Corrosion considerations in the design and operation of rock support systems

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Abstract

The selection and design of rock support systems rarely takes into explicit consideration the susceptibility of the systems to corrosion. The loss in capacity associated with the corrosion of support systems can be a major safety and economic concern in underground hard rock mines. This paper reports on the influence of atmospheric, aqueous and microbiological corrosion on the performance of support systems in several, hard rock underground mines. In situ observations were complemented by laboratory investigations aiming to quantify the potential in loss of capacity of the installed support systems. A methodology is proposed to contribute to the selection and design of support systems in corrosive environments.

1   Introduction

An important issue in the design and implementation of ground control systems is the reduction in support capacity over time due to corrosion of the reinforcement and surface support units. This can have important ramifications in the ability of a support system to perform satisfactorily over its intended working life. This can have important economic and safety implications in the form of required rehabilitation and managing falls of ground (Figure 1).

a)   b)

Figure 1 a) Mesh that failed as result of corrosion; b) Fall of ground attributed to corroded rock support

A support system is considered to have failed when it no longer provides the support it was designed for. This can be brought about by failure of any element of the support, such as the rock bolt or mesh. The reduction in support capacity due to corrosion is currently not explicitly considered in the selection and design of an underground support system. Quite often, corrosivity is recognised as an issue during an investigation in the mechanisms and causes of failure that may have resulted in a fall of ground. Usually the emphasis is on fracture analysis aiming to identify the contribution of corrosion to a unit or system failure, Hadjigeorgiou et al. (2002). Fracture analysis focuses on the separation of a solid body into two or more parts under the action of stress that initiates and propagates the formation of cracks. A ductile fracture mechanism is characterised by considerable plastic deformation prior to and during propagation of a crack.

In recognition of the importance of potential degradation of support, efforts have been made to develop classification systems to identify the corrosivity of mining environments, Robinson and Tyler (1999), Li and Lindblad (1999), Villaescusa et al. (2008). Currently, however, no classification systems linking corrosivity with ground support is widely accepted or implemented at mine sites. This can be attributed to a variety of reasons, such as site specific considerations, lack of substantial data to support the assertions of the classification systems and to back their recommendations, and possibly the lack of onsite expertise to implement these systems.

Based on in situ investigations and comprehensive laboratory experiments and testing, mine environments that contribute to the corrosion of support have been scrutinised. After collecting sufficient data for a comprehensive analysis, a framework was developed for the selection of appropriate support strategies for underground hard rock mines conditions susceptible to corrosion. Furthermore, this work provides recommendations that can be used to predict, with some degree of confidence, the operational life of a given support system. This can have important safety and economic repercussions for underground mines.

2   In situ and laboratory investigations

During the last five years, seven underground mines in Canada have participated in a long term study of the influence of corrosion on support performance. Participating mines were selected to obtain a wide range of different mining environment, geology, ore deposit, mining methods, etc. (Dorion and Hadjigeorgiou, 2008).

The visual corrosion system developed by Hadjigeorgiou et al. (2008) was used to qualify the impact of atmospheric and aqueous conditions on the support. This was complemented by a comprehensive testing program to monitor aqueous and atmospheric corrosion that involved direct measurements using corrosion coupons and analytical methods. An analysis of water samples is summarised in Table 1. Parameters recorded included: acidity or alkalinity; conductivity; solubility; salinity, etc.

Acidity or alkalinity, measured by a pH value defined as $-\log(H+)$. Alkaline environments are characterised by high pH values with acidic solutions having low pH values. Acidic solutions are more corrosive and attack metals. Conductivity, the ability of a solution to transport current and is recorded in Siemens per meter (S/m) in S.I. units. As the conductivity of a solution increases, in most cases, so does the corrosion of immersed metals. Solubility is the quantity of an ion or gas in a solution. A high oxygen concentration in water results in a high rate of corrosion of iron. The corrosion rate of iron increases in the presence of higher dissolved oxygen. Salinity is reported as Total Dissolved Solids (TDS) and quantified as parts per thousand or parts per million. In general saline waters have a higher conductivity. The dissolved oxygen readings were calibrated to take into account the atmospheric pressure and water salinity and are reported in parts per million (ppm). Water sample temperature recorded in °C. Typically corrosion rates increase as temperatures increase.

An appropriate interpretation of the results presented in Table 1 requires attention to the specificity of each mine. For example, Mine #4 operates at greater depth and as a result of the geothermal gradient the ground water at two sampling sites is almost 20°C higher. High temperatures increase the susceptibility of a support system to corrosion. Only mines 4 and 5 were characterised as acidic environments the rest of the mines described as weak alkaline or normal environments. The pH values of collected water samples varied from 3.4 to 8.0 and oxygen solubility ranged from 5.9 to 15.6 ppm.

The undertaken chemical analysis revealed a high concentration of aggressive ions such as Cl^- and SO_4^-. Mine 1 is an example of high Cl^- concentrations ranging from 1,938 to 5,701 ppm while the higher SO_4^- concentrations are associated with Mine 6 (2,737–18,053 ppm) and Mine #4 (19,029–45,757 ppm). Aggressive ions in a solution attack the thin protective film that forms on the surface of metals thus making the metal more susceptible to corrosion. Again the impact of selected ions on the corrosivity of an environment has to be interpreted with reference to the presence or absence of inhibitors such as HCO_3^- and Ca^+.

