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Long-term monitoring of electrically connected rockbolts in different corrosive environments

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Abstract

Corrosion of metallic ground support can vary widely within different areas of a single mine depending on the local environment or geology. Steel mesh often runs continuously in long stretches within mine access drifts and tunnels, potentially electrically connecting areas of higher to lower corrosion. The National Institute for Occupational Safety and Health (NIOSH) investigated whether corrosion levels may be locally heightened from current flowing between ground support with different electrical potentials in their respective areas. Rockbolts placed in dissimilar laboratory environments were electrically linked to each other and monitored for current flow, thickness, and weight loss against control samples. Within these tests, 2 isolation methods – resin and phenolic plates – were evaluated to observe their effect on the current flow and corrosion rates. Rockbolts had an initially higher corrosion rate when linked to a differing environment without grouting and/or phenolic plate isolation methods before the reactions reached their stable passivated rates. The current flow for environment pairings with one or both isolation types had a lower cumulative current over time, supporting their efficacy. Investigating methods to limit corrosion rates is necessary to boost safety and understanding of the longer-term structural integrity of ground support in corrosive mine environments.

Keywords: *corrosion, ground support, electrical monitoring, electrical isolation, support degradation*

1 Introduction

Although corrosion is a quickly growing topic within the mining industry, there is still much research required to fully understand its impact. There are large disparities between mining and other industries with respect to corrosion inspection, maintenance, and mitigation practices. Corrosion of ground support is costly and can have dangerous consequences for mine safety for both personnel and infrastructure. Upon installation, steel rockbolts are expected to perform at their design-bearing capacity, which can decrease significantly from corrosion (Dorion & Hadjigeorgiou 2019).

Corrosivity classification methods for the mining industry are continuing to be developed; however, many contributing parameters are currently overlooked. Some atmospheric measurements, groundwater analysis, and visual rock mass observations are typically included in inspections established by Hassell (2008). This study explores the impact that electrochemical properties of the rock mass and electrolyte may have on the resulting corrosion of metal ground support.

For corrosion to occur, 4 elements are required:

- Anodic site
- Cathodic site
- Electron path (metallic connection)
- Ionic path (electrolyte).

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When one of these factors is removed, the reaction is terminated (AMPP n.d.). The anodic and cathodic sites can be areas of a different potential located on a single metal object, as well as that object being the electron path. Specific to mining, the electrolyte can be humid air or condensing moisture for atmospheric corrosion or liquid/moisture within the rock mass for other types of corrosion (Rafiquel Islam 2023).

Often overlooked, the composition and electrochemical properties of the rock mass may also contribute to the corrosivity within a mine. Depending on the geology of the rock, it may be a low resistivity electron path or potentially form a galvanic couple between itself and the metal support (Stazick et al. 2023).

The extensive use of metal mesh materials in mines for secondary support also provides a way for electrons to flow in the mining environment. Without interruptions to the mesh, long stretches of rock and bolts are electrically connected because of their contact (British Standards Institution 2006). Humid air in the mine or moisture in the rock mass can both serve as an electrolyte for corrosion reactions to occur (Zhang 2011). This would indicate that metal ground support in some areas of the mine with very low corrosion could be connected to other metal ground support in zones of extreme corrosion, producing an opportunity for a galvanic coupling. Corroded steel can form a galvanic couple with non-corroded steel when in electrical contact and exposed to an electrolyte because of their potential difference.

Grouted bolts are one method of isolating a large surface area of a rockbolt from a galvanically active rock mass. This involves a steel bolt being secured in place by grout that is injected into a hole, bonding them together (Chen et al. 2020). Although this process reduces interactions between the steel and the corrosive environment, the contact between the bolt plate, mesh, and rock mass provides an electron path for corrosion reactions. In addition, ground movement induced by further mining can fracture the grout column and expose the steel rockbolt to a potentially corrosive environment (Nourizadeh et al. 2025). The possibility of including synthetic meshes, grouting, and phenolic-based insulating plates may serve as potential solutions for electrically separating sections of ground support, reducing corrosion rates (Hussein Farh et al. 2023). NIOSH is currently conducting tests to dynamically determine the strength and energy absorption abilities of synthetic mesh in comparison to steel (Benton & Emery 2022).

