field, and with competent inspection and supervision, would have prevented most, if not all, reported longevity or performance difficulties.

INTRODUCTION

Rock reinforcement, having only a history of performance measured in decades, relying upon natural systems for its functioning, and not subject to easy inspection, is often questioned as to its longevity in engineering design. In order to perform its function, rock reinforcement must maintain the ability to reinforce the rock mass through one of several mechanisms such as supporting the weight of loose rock, beam clamping in laminated strata, maintaining an arch or zone of fractured rock in which shear displacements are prevented, or keying-in critically located rock blocks, amongst others. The elements of a typical rock reinforcement fixture include some or all of the following (from inside of the hole out):

- Anchoring device
- Grouting material
- Bar or tube
- Plate
- Head bolt

The anchoring device today is a mechanical expansion shell, which expands as the threaded bar stock is rotated inside an expansion nut inside the expansion shell, causing its sides to expand radially outwards and grip the rock of the drilled hole sides. To obtain a sufficient anchor, the expansion shell must push out into the rock, usually damaging or deforming the rock. As a consequence, the rock creeps or slowly fractures, leading to loss of anchor. If not retorqued, the bolt becomes minimally effective. This loss of anchorage is time-dependent and dependent as well on the type of rock, with shales leading to quick loss of anchorage. To maintain the proper anchorage with time, retorqueing is necessary. This author often explains to clients with little familiarity with rock reinforcement technology that a mechanical-anchor rockbolt is a *machine*, and machines require *maintenance*.

Bolt heads can be sheared off by passing equipment, or they can be broken off by excess stress in the bar and bolt head. Indeed, this author, as a young miner trainee assigned to rebolting, scaling, and rockbolt tightening in a 65-ft-high stope zinc mine often heard the loud pops of bolt heads flying off at high speed and ricocheting around the stopes.

The plate, whether steel (popular in non-coal mines and tunnels) or steel and wood (popular in coal mines), serves to distribute the load at the bolt head and helps transfer the force into the surface rock at the skin of the opening. Its loss or failure can lead to increased falling out of rock between bolts.

While all of the elements above are critical to successful long-term rock reinforcement, the bar or tube and grout material are perhaps the most important in today's rock reinforcement applications.

The bar or tube is subject to corrosion because it is usually manufactured of steel. Though for aggressively corrosive environments, stainless steel fixtures are available, as are fiberglass and plastics, which, while also inert, can be mined or cut through without damaging mining equipment—a useful property in many applications.

The grout material is either Portland cement, or polyester, vinyl or amine resin, all of which are very inert in most rock mass environments.

Cured Portland cement grout is not subject to significant time-dependent creep under load, and resins are designed by their manufacturers for very low creep potential of about 4.5% (Avery[1] 1988).

Corrosion, then, is the chief consideration in rock reinforcement longevity.

Mechanical expansion-shell anchor rock reinforcement is less expensive than Portland cement or resin-grouted rock reinforcement, and is often preferred by users on this basis alone. However, the tendency for loosening and torque bleed-off in many rock formations, may make them less desirable for long-term installations.

Portland-cement grouting is slow and time-consuming, and is not readily compatible with high-speed mine development or tunneling. It is popular in civil engineering applications where great security of the structure is desired, and time and money are available for the more complex installation procedure.

Resin-grouted reinforcement installation has been automated by equipment manufacturers so that the drilling and bolting machine drills the hole, injects the packages, and inserts and rotates the bar in a nearly continuous operation.

Relatively up-to-date design texts on rock engineering such as Hoek, Kaiser, and Bawden[2] (1995) question the longevity of resin-grouted rock reinforcement with statement such as "However, where very long service life is required, current wisdom suggests that [Portland] cement grouted bolts may provide better long term protection."

What is the basis for such a statement?

CORROSION

Mechanical-anchor non-grouted rockbolts or rock reinforcement have been known to corrode in aggressive or even non-aggressive ground-water environments. They are fabricated from steel with no corrosion protection unless special-ordered. Steel rusts when in contact with oxygen and water. Corrosion of steel in the ground is due to electrochemical loss of metal ions at anodic points or areas, in which oxygen available in the water combines with the iron in the steel to form ferrous hydroxide, Fe(OH)2 (Smith[3] 1924, Uhlig[4] 1948, Romanoff[5] 1957). Dissolved oxygen resulting from recently infiltrating surface waters, or from waters near the surface of the rock excavation, also acts in a similar fashion.