Table 1 Analysis of water samples collected at several mines

Parameter	Units	Mine 1					Mine 2			Mine 3	
		Site #1	Site #2	Site #3	Site #4	Site #5	Site #1	Site #2	Site #3	Site #1	Site #2
HCO_3	mg/L	170	100	NA	NA	NA	230	130	NA	270	250
Ca	mg/L	145	245	296	151	470	218	65	1,370	62	61
Cu	mg/L	-	-	-	-	-	-	-	-	-	-
Fe	mg/L	-	-	-	-	-	-	-	-	1	-
K	mg/L	23	30	49	29	52	5	2	3	3	4
Mg	mg/L	56	104	97	49	149	19	7	1	21	22
Na	mg/L	851	910	2,020	1,010	3,070	65	4	425	13	12
Zn	mg/L	-	-	-	-	-	-	-	-	-	-
Cl	mg/L	1,933	2,230	4,432	1,938	5,701	20	7	3,128	6	7
NO_3	mg/L	NA	NA	348	21	-	14	?	-	NA	NA
SO_4^{2-}	mg/L	NA	NA	78	182	247	452	32	733	NA	113
pH		7.3	7.1	7.8	8.0	7.7	7.0	7.1	6.9	7.3	7.5
Conductivity	µS	1,968	4,510	9,150	6,530	13,630	439	282	6,540	328	352
Salinity	ppt	1.3	3.2	6.7	-	10.1	0.3	0.2	4.9	0.2	0.2
Dissolved oxygen	ppm	9.0	12.7	7.4	8.8	8.7	7.3	11.1	5.9	13.0	15.6
Temperature	°C	13.5	13.3	13.5	15.0	14.2	8.5	10.3	11.6	7.4	10.0

Parameter	Units	Mine 4				Mine 5				Mine 6	
		Site #1	Site #2	Site #3	Site #4	Site #1	Site #2	Site #3	Site #4	Site #1	Site #2
HCO_3	mg/L	44	150	NA	NA	120	-	NA	NA	NA	NA
Ca	mg/L	278	295	404	449	585	336	424	381	290	182
Cu	mg/L	-	-	154	0	-	-	14	-	-	-
Fe	mg/L	90	57	589	33	106	675	334	2,170	1	0
K	mg/L	6	5	17	117	8	4	7	14	12	5
Mg	mg/L	56	55	591	187	154	106	380	446	46	29
Na	mg/L	57	43	821	859	113	9	132	63	416	136
Zn	mg/L	33	8	14,000	13,000	3	2	10	4	7	2
Cl	mg/L	78	80	368	789	10	19	50	140	1,450	49
NO_3	mg/L	NA	NA	-	1,696	6	519	93	-	-	-
SO_4	mg/L	NA	NA	45,757	19,029	88	NA	5,128	18,053	67	84
pH		5.7	6.4	3.4	4.4	5.9	3.3	2.9	4.0	7.2	7.1
Conductivity	µS	1,614	1,400	30,800	9,650	2,894	3,106	5,240	11,250	2,743	1,301
Salinity	ppt	1.2	1.0	17.9	5.0	2.0	2.1	3.5	8.2	2.2	1.0
Dissolved oxygen	ppm	12.8	12.3	6.5	7.4	11.8	12.9	8.0	8.8	11.2	9.3
Temperature	°C	10.5	9.8	27	28.4	13.4	13.6	15.7	14.6	8.0	7.9

Atmospheric corrosion is the natural degradation of material exposed to air and its pollutants. The rate of atmospheric corrosion is influenced by the relative humidity (the ratio of the quantity of water vapour present in the atmosphere to the saturation quantity at a given temperature). Corrosion rate increases beyond a critical humidity of over 60%. Atmospheric corrosion is further accentuated by the presence of pollutants such as gas and particles. All these conditions are often present in underground mines. Furthermore, the ambient heat in deep mines also has a direct impact on the corrosion resistance of support systems. It is generally accepted that corrosion activity will double for each 10°C raise in temperature.

Table 2 provides a summary of information collected during the mine site visits. Most mine sites were characterised by high relative humidity that contributes to corrosion.

Furthermore, the authors successfully used corrosion coupons to quantify corrosion rates under different mine conditions following ASTM G4 -01 and ASTM G1 -03 standards (Figure 2). Finally the loss of tensile strength as a function of corrosion rate was determined in the laboratory, Dorion et al. (2009, 2010).

Table 2   Average atmospheric data at selected sites between July 2008 and January 2009

	Mine 1			Mine 2			Mine 3		
Parameter	Site #3	Site #4	Site #5	Site #1	Site #2	Site #3	Site #1	Site #2	Site #3
Temperature (°C)	15.4	14.5	16.7	12.3	12.2	12.5	15.1	11.5	11.7
Relative humidity (%)	68	58	73	>85	85	>80	68	69	76
Condensation	Weak	Weak	Dry	Wet	Weak	Wet	Splashing	Dry	Dry
Dust	Weak	No	Strong	No	No	No	Yes	No	Yes
Gas	No	No	Yes	No	No	Weak	Yes	No	Yes
Air flow (cfm)	45,000	132,500	47,000	0	42,000	0	88,000	52,000	262,000
Air quality	Fresh	Fresh	Operation	Stagnant	Fresh	Stagnant	70% recycled	Fresh	Exhaust

	Mine 4			Mine 5		
Parameters	Site #1	Site #2	Site #3	Site #1	Site #2	Site #3
Temperature (°C)	13.3	14.1	29.3	13.0	13.6	16.9
Relative humidity (%)	96	96	79	90	90	81
Condensation	Wet	Wet	Dry	Wet	Wet	Weak
Dust	No	No	Yes	No	No	No
Gas	Yes	Yes	Yes	Yes	Yes	No
Air flow (cfm)	120,950	80,400	34,000	330,000	33,000	0
Air quality	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Stagnant

Figure 2 Corrosion coupons attached to the mine screen on the drift wall, exposed to atmospheric and aqueous conditions