2 Experimental design

This experiment investigates whether metal ground support in areas of high corrosion (anodic site) could experience a heightened corrosion rate resulting from an electrical/metallic connection to ground support in an area with lower corrosion (cathodic site). The increased corrosion rate could be a result of the electrically linked metals having a large difference in polarisation potential in their disparate environments. It also explores the effectiveness of isolating bolts from the rock as an electron path using grout or the use of both grout and an isolation plate to separate from the electrically connected mesh network. The number of control and test environments investigated was limited by material and space constraints. This experiment was setup as an initial investigation into this hypothesis based on field findings.

2.1 Box design

Two types of boxes were constructed for the experiment. One type was an enclosed corrosion environment for a single bolt setup to serve as a control samples, as shown in Figure 1.



Figure 1 Control bolt sample box design. Each box contains one bolt, crushed rock, and an electrolyte (credit NIOSH)

Three sets of box pairs were also constructed with a pipe connector to allow them to share an electrolyte (ion path). The electrolyte is shared through this path and submerges at least 50% of the bolts in their respective boxes. The electron path of each system was formed by using a jumper cable to connect the 2 rockbolts. The jumper cables serve as a proxy for connected mesh underground. Figure 2 notates these structures for reference.

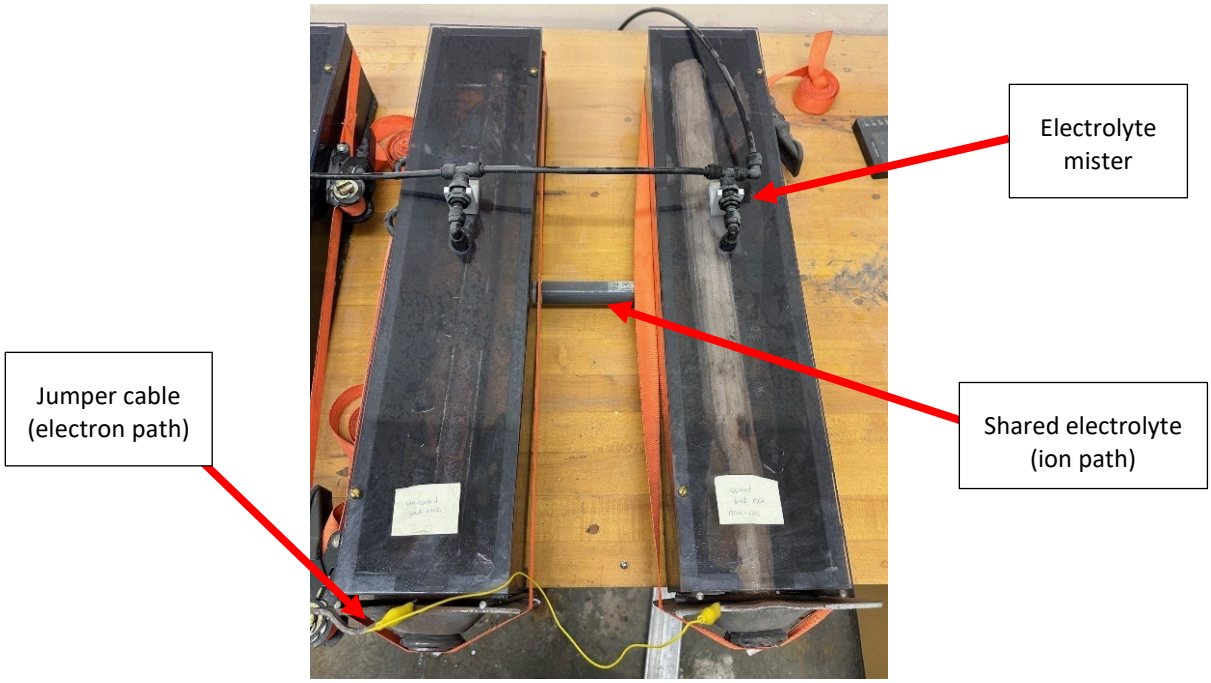


Figure 2 Labelled diagram for a bolt pairing. Each box contains one bolt, crushed rock, and an electrolyte (credit NIOSH)

Each individual box contained a rockbolt (some grouted, others not) and a rock media. Carbon steel friction rockbolts cut to a 0.457 m length were used in this experiment. The bolts were uncoated high strength, low alloy steel. Certain boxes contained inert rocks and others contained those from a US mine with extreme corrosion rates that form galvanic couples with steel similar to that of steel and graphite pairings. Sodium chloride (NaCl) was also added in equal amounts to each box as chlorides lead to heightened corrosion rates. Each box was hooked to a misting system that wet each environment for a 30-second period once an hour and the tests were run for 400 days consecutively.

2.2 Bolt pairings