The U. S. Bureau of Standards (Romanoff[5] 1957) has developed an empirical relationship for calculating pitting corrosion rates for steel in soils of various types

$$P = kT^n$$

where P = pit depth in 0.001-inch units
k = 28.8 for open-hearth low-alloy steels
n = 0.58 for open-hearth low-alloy steels
T = time in years

which can be rearranged to

$$T = (P/k)^{(1/n)}$$

to allow calculation of an estimated lifetime of steel in a corrosive environment. For example, a steel shank for a mechanical expansion-shell rockbolt may be 0.625 inches (⅝ inch) in diameter or 0.3125 inches half-diameter, and could be expected to survive

$$(312.5/28.8)^{(1/0.58)} = 61 \text{ years}$$

in a typical environment. There have been no reports of expansion shells, themselves, failing by corrosion, only bolt shanks. For a Split Set™ or Swellex™ type of rock reinforcement with a steel tube wall thickness of, say, 0.10 inches, the lifetime can be estimated at 2.6 to 5.2 years, respectively. Of course, this calculation is for the entire steel section to corrode through, and it is likely that effective failure would occur much earlier.

However, more aggressive waters have led to much shorter lifetimes for rockbolts in many instances. Caverson and Parker[6] (1971) and Parker[7] (1979) at the White Pine Copper Mine in the Upper Peninsula of Michigan reported expansion-shell rockbolts corroding and failing in less than 5 years inside the bolt hole with no exterior evidence other than rust. E/MJ[8] (1972) and Sergmon[9] (1979) reported at the Globe Refractories Clay Mine in West Virginia that similar bolts lasted only 5 years.

When Split Set™ or Swellex™ type of rock reinforcement were introduced in the early 1970s and 1980s several researchers investigated the corrosion potential for these thin-walled steel tubes. For Split Set™ fixtures, Tilman, Jolly, and Neumeier[10] (1985) and Jolly and Neumeier[11] (1987) reported the corrosion potential using waters from lead, iron, and coal mines for both galvanized and ungalvanized units, with the lead and iron mine waters attacking galvanized and ungalvanized units alike. However, the manufacturers have recognized that, while often easier to install and more economical than grouted rock reinforcement, these fixtures need corrosion protection in some environments and now market corrosion-protected models (Stillborg[12] 1986, Woof[13] 1999).

In the short term, however, Stimpson[14] (1998) has reported that corrosion initially *improves by over 100%* the pull-out strength of Split Set™ fixtures in laboratory tests in concrete due to improved bonding, but concludes that in the long term, pull-out strength can only decrease with continued corrosion.

Rock reinforcement fixture elements can all be made of stainless steel, as mentioned above, or can be galvanized or epoxy-coated for greater corrosion protection. If long-term performance is desired, exposed rock reinforcement fixture elements not encased in grout should be protected by coatings if in an environment subject to corrosion.

GROUT DISTRIBUTION

In Portland-cement-grouted rock reinforcement, the grout, consisting of the cement and water, often with additives or extenders (such as fly ash), is pumped into the annulus between the bar and the drilled hole using either a central hole in the bar as the grout intake or air vent, or a plastic tube alongside the bar for either purpose. If the installation is vertically down or inclined down, the grout may be poured in the annulus.

In resin-grouted rock reinforcement, the resin is in two components in a frangible Mylar plastic package sized to fit the hole diameter. The package has two components—the resin and a setting catalyst—separated by either a plastic barrier or a thin zone of set-up resin at the interface of the resin and catalyst. When the package is broken by inserting the rock reinforcement bar through it and rotating the bar, the resin and catalyst are mixed and the resin set begins. The time of setting can be engineered by the manufacturer. The resin is not an adhesive or glue, but a filler. It develops the strength of the bar and rock by filling in irregularities in the drilled hole and bar deformations. Because of the cost of the resin, and the undesirability and mess of excess resin leaving the hole, the manufacturers all specify

- Hole diameters appropriate to the bar diameters,
- Maximum drilling depths for holes, and
- Number and size of packages for the bar diameter and length

so as to achieve full grout distribution and encapsulation of the bar and anchor (if any). Too little resin means an incomplete bar grouting and anchorage; too much resin means spillage and waste. (The very first resins sold for this use were not packaged for insertion in a drill hole, and had to be mixed with their catalysts in a container and then quickly placed in the hole in some way. This author was part of a team investigating the use of this resin reinforcement as a junior engineer in 1971 or 1972, and still has some of it on his hard hat.)

In either Portland-cement-grouted reinforcement or resin-grouted reinforcement, if the manufacturer's instructions or engineer's specifications are not followed, and quality control is not adhered to, then the grout will not be properly or fully distributed around the bar or in the hole. This will minimize the bar anchorage in the ground, and also expose the bar to corrosion.

