Support system performance under different corrosion conditions

by J. Hadjigeorgiou*, J.F. Dorion* and E. Ghali*

Synopsis

This paper reports on recent field observations on the performance of support systems under different corrosion environments in Canadian underground mines. Phenomenological data are used to gain a better understanding of the main causes of corrosion in underground metal mines. Preliminary field data collected from five metal mines have been complemented by atmospheric and water sample analysis as well as fractography and metallographic studies. This has identified dominant factors that control the corrosion of support systems. The data are analysed in order to develop a support strategy for mines operating in corrosion environments.

Introduction

Ground control strategies employ reinforcement and surface support units to create a support system that can ensure the stability of excavations in rock. There are several tools that can be used to design a successful support system. These include rules gained from past experience, empirical classification systems, and analytical and numerical methods. An inherent assumption in the choice of support is that it will perform as designed, and maintains its capacity over the service of the excavation.

Loss of support capacity can be attributed to blast damage, poor installation procedures and at times to corrosion of any component of the reinforcement system. A support system is considered failed when it no longer provides the support for which it was designed. The different types of corrosion forms that may attack support systems are illustrated in Figure 1, after Hadjigeorgiou *et al.* (2002).

Although the importance of corrosion in the Canadian mining industry has been recognized for some time, Sastri *et al.* (1994), there have been no major investigations on the influence of corrosion on support capacity in Canadian mines. The case is different in Australia where Hassel *et al.* (2004) have conducted comprehensive studies of corrosion in metal mines and Hebblewhite *et al.* (2004) report on bolt failures in coal mines.

Hebblewhite *et al.* (2004) provide a practical description of stress corrosion cracking as 'slow, progressive crack growth under application of sustained load (either residual or applied) in a mild corrosive environment, with failure occurring below the ultimate tensile strength of the material'. They have identified the following indicative factors that may contribute to premature rock failure:

- Presence of clay bands within the roof strata
- Limited shearing within the strata inducing bending within the bolts
- High tensile steel bolts
- Some groundwater present in the strata
- Presence of bacteria to promote localized corrosion or growth of already present faults within bolts.

Robinson and Tyler (1999) have classified corrosion of support at Mount Isa mines while Hassel *et al.* (2004) describe a very comprehensive investigation on corrosive mining environments in several Australian metal mines. Based on collected field data they concluded that existing corrosion classification systems were generally not appropriate for the encountered conditions in Australian metal mines. Consequently they looked into developing a more accessible corrosivity classification system for Australian metal mines.

In Scandinavia, Li and Lindblad (1999) developed two corrosivity classification systems for rock bolts exposed to dry and wet conditions. Satola and Aromaa (2003, 2004) present the results of comprehensive laboratory corrosion testing in rebar bolts and cable strands. The main interest was to distinguish the differences in corrosion

* *Université Laval, Canada.*
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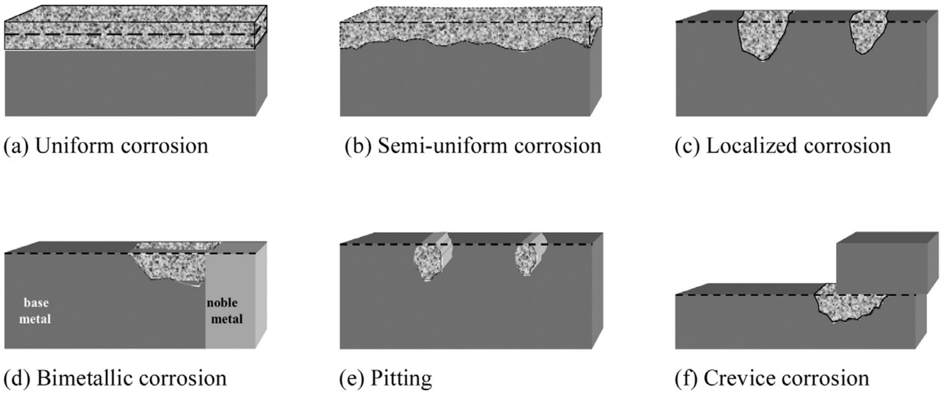