Three box pairings were created to investigate the goals of the experiment. Pairing no.1 investigated if ground support in an area of high corrosion was connected to one with a lower corrosion environment, the corrosion rate would increase for the lower system. The potential difference of the 2 metal rockbolts (bolts 5 and 6) would potentially change based on their environment causing galvanic corrosion. This system can be seen in Figure 3.



Figure 3 Box pairing no.1 (bolts 5 and 6). One bolt is in a low corrosive environment (right), while the other is in a high corrosion environment (left). Boxes share an electrolyte through the tubing in the centre and are connected with a jumper cable (credit NIOSH)

Bolt pairing no.2 focused on the use of grout to investigate whether grouting a bolt to isolate it from the corrosive environment underground provides substantial protection while it is still electrically connected to mesh and other metal support in the mine environment (bolts 1 and 2). One bolt was manually covered in a 2-part grout that was mixed by hand. Both rockbolts in this pairing had the same corrosive mine rock in their environment, with one bolt being grouted and the other left plain. This system can be seen in Figure 4.



Figure 4 Box pairing no.2 (bolts 1 and 2). Both bolts are in a high corrosion condition, but bolt 1 is grouted as a protective coating from the environment. Boxes share an electrolyte through the tubing in the centre and are connected with a jumper cable (credit NIOSH)

Lastly, pairing no.3 was a bolt in the highly corrosive rock which was grouted and had an isolation plate between it and the mesh electrically linked to an ungrouted bolt in the same rock (bolts 3 and 4). This pairing was made to investigate whether fully isolating a bolt in an area of high corrosion effectively lowers the corrosion current that may flow to bolts in a lower corrosion area. Without the isolation, the support in the lower corrosion area would increase from the galvanic coupling effects of the metals that have different potentials from their respective environments. Bolt 3 was fully isolated; however, the electrical connection to bolt 4 through a jumper cable still allows for a corrosion current to flow. This system can be seen in Figure 5.



Figure 5 Box pairing no.3 (bolts 3 and 4). Both bolts are in a high corrosion condition, but bolt 3 is grouted as a protective coating from the environment and has a phenolic isolation plate to fully separate it from its corrosive environment. The boxes share an electrolyte through the tubing in the centre and are connected with a jumper cable (credit NIOSH)

Table 1 summarises the bolt pairings.