Collected corroded rock reinforcement and support elements were brought to the laboratory to determine the capacity of corroded mesh, plate and friction bolts. These were complemented by microphotography to identify the type of corrosion on collected sample (Figure 3) and X-ray diffraction to determine the most abundant mineral species in the corrosion products. Microscopic observations helped identify the main corrosion forms and provided an insight on the impact of rock and mineral particles on corrosion of the

steel support. (S.E.M.) was used to identify and compare forms of corrosion and corrosion products observed at the collected rock support units (Figure 4).
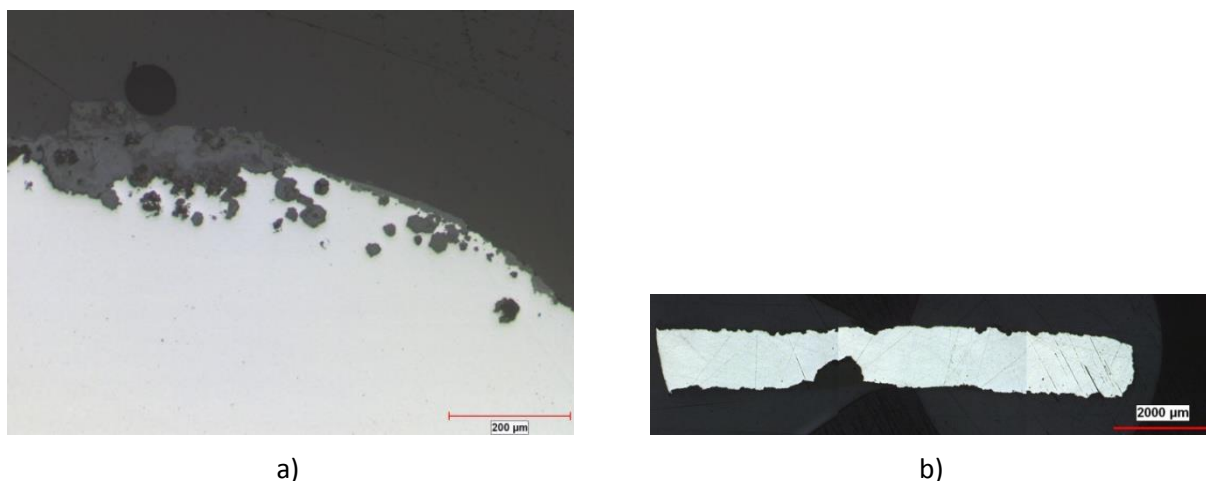

a)

b)

Figure 3 a) Microphotography of mesh subject to pitting corrosion; b) Microphotography of a piece of a corrosion coupon exposed to atmospheric condition with non-uniform and pitting corrosion
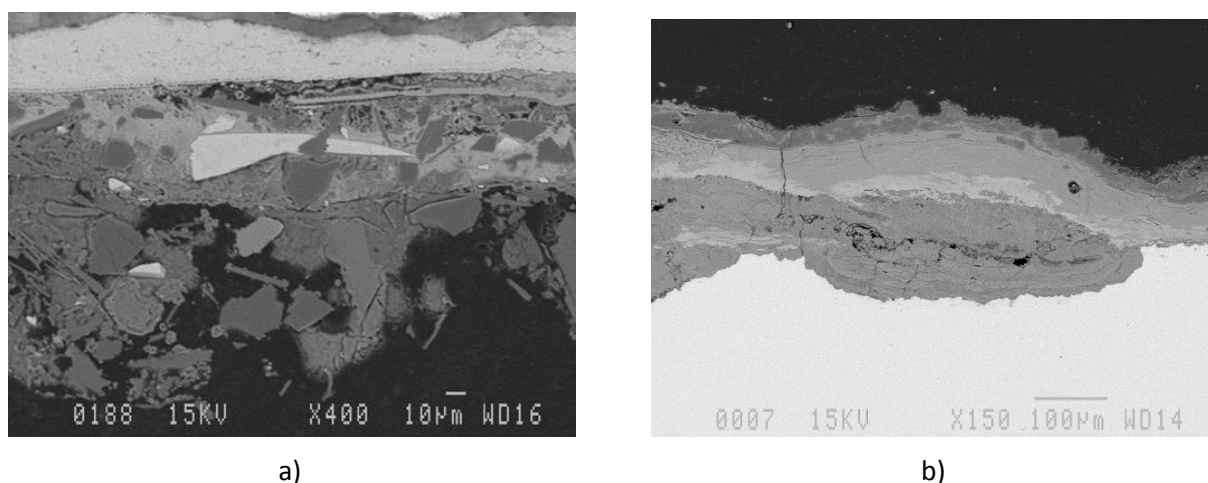

a)

b)

Figure 4 a) S.E.M. photography of a plate corrosion crust containing many different minerals particles; b) S.E.M. photography of a corrosion coupon exposed to atmospheric corrosion

3 Interpreting in situ observations and laboratory investigations

For practical purposes it is useful to be able to link in situ observations of corrosion on support to estimates of corrosion rates. Table 3 provides a series of recommendations linking on site observations on the level of corrosion to resulting corrosion rate and loss of capacity. Furthermore, it makes suggestions on the need for required intervention that may involve replacing of corroded units or rehabilitation.

Although aqueous corrosion is often attributed to low pH other factors come to play. For example, concentrations of dissolved oxygen in water were seen to contribute to corrosion in underground mines, Hassell et al. (2004). During the present investigation corrosion coupons were installed under a range of aqueous conditions. It was observed that conductivity was the controlling factor for water with pH between 5 and 8. The influence of iron bacteria is also important as with coupons installed for 12 months in water with iron bacteria showing high corrosion rates. Solid mineral deposits on the reinforcement and support steel create a barrier and result in lower corrosion rates over time. The corrosion rate of steel as a function

of water conductivity is illustrated in Figure 5. This applicability of this graph is for water of pH between of 6 to 8 and conductivity under 6,000 µS.