Figure 1—Types of corrosion that may attack rock bolts, modified from Dillon after Hadjigeorgiou *et al.* (2003)

(a) (b)

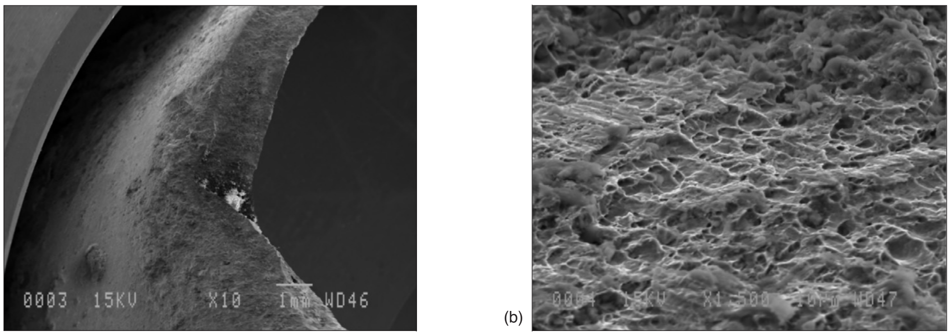


Figure 2—(a) Fractography of fracture surface at 10X; (b) Close –up of the fracture surface at 1500X, after Hadjigeorgiou *et al.* (2002)

resistance and different types of cable strands. They demonstrated that treating the surface of strands to protect against corrosion resulted in higher bond strengths between bolt and grout and in bolts that display a high stiffness.

In a rock support context there are several approaches towards addressing corrosion issues. Quite often the major task is to undertake failure analysis of support systems whereby corrosion may be one of the possible causes. Fundamental investigations aim to help us understand the phenomenon. Furthermore, there is a necessary effort to identify and protect mine areas susceptible to corrosion. This is motivating ongoing work to develop protective coatings for support systems that would make them corrosion resistant.

Support system failure analysis

In Canadian mines it is required to investigate all reported ground falls. The main objective is to identify the underlying causes of failure and provide recommendations on how to prevent or mitigate the impact of ground falls in the future. A failure analysis involves a reassessment of the employed design parameters, geomechanical conditions, quality of installation, performance of the support system, etc. A back analysis is then used to identify plausible failure mechanisms of the support system.

In cases where there are reasons to suspect that corrosion was a contributing factor to support failure, a visual assessment of the failed support system components should be followed by macro photography and a microscopic analysis using a scanning electronic microscope. Closer inspection requires the preparation and analysis of metallographic sections. This is often combined with some localized analysis of water samples.

Fractography

Support systems can fail under several circumstances. Figure 2a illustrates the fracture surface of a rock bolt recovered following a fall of ground from a hard rock mine under a 10X magnification. Figure 2b provides a close-up under 1500X. This ductile fracture was characterized by the presence of shallow and inclined dimples. Ductile fractures display significant plastic deformation prior to and during crack propagation. Brittle fractures show no gross deformation and very little micro-deformation and are characterized by a rapid rate of crack propagation.

Metallography

Figure 3a shows an extreme irregular corrosion attack of the external surface of a longitudinal section of a rock bolt. The presence of the oxide layer in Figure 3a and the dispersion of a metallic piece in Figure 3b support the analysis that, for this particular rock bolt, corrosion attack was rigorous and probably contributed to the failure of the rock bolt. In this example the metallographic analysis allowed the determination of the surface reduction along the fracture. A longitudinal section was used to determine the extent of corrosion close to the surface of the fracture.