Table 1 Description of each bolt's experimental conditions

Bolt number	Grout	Corrosion environment	Isolated	Pairing
1	Yes	High	No	No.2
2	No	High	No	No.2
3	Yes	High	Yes	No.3
4	No	High	No	No.3
5	No	Low	No	No.1
6	No	High	No	No.1
7	Yes	High	No	Control
8	No	Low	No	Control
9	No	High	No	Control

2.3 Measurements

Prior to assembly, each bolt sample underwent thickness and weight measurements for comparison after the experiment concluded. The initial weight of the bolts was recorded to perform corrosion rate calculations using ASTM Standard G1-03 (ASTM International 2017). Once the final weight was obtained, the corrosion rate of rockbolts was calculated using Equation 1:

$$CR = \frac{(K \times W)}{(A \times T \times D)} \quad (1)$$

where:

CR = corrosion rate (mm/y)

K = a constant = 8.76×10^4 for mm/y

W = mass loss (grams)

A = area (cm^2)

T = time of exposure (h)

D = density (g/cm^3).

Initial and final thickness measurements of the rockbolts were also recorded as another way to track the amount of corrosion on bolts that were not grouted. For consistency, a cable tie was placed as a marker of where to measure the final thickness.

Lastly, for each of the 3 box pairings, the corrosion current was manually recorded using an Agilent 34410 A multimeter in DC current mode at differing intervals over 399 days to observe how it behaved over an extended period of time.

3 Results

Data for the current flow, weight loss, and corrosion rates are detailed below.

3.1 Current flow

The current in each box pairing was manually tracked over a period of 400 days. The readings are shown in Table 2 below.

Table 2 Corrosion current readings over the testing period for each bolt pairing configuration

	Current (µA)		
Days	**Maximum**	**Minimum**	**Average**
Pair No.1	45.3	0.8	17.8
Pair No.2	8.0	0.4	4.5
Pair No.3	12.5	0.1	5.0

This data is also shown graphically in Figure 6 with the days truncated to focus on the early behaviour of the system before they reached roughly steady state values.