Table 3   Linking on site observations to resulting loss of capacity and required intervention

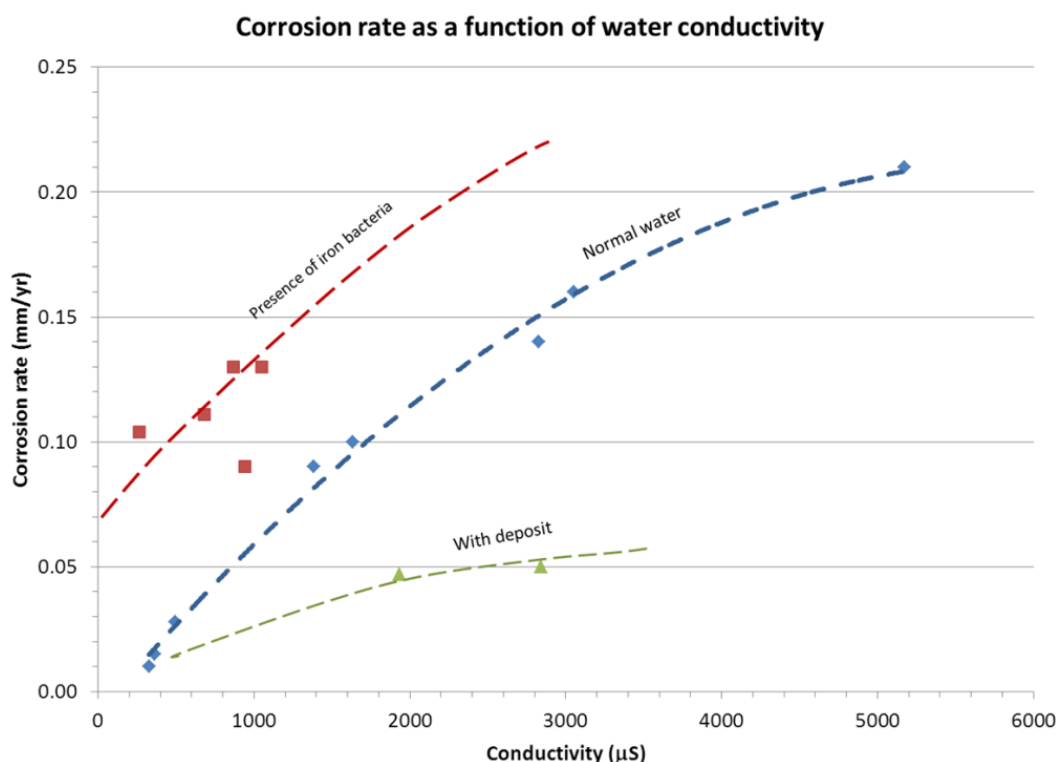| Corrosion Level	Description	Corrosion Rate	Loss of Capacity	#6 Mesh Diam.	Required Intervention
C1: Negligible corrosion	Steel is in excellent condition and corrosion signs only on surface. A few localised spots, less than 10% of the surface is corroded.	<0.02 mm/yr	<10%	>4.75 mm	None
C2: Localised corrosion	Corrosion is characterised by localised spots on the surface. Between 10 and 75% of the surface is corroded. Steel is in good condition.	0.02 to 0.04 mm/yr	10 to 20%	4.50 to 4.75 mm	None
C3: Surface corrosion	Corrosion over 75% of the surface. Corrosion is only on surface. If a corrosion crust is present it is very thin. Can identify blisters.	0.04 to 0.15 mm/yr	20 to 35%	4.00 to 4.50 mm	None to follow up.
C4: Advanced corrosion	100% of the surface is corroded. Can identify blisters. Thin corrosion crust (<1 mm) easily removed.	0.15 to 0.30 mm/yr	35 to 50%	3.50 to 4.50 mm	Follow up. If installed over 12 months it will display signs of severe corrosion.
C5: Very advanced corrosion	100% of the surface is corroded. Thick corrosion crust (>1 mm) and flaky.	0.30 to 0.60 mm/yr	50 to 75%	2.50 to 3.50 mm	Consider replacement of installed units.
C6: Extreme corrosion	Corrosion goes through the steel. Integrity of steel has been damaged. Pieces are easily breakable by hand.	>0.50 mm/yr	>75%	<2.50 mm	Reconditioning. May require immediate intervention.

Figure 5 Determining corrosion rate as a function the conductivity of the water to pH 6 to 8

4 Loss of capacity due to corrosion

4.1 Loss of capacity of reinforcement elements

The loss of capacity of bolts exposed to 'low to moderate corrosion conditions' and to 'moderate to high corrosion conditions' has been demonstrated by pull out tests on Swellex bolts as reported by Charette et al. (2004) and Charette (2012). Villaescusa et al. (2008), simulating conditions in Australian hard rock mines, suggested service life estimates for cable strand in strong groundwater flow environments. In our work we have addressed the loss of capacity of friction bolts by extrapolating from work in corrosion chambers, laboratory testing and on site observations.