Water-filled or -flowing drill holes pose special problems. The water can displace the resin in the annulus between the bar and the drill hole wall, leading to under-grouting. Avery[1] (1988) provided guidelines for improving installation in water environments, which included:

- Abandon the water hole and drill another next to it,
- Use the smallest hole diameter practicable to maximize the resin distribution,
- Fill the entire hole with resin cartridges to force resin into water conduits and provide an abundance of resin for encapsulating the bar, or
- Pre-grout the rock mass to minimize water flow.

Resin-grouted rock reinforcement has been installed in submerged conditions and performed well. Avery[1] (1988) presented pull-strength tests of very short (1-ft-long) bars and longer (2-ft) bars installed under water wherein the short bars were under-grouted, but the longer resin-grouted bars developed the strength of the steel bar, even though the upper (closer to collar) 1-ft length of grout was only partial and under-grouted.

CASE HISTORIES

In the early to mid-1960s, when rock reinforcement began to be incorporated as a structural member as part of the permanent support of underground openings for civil engineering purposes, the corrosion problem was recognized and rock reinforcement was supplemented with Portland cement full-column grouting for corrosion protection (Pender, Hocking, and Mattner[15] 1963, Underwood and DiStefano[16] 1964, and Széchy[17] 1966).

In a significant study in the Yxhult Mineral AB's Centralgruvan Mine in Sweden, Helfrich[18] (1990) overcored different types of rock reinforcement installations in a corrosive underground environment with the following results shown in Table 1.

Helfrich[18] (1990) concluded that grouting helps performance, but that grouting effectiveness in terms of degree of encapsulation and grout distribution varied greatly, especially in Portland-cement-grouted installations. As reported by Helfrich[18] (1990), the mine rooms in which the observations were made had been continually monitored for convergence and no deleterious

Table 1 Rock Reinforcement Longevity Results of Helfrich[18] (1990)

Type	Age (years)	Results
Ungrouted expansion-shell	16	General corrosion
Swellex™	7	Severely corroded, lost anchorage
Portland-cement-grouted	20	General to severe corrosion
Resin-grouted	16	Local to thin films of rust

movements had apparently been observed. He speculates that once the rock reinforcement had done its initial task of stabilizing the rock, the rock mass maintained its stability even with corroded and lower-strength rock reinforcement.

In a study of longevity of resin-grouted bolt anchorages in a U. S. coal mine environment, Wuest and Stateham[19] (1991) reported no significant pull-out strength differences for 48-inch long bolts with 18, 24, and 48 inches of grouted length for tests extending to 37 months after installation.

In the White Pine Copper Mine, mentioned above, the ground water is saline leading to the corrosion problems. After switching to resin-grouted rock reinforcement, rare problems still occurred (Litsenberger[20] 2000) when fractures in the rock intersected and fractured the resin-grout column, and exposed the bar to corrosion. A few roof falls had such bars showing.

Baxter[21] (1996) reported that in the Eucumbene—Snowy Tunnel in Australia spalling of the rock mass occurred 10 years after construction and 3 years into service where falls were large enough to bring down Portland-cement-grouted rockbolts, which showed no evidence of corrosion on grouted sections, but unprotected and exposed sections were corroded. In some areas, the rock had fallen out between bolts, but bolts remained anchored and uncorroded.

Baxter[21] (1996) also reports that in underground caverns of the Hydro-Electric Commission in Tasmania, Portland-cement-grouted rockbolts were inspected by removing the plates and found to be sound.

In an 1896 Bondi Sewer in Australia, Baxter[21] (1996) reported that Portland-cement-grouted steel (apparently) bars used to support formwork for the tunnel were found to be severely corroded for the portion in air, ". . . but within 10 mm of the rock surface, the dowel was in perfect condition."

Baxter[22] (1998) reported that in Canada, resin-grouted rock reinforcement failed after 3 months' service in Ontario Hydro's Niagara River Hydroelectric Development exploratory adit, and it was found that the "fully grouted" bolt exhibited only 25% of the length grouted.

In Sweden's Vatterfall Hydroelectric Plant, Baxter[22] (1998) reported that Portland-cement-grouted rock reinforcement with no corrosion protection ". . . have been used since 1958. Inspections have shown only minor rock falls due to malfunctioning bolts."

Avery[1] (1988) reported that the U. S. Army Corps of Engineers experienced resin-grouted anchor problems at the Monongahela River Lock and Dam 3 (Krysa[23] 1982) when flowing water in bolt holes led to the resin grout entering the water conduits and under-grouting the bar.