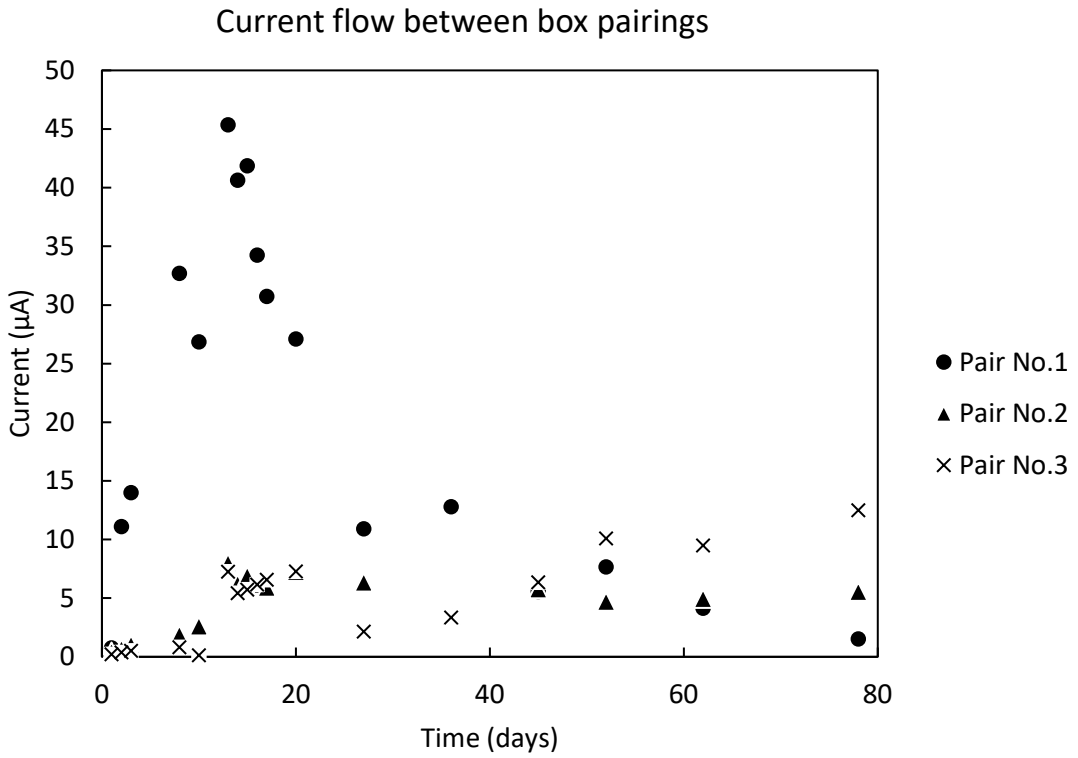


Figure 6 Graphical representation of the corrosion current over time for each bolt configuration before values levelled off

3.2 Weight loss and corrosion rates

Weight loss, percent mass loss, and corrosion rates for each bolt are shown in Table 3.

Table 3 Weight loss, percent mass loss, and corrosion rate data for all bolt samples

Bolt number	Weight loss (g)	Percent mass loss (%)	Corrosion rate (mm/y)
1	207	9.57	0.220
2	13.6	1.20	0.014
3	198	9.15	0.222
4	22.7	2.00	0.024
5	31.8	2.79	0.033
6	9.07	0.80	0.010
7	239	10.9	0.253
8	9.07	0.81	0.010
9	4.54	0.40	0.005

Bolts 7 and 9 are the control references for each environment and a grouted bolt. Figure 7 shows a picture of the bolts immediately after being removed from the boxes.



Figure 7 Bolt samples after removal from test boxes (credit NIOSH)

Figure 8 shows the bolts once they had been cleaned following ASTM standard G1-03 to collect the weight loss measurements (ASTM International 2017). There was no thickness loss at the designated measurement sites for these samples, indicating that the mass was lost at other sites on the metal. The metal loss occurred more in areas with direct rock contact from the galvanic coupling and sites consistently wetted throughout the experiment.



Figure 8 Bolt samples after undergoing cleaning per ASTM standard G1-03 (credit NIOSH)

4 Discussion

4.1 Current flow

Table 2 and Figure 6 show that the bolts in box pairing no.1 had the highest initial current flow between them; this being the corrosion current of the system. This result was expected as the bolts in the system were in contrasting high and low corrosion environments and had neither of the methods tested to reduce the corrosion of the bolts. It would have been expected for box pairing no.2 to have the next highest current and pairing no.3 to be the lowest. Pairing no.2 had one method to reduce corrosion (grouting), while pairing no.3 had both grout and an isolation plate on bolt 3. Despite this, these 2 box pairings had very similar current flow throughout the experiment. This suggests that the addition of a single protection measure, such as grouting, is beneficial. More experimentation is needed to understand if 2 or more methods are necessary based on this preliminary study.

In later readings, the corrosion current of all pairings had mostly levelled out which may be attributed to the corrosion reactions slowing down. This often occurs from the formation of passive films and corrosion products on the surface of the metal protecting it (Ansari et al. 2019). Having a layer of corrosion products on the metal surface can act as a barrier. Its presence restricts access of oxygen and electrolytes to underlying metal, which are required for the reaction to occur, slowing rates down over time.

4.2 Weight loss and corrosion rates

In all 3 box pairings, the bolt placed in the less corrosive environment or with methods to reduce corrosion had the most weight loss. This aligns with the hypothesis that linking ground support metals together in differing environments may lead to heightened corrosion rates in locations that otherwise would be expected to have lower reaction rates. It would have been expected for the bolts with isolation or protection methods to have the lowest corrosion rates if they were not electrically connected to another bolt and its environment. However, since they were connected to a bolt that was not protected by any method in a high corrosion environment, the current passing between them promoted a higher corrosion rate than expected for bolts such as 1 and 3.