4.2 Loss of capacity of #6 mesh

During this project more than 60 samples of #6 mesh screen, displaying a range of corrosion levels, were tested in tension (ASTM E8-99). Results were compared with non-corroded samples and results from Villaescusa (2004). Prior to conducting measurements of the diameter of the strands of wire, the corrosion crust was peeled off using a scraper and steel wool and the minimum diameter of the strands (in mm) was measured using a calliper. It was thus possible to determine the residual tensile strength of the wire, or the loss in strength, since installation. The relationship between the break capacity and the diameter of the wire strands, and the correlation between percentage of residual capacity of wires # 6 and their diameter were estimated as:

$$\#6 \text{ mesh capacity (kN)} = 0.38 \, D^{2.2} \tag{1}$$

$$\text{Residual capacity of \#6 mesh (\%)} = 2.8 \, D^{2.2} \tag{2}$$

Where:

D = diameter in mm.

For design purposes it is possible to use Figures 7 and 8 showing the curve obtained using the above relationships and levels of corrosion. This provides a link to the onsite observations described in Table 3.
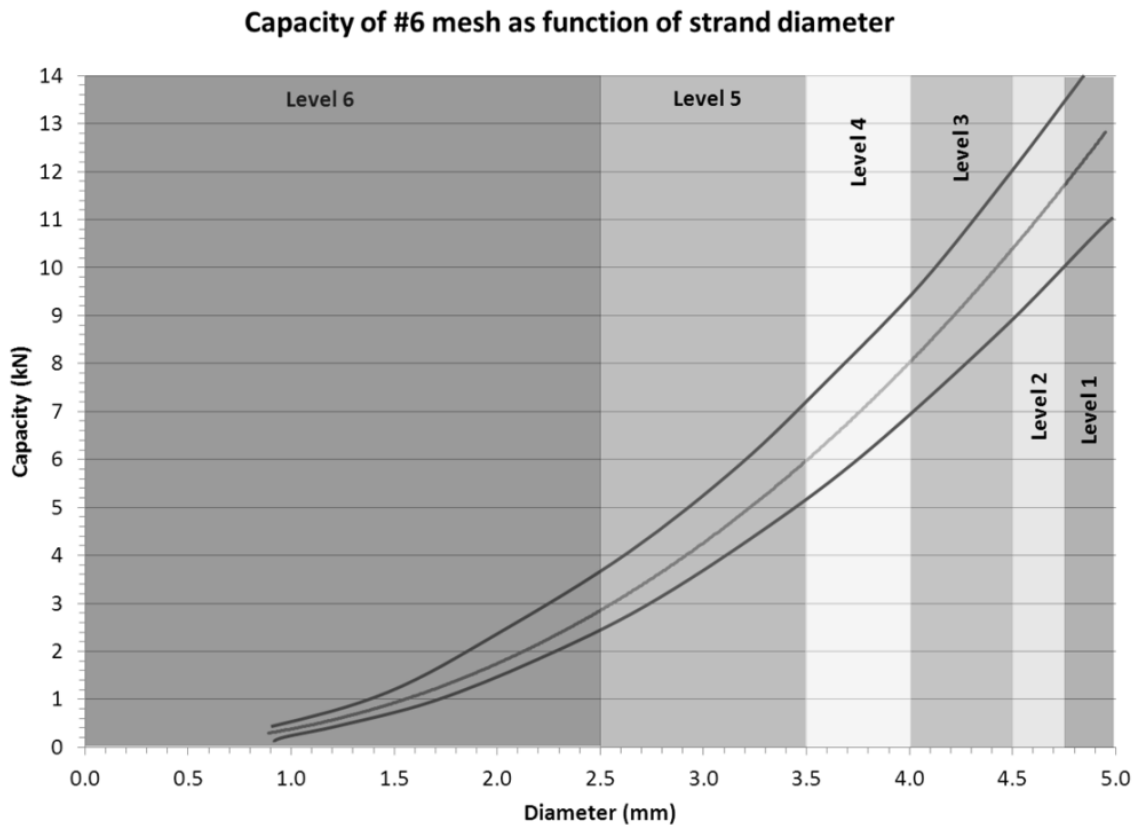

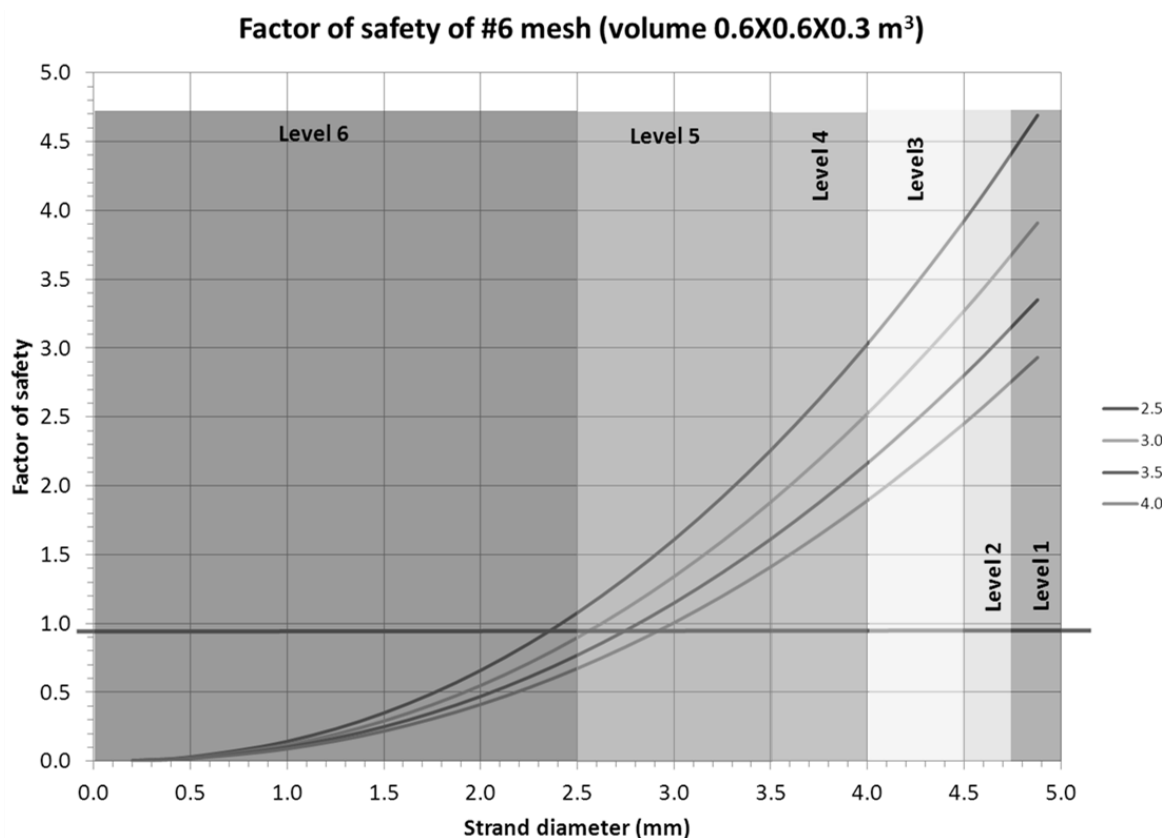**Figure 6 Theoretical relationship between the breaking force and the diameter of wire strand**