Avery[1] (1988) also reported low anchorage strengths for resin-grouted bars at the Bonneville Navigation Lock near Portland, Oregon. Drilled holes were not blown out or flushed after drilling, and the drill cuttings and drilling water left a mud coating in the hole. When installing the resin-grouted reinforcement, it was realized that the resin was being mixed in a hole lined with mud.

Thompson and Martin[24] (1984) reported the failure of a retaining wall constructed in shale with tensioned Portland-cement-grouted rock anchor tie-backs. The wall had been in service for 7 years when it failed. Their investigation revealed several earlier tie-back failures and final tie-back failures during the collapse. While the protruding unprotected portions of the tie-back bars were all corroded severely, failure causation was assigned to overloading of the tie-backs due to the initial method of construction and over-stressing of the stressing end of the tie-backs at the wall.

Baxter[21] (1996) suggested that, like Helfrich[18] (1990), rock reinforcement may not be a permanent necessity in maintaining a stable rock mass. Once the rock reinforcement has made its contribution to stabilizing the rock mass early in the excavation and construction process, the rock mass reaches a new equilibrium of its own, regardless of the rock reinforcement's functioning.

It is this author's experience, and that of others interviewed for this publication, that most resin-grouted rock reinforcement failures are the result of incomplete encapsulation of the bar by the resin due to difficulties in installation or from lack of adherence to manufacturer's recommendations or the specifications. Particularly important are limiting hole depth so that the resin does not get pushed into the empty hole end and become unavailable for grouting the bar, and in being careful about hole diameters.

CONCLUSIONS

Baxter[21] (1996) states a few rather forceful conclusions:

> The inevitable defects and unpredictable integrity of grouts (cement and resin) lead to corrosion.
>
> The many mechanisms of corrosion possible indicate that bolts will eventually rust, the timing of which is dependent on the corrosion protection measures adopted.

> Based on overseas standards and practices for rock anchorages—there being no standards for rockbolts—the minimum corrosion protection required for a long design life (> 50 years) is one physical barrier e.g. galvanizing or epoxy coating. A double corrosion protection system will assure a longer design life (100 years) e.g. a sheath where the internal grout acts as the second physical barrier. Grout that bonds to the rock is not acceptable as a physical barrier because of the inevitable defects.
>
> Galvanizing is not recommended because of its sacrificial nature, possible effect on bond, and vulnerability to damage.
>
> Problems with resin anchoring appear to be widespread.

Baxter's last sentence of this quotation is not further detailed or justified in his paper.

Baxter[22] (1998) adds:

> Quality control of resin anchored bolts is difficult in large permanent installations.
>
> Corrosion rates for rockbolts cannot be precisely predicted.
>
> Long resin-anchored bolts should not be used as primary support in large permanent excavations.
>
> Resin anchored bolts should not be longer than 3m.

The quotes of Baxter[21, 22] (1996, 1998), above, and of Hoek, Kaiser, and Bawden[2] (1995), earlier in this text, preferring Portland-cement grout over resin grout were apparently based on the more limited, at that time, experience with resin grouts. If the resin grout is installed with the same care and attention to proper procedures as is usual with the slower and more time and labor intensive Portland-cement grout, the two systems would afford equal longevity.

This survey, interviews, and author's experience lead to the conclusions that unprotected mechanical-anchor rock reinforcement and Split Set™ or Swellex™ type reinforcement have limited lifetimes in most water-bearing rock mass environments. However, if longevity is not a consideration, then there is no potential stability problem. These types of reinforcement are all available in corrosion-protected models at greater cost. Typical ground-water environment corrosion rate estimates for unprotected units indicate a few decades of longevity for expansion-shell anchor bolts, and a few years of longevity for Split Set™ or Swellex™ type reinforcement.

Portland-cement- and resin-grouted reinforcement have many decades of longevity if installation is carefully controlled and the grout fully encapsulates the bar. Exposed fixture elements such as bolt lengths extending from the drill hole, bolt heads, and plates can corrode and fail sooner if not protected. Competent inspection and supervision at the time of installation is very important if longevity is desired of the rock reinforcement system.

In most mine and tunnel situations, if longevity of already-installed rock reinforcement systems is questioned or suspected, coring out and examining some installations will reveal their condition. It may be more economical to simply rebolt an area every few decades where long-term performance is desired, thereby "resetting the clock."

The case histories of difficulties with resin-grouted rock reinforcement can each be assigned to specific problems, which, once recognized, can be readily overcome, leading to successful long-term performances.

The best long-term performance for Portland-cement- and resin-grouted installations can be provided by a "double barrier" of epoxy-coated bars and full encapsulation with Portland cement or resin.