The corrosion rate was the highest for the bolt in the less corrosive environments or with protective measures. For box pair no.2, the grouted bolt had a rate that was 15.7-times higher than its non-grouted counterpart in the high corrosion environment. Under the same conditions but with the addition of the isolation plate, in pairing no. 3, the more protected bolt's rate was 9.26-times higher. Finally, pairing no. 1 had a corrosion rate that was 3.30-times higher in the lower corrosivity environment because of the connection.

Bolt 7, which was the control for a grouted bolt in the high corrosion environment, had the highest weight loss and corrosion rate, which was unexpected. From visual analysis, on all grouted bolts there were areas where the grout cracked during the curing process as seen in Figure 9.



Figure 9 Bolt 7 during testing displaying corrosion products at cracks in grouting materials (credit NIOSH)

For many corrosion-resistant coatings, damage to the coating is often referred to as a 'holiday'. Holidays become a localised point of accelerated corrosion as a result of the lack of the coating protection (Moran et al. 2019). The grout for the bolts was applied by hand and was subsequently not as thick as it would be surrounding a bolt in a borehole. Having multiple cracks from this method would allow for many concentration areas of corrosion, possibly explaining bolt 7 having the highest weight loss. Figure 10 shows a closer look at a crack in the grout that displayed corrosion more heavily than other sections of bolts.



Figure 10 Microscope view of corrosion at cracks in the grouting material (credit NIOSH)

Bolt 8 also had unexpected results as the rock used for this bolt's environment was not expected to cause elevated corrosion rates through galvanic coupling like those used in the more aggressive experimental environment. The same 0.1 M NaCl electrolyte was used across all boxes, indicating that a factor – potentially linked to the rock samples in setup – contributed to slightly higher corrosion rates than expected. This may have led to the protected bolt having a 3.46-times higher corrosion rate, which was expected, but not as large of a disparity as the other 2 box pairings. In the future, more electrochemical and resistance testing may be needed for better rock selection to ensure a low corrosion environment.

5 Conclusion

Between the corrosion current and rates obtained over this experiment, it was observed that metal ground support in differing environments can experience reaction rates higher than expected by being linked to metals in a higher corrosion potential environment. The bolt placed in either a less corrosive environment or with one or both methods to reduce corrosion had the most weight loss in all box pairings, which would not be expected if they were not coupled. It was seen, however, that the corrosion currents levelled out over time, suggesting that this phenomenon may accelerate corrosion initially and then become less of a threat depending on the corrosivity of the localised mine environment. This may be important for temporary and permanent drifts or travel ways to understand the short-term and long-term effects of corrosion on the chosen ground support. More electrical research needs to be performed underground to understand the current flow and passivation of the metals after installation.

Heightened corrosion of the grouted bolts was witnessed in this experiment, which could be attributed to increased localised reactions at sites where the grout had cracked. This led to the grouted control bolt in the high corrosion environment having the highest corrosion rate, with the other grouted bolts having similar rates to their control. This may imply that like coatings, having cracks in grouting can lead to heightened corrosion at those sites, which can be more intense than generalised corrosion.

Future studies are needed to explore the multiple dynamics related to electrically isolating metal ground support. The frequency and distance that metal support may need to be separated by segments of non-metallic ground support elements can depend greatly on characterising the composition and electrochemical properties of the rock mass. More experimental samples would be beneficial to numerically understand the rate differences that may be influenced by electrically connecting the mesh and bolts. Characterising its resistivity along with open circuit potential, remote earth, and current measurements between bolts can all contribute to more informed ground support planning.

Future studies may include understanding the corrosion failure modes for resins and grouts for underground support. Much like thermal coatings on pipelines, at cracks or openings in the resin/grout media, there is a potential for acute but intense corrosion that can lead to quick point failures along the length of the support. These failures are harder to predict as they may occur faster than general corrosion and can cause unexpected failures. This study included a single type of ground support to begin the investigation in a laboratory setting. Additional empirical laboratory evaluation combined with active mine studies would be needed to validate findings.

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Disclaimer

The findings and conclusions in this report are those of the author/s and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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