Factor of safety of #6 mesh (volume 0.6X0.6X0.3 m³)

Figure 7 Relationship between the residual capacity of the strands and their diameter (Numbers refer to factor of safety)

A first approximation of the residual capacity can be estimated, under different corrosion rates, based on the time of exposure. For example, for an initial diameter of #6 mesh of 4.88 mm exposed to a corrosion environment that is characterised by a corrosion rate of 0.05 mm/year. Based on the design chart in Figure 7, the loss in mesh capacity after 2 years of exposure (2 years × 0.05 mm/year) and assuming a constant corrosion environment, the mesh diameter will be reduced to 4.78 mm.

$$\text{Residual capacity (\%)} = 2.8 \times D^{2.2} = 2.8 \times (4.78)^{2.2} = 87\% \qquad (3)$$

If the mesh is exposed for 20 years:

$$2.8 \times D^{2.2} = 2.8 \times (4.88 - (0.05*20))^{2.2} = 55\% \qquad (4)$$
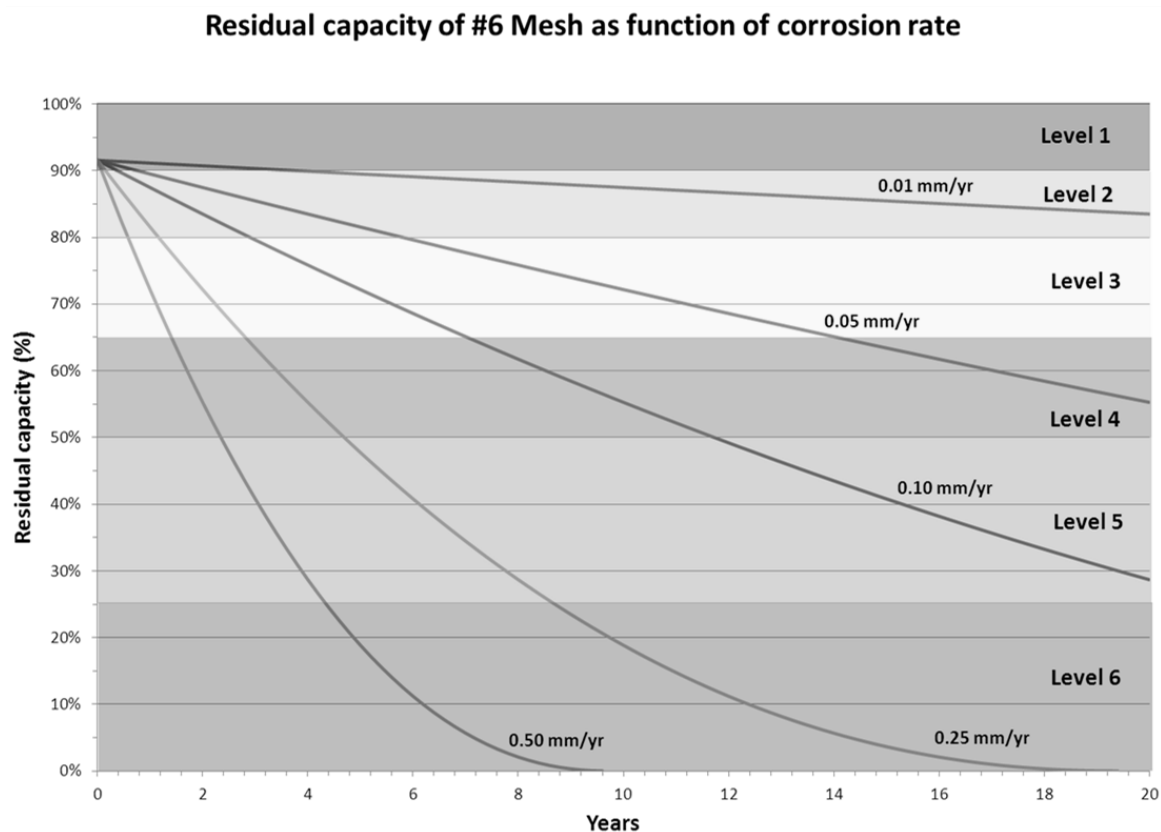
Figure 8 Residual capacity of the mesh #6 in function of time for various corrosion rates

5   Selection and design of support systems accounting for corrosion

There are several guidelines for the selection and design of support systems. Quite often mine operators rely on experience, or the use of empirical and analytical tools. A common limitation of most approaches is that they do not seem to account for the potential impact of corrosion on the longevity of a reinforcement or support element. Table 4, based on the in situ and laboratory investigations of the authors, aims to provide a tool to alert mine operators on the susceptibility of reinforcement and support elements to corrosion. It is recognised that failure of any element can result in failure of the support system.