It is still premature to consider that the rock reinforcement may not have a functional use after the rock mass has stabilized and found a new equilibrium of its own as speculated by Helfrich[18] (1990) and Baxter[21] (1996). The rock reinforcement will certainly help keep the rock mass exposed surface from raveling and progressively deteriorating if no other liner or supports are in place and functional.

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REFERENCES

1. Avery, T. S., "Performance of Polyester Resin Grouted Rockbolts," *Developments in Geotechnical Engineering*, Central Pennsylvania Section, American Society of Civil Engineers, September 7–8, 1988, Hershey, PA, 1988, 21 p.
2. Hoek, E., Kaiser, P. K., and Bawden, W. F., *Support of Underground Excavations in Hard Rock*, A. A. Balkema, Rotterdam, 1995, 215 p.
3. Smith, M. B., "Corrosion," *Mechanical Engineers Handbook*, McGraw-Hill Book Company, New York, 1924, p. 587–598.

4. Uhlig, H. H., "Corrosion in Liquid Media, Atmosphere, Gases," *The Corrosion Handbook*, John Wiley & Sons, Inc., New York, 1948, p. 124–133.
5. Romanoff, M., "Underground Corrosion," National Bureau of Standards *Circular 579*, 1957, 227 p.
6. Caverson, B. and Parker, J., "Roof Bolts Hold Best with Resin," *Mining Engineering*, 1971, May.
7. Parker, J., Personal Communication, 1979.
8. Engineering and Mining Journal (E/MJ), "Clay Mine Switches Rather than Fight," 1972, June.
9. Sergmon, W., Personal Communication, 1979.
10. Tilman, M. M., Jolly, A. F. III and Neumeier, L.A., "Corrosion of Roof Bolt Steels in Missouri Lead and Iron Mine Waters," U. S. Bureau of Mines *Information Circular 9055*, Washington, DC, 1985, 9 p.
11. Jolly, A. F. III and Neumeier, L. A., "Corrosion of Friction Rock Stabilizer Steels in Underground Coal Mine Waters," U. S. Bureau of Mines *Information Circular 9159*, Washington, DC, 1987, 14 p.
12. Stillborg, B., *Professional Users Handbook for Rock Bolting*, Clausthal-Zellerfeld, Germany, Trans Tech Publications, 1986, 145 p.
13. Woof, M., "Reinforcement Rodeo," *World Mining Equipment*, v. 23, n. 5, 1999, p. 49.
14. Stimpson, B, "Split Set Friction Stabilizers: An Experimental Study of Strength Distribution and the Effect of Corrosion," *Canadian Geotechnical Journal*, v. 35, 1998, p. 678–683.
15. Pender, E. B., Hocking, A. D. and Mattner, R. H., "Grouted Rock Bolts for Permanent Support of Major Underground Works," *Journal of the Institution of Engineers*, Australia, v. 135, n. 7-8, 1963, p. 129–150.
16. Underwood, L. B. and DiStefano, C. J.,"Development of a Rock Bolt System for Permanent Support at NORAD," *Proceedings of the 6th Symposium on Rock Mechanics*, 1964, p. 43–85.
17. Széchy, Károly, *The Art of Tunnelling*, Budapest, Hungary, Akadómiai Kiadó, 1966, 891 p.
18. Helfrich, H. K.,"The Durability of Rock Bolts," *World Mining Equipment*, April 1990, p. 19–22.
19. Wuest, W. J. and Stateham, R. M.,"Time Effects on Resin-Grouted Bolt Anchorage Characteristics," U. S. Bureau of Mines *Report of Investigations 9388*, Washington, DC, 1991, 11 p.
20. Litsenberger, J. A., Personal Communication, 2000.
21. Baxter, D. A.,"Do All Rockbolts Rust? Can Q.A. Help? But Does It Matter?" *IX Australian Tunnelling Conference*, Sydney, Institution of Engineers, Australia, 1996, p. 175–189.
22. Baxter, D. A.,"Rock Solid," *International Water Power & Dam Construction*, v. 50, n. 11, 1998, p. 38.
23. Krysa, A.,"Experience and Problems in the Pittsburgh District Installing Rock Anchors at Lock 3, Monongahela River," *Concrete Structures Repair and Rehabilitation*, U. S. Army Corps of Engineers, v. C-82-1, 1982.
24. Thompson, B. L. and Martin, D. C.,"Catastrophic Failure of a Tied Back Wall on the Interstate in Charleston, West Virginia," *Proceedings of the 25th Symposium on Rock Mechanics*, New York, Society of Mining Engineers of AIME, 1984, p. 914–929.