The flowcharts in Figures 10 and 11 provide a pathway to characterise the corrosivity of different mining environments, and guide the planning and conduct surveillance (monitoring) of support in place. These charts should be used with classification charts of aqueous and atmospheric corrosion and with respect of support susceptibility guide for assessing corrosion.

Table 4   Susceptibility of support systems to corrosion

Support Category	Support Element	Corrosion Susceptibility	Justification
Reinforcement	Friction bolts (Split Set) Swelling bolts (Swellex)	High	Hollow bolts with low thickness steel. Decrease in thickness of bolt can result in large loss of capacity. Borehole conditions susceptible to exposure to water. Contact with rock or sulphides.
Surface support	Mesh Push-plate	High	Strands of thin mesh are exposed over large areas. Push plate thickness is thin.
Reinforcement	Rockbolts Bolt nuts Eye-bolt, J-bolt	Medium	Bolt rods are solid and have a relatively thick diameter.
Surface support	Plates Straps	Medium	Plate thickness is greater.
Reinforcement	Reinforcement elements that have been treated (galvanised, Mn, etc.)	Medium to low	Corrosion attack delayed by protection and use of inhibitors. In some corrosive environments, galvanisation can offer long term protection. Thickness of bolts is important.
Surface support	Support elements that have been treated (galvanised, Mn, etc.)	Medium to low	Attack delayed by protection and inhibitors. In some corrosive environments, galvanised support protects for the long term. Plate thickness is an important factor.
Reinforcement	Resin rebar or grout rebar Grout cable	Low	Protection from environment (air, water). Corrosion localised and/or stress cracking corrosion if the resin or cement is cracked.
Surface support	Support installed under shotcrete	Low	Protection from environment (air, water). Corrosion localised and/or stress cracking. Corrosion if the resin or cement is cracked.

There are several tools that can be used to characterise the corrosivity of a mining environment exposed to aqueous and atmospheric conditions. As the field studies demonstrated, a number of variables can result in aggressive corrosive environments for rock support systems. The use of the analytical tests in conjunction with the corrosivity classification can provide a design tool and can allow the reporting of corrosion in a consistent matter by those responsible for quality control of rock support systems. It furthermore provides a tool to monitor the evolution of support system corrosion support over time and allow time for prompt intervention as required.
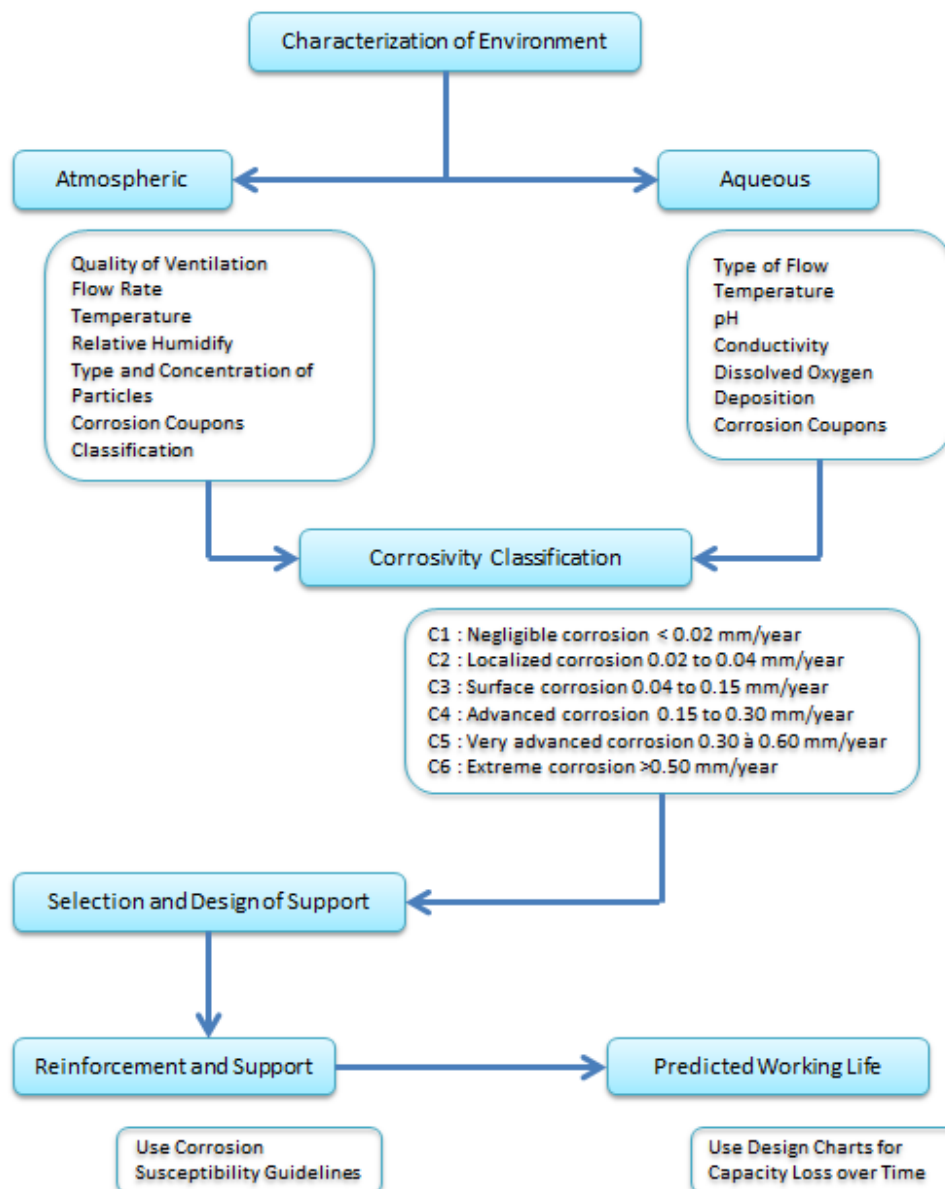
Figure 9 Design methodology for corrosivity classification and selecting of reinforcement and support

This process does not replace the geomechanical design guidelines for the selection of support systems. Rather it complements the selection and design process as it identifies the implications of using a particular reinforcement or surface support element in a corrosive environment. As such it can be useful in any trade-off study that has to account for geomechanical, corrosion, economic and production considerations in the choice of a support system.

Figure 10   Use of monitoring data for decision making

6   Conclusions

The corrosion of support systems has significant economic and safety consequences for operating mines. A better understanding of the conditions that control the corrosion rate of support systems can be used to predict how long it will take for the support capacity to be reduced based on the mineralogy of an orebody. This in turn can be used by mine operators in mine planning, to improve strategies for choosing support. For instance, different support materials may be used depending upon whether an area is for short or long term access. In addition, it can be used to identify areas that may need reconditioning of support.

It has been demonstrated that corrosion coupons provide an excellent method to quantify the corrosion rate of support in an underground mining environment. Coupons installed at different sites provided a consistent narrative on the evolution of corrosion of support in a range of environments. The implementation of a tensile test program demonstrated the direct relationship between the tensile strength of corroded samples and the recorded corrosion rate, or thickness, of the component. This has allowed the construction of a design chart to quantify the impact of corrosion on the loss of capacity of rock support. A review of on-site observations over a five year period and from the experimental program has allowed the authors to prepare a series of guidelines on the susceptibility of different support elements. This can provide an additional design tool to identify the optimum support strategy for a given mining operation.

Acknowledgement

References

ASTM Standard, Designation: G4–01 (2003), Standard Guide for Conducting Corrosion Tests in Field Applications, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

ASTM Standard, Designation: G1–03 (2001), Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

ASTM Standard, Designation: E8– 99 (1999), Standard Test Methods to Tension Testing of Metallic Materials, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

Charette, F. (2012) Stochastic Approach to the Corrosion Assessment of Rock Bolts, ROCKENG12, in Proceedings 21st Canadian Rock Mechanics Symposium, May 5–9 2012, Edmonton, CARMA, pp. 303–310.

Charette, F., Germain, P. and Hadjigeorgiou, J. (2004) Corrosion Behaviour of Swellex Bolts in Underground Mining Environments, Canadian Institute of Mining, Annual General Meeting, Edmonton.

Dorion, J.F., Hadjigeorgiou, J. and Ghali, E. (2010) Influence of corrosion rate on the capacity of rock support, ARMA 10-259, American Rock Mechanics Association, in Proceedings 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, 27–30 June 2010, Salt Lake City, UT.

Dorion, J.F., Hadjigeorgiou, J. and Ghali, E. (2009) Quantifying the rate of corrosion in selected underground mines, in Proceedings Rock Eng09, May 9–14 2009, Toronto, CARMA.

Dorion, J.F. and Hadjigeorgiou, J. (2008) Caractérisation des environnements miniers menant à la corrosion des systèmes de soutènement, in Proceedings Maintenance Engineering Underground Mine Operators Conference, CIM, Val D'Or, CD-rom only.

Hadjigeorgiou, J. Dorion, J.F. and Ghali, E. (2008) Support System Performance Under Different Corrosion Conditions, The Journal of the Southern African Institute of Mining and Metallurgy, Vol. 108 June 2008, pp. 359–365.

Hadjigeorgiou, J., Ghali, E., Charette, F. and Krishnadev, M.R. (2002) Fracture analysis of friction rock bolts, in Proceedings 5th North American Rock Mechanics Symposium and the 17th Tunnelling Association of Canada, Conference: NARMS-TAC, 7–10 July 2002, University of Toronto Press, pp. 881–887.

Hassell, R., Villaescusa, E., Thompson, A.G. and Kinsella, B. (2004) Corrosion assessment of ground support systems, in Proceedings Fifth International Symposium on Ground Support, Ground Support in Mining and Underground Construction, E. Villaescusa and Y. Potvin (eds), 28–30 September 2004, Perth, Australia, Balkema, Rotterdam, pp. 529–542.

Li., C. and Lindblad, K. (1999) Corrosion classification of the underground environment, Rock Support and Reinforcement Practice in Mining, E. Villaescusa, C.R. Windsor and A.G. Thompson (eds), Balkema, Rotterdam, pp. 69–75.

Robinson, J. and Tyler, D.B. (1999) A study of corrosion in underground reinforcement at Mount Isa Mines, Corrosion classification of the underground environment, Rock Support and Reinforcement Practice in mining, E. Villaescusa, C.R. Windsor, and A.G. Thompson (eds), Balkema, Rotterdam, pp. 77–82.

Villaescusa, E., Hassell, R. and Thompson, A.G. (2008) Development of a corrosivity classification for cement grouted cable strand in underground hard-rock mining excavations, The Journal of the Southern African Institute of Mining and Metallurgy, Vol. 108 June 2008, pp. 301–308.

Villaescusa, E. (2004) Weld Mesh for static rock support in Australia, in Surface Support in Mining, Y. Potvin, T.R. Stacey and J. Hadjigeorgiou (eds), Australian Centre for Geomechanics, Perth, pp. 385–389.