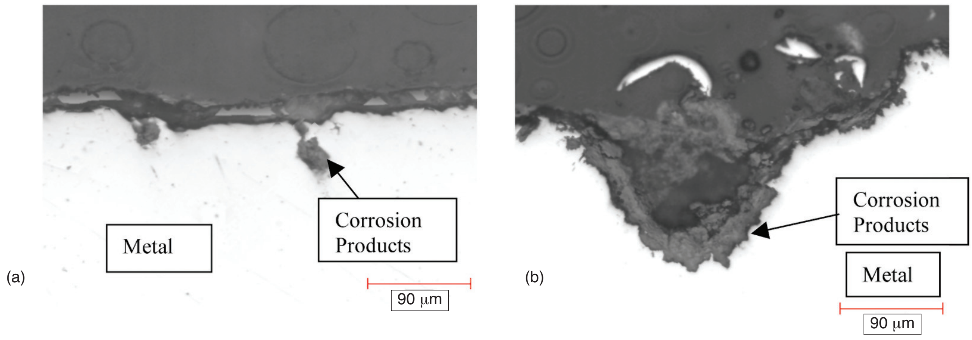


Figure 3—(a) Longitudinal sections showing extreme localized attack; (b) fragmentation of metallic surfaces

In situ pull-out tests

Charette *et al.* (2004) investigated the loss of capacity of Swellex bolts over time by analysing the results of field pulls out data from several mining operations in North America. The tested bolts were grouped into those exposed to low to moderate corrosive conditions and those that were installed to moderate and highly corrosive environments. It was then possible to provide an indication of the remnant bolt capacity as a function of observed corrosion rates for the Swellex bolts. The observed corrosion rates were 0.04 mm/year to 0.07 mm/year for low to moderate corrosion environments. In highly corrosive environments the corrosion rates ranged from 0.15 to 0.70 mm/year. Another interesting observation was that the onset of corrosion was approximately 12 months after installation for the more corrosive environments and 18 months for the less corrosive conditions.

Underground metal mines

Underground mines rely on a variety of support systems to ensure the stability of temporary and permanent underground excavations. There is strong anecdotal evidence that corrosion can be responsible for loss of support capacity. Once this is recognized it is necessary to undertake necessary rehabilitation to ensure the stability of excavations. Mines that experience corrosion problems often develop local empirical rules such as 'loss of support after 10 months'. Quite often these rules are not based on comprehensive analysis. There is a clear need to establish a standardized methodology that can provide the necessary framework to record in a consistent way all cases of corrosion and analyse the available data in order to identify any trends. As more data become available it will be possible to develop consistent support strategies.

A field campaign was undertaken in 2007 in order to provide a preliminary database of corrosion related parameters in underground metal mines. The following mines participated in this investigation: Niobec, Mouska, Doyon, LaRonde and Géant Dormant. The selected mines provided access to a range of mining and operational conditions. The sampling methodology was similar to that used by Hassel *et al.* (2004) in Australian mines.

Groundwater

Water samples were collected and analysed *in situ* to determine their relative conductivity, acidity, dissolved oxygen and temperature. The conductivity of a solution is a measure of its ability to transport current. As the conductivity of a solution increases so does the corrosion of metals in that solution. Conductivity is recorded in Siemens per metre (S/m) in SI units or as microohm per cm (µΩ/cm) in the United States. Drinking water has a conductivity of 0.005–0.05 S/m. The acidity or alkalinity of a solution is measured by its pH value defined as $-\log(H^+)$. Alkaline environments are characterized by high pH values, with acidic solutions having low pH values. Solubility is a measure of 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 with higher temperatures. 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). The results of the *in situ* tests are summarized in Table I.

It is of interest to note the relatively high water temperatures at LaRonde. These are attributed to the fact that the water samples were taken at greater depth than the other operations. Typically corrosion rates increase as temperatures increase. Table I also illustrates that the analysed water samples had pH values ranging from 3.4 to 8.0. Acidic environments were present at LaRonde and Doyon mines with the rest of the sites displaying weak alkaline or normal environments. The higher conductivity ratings are also a source of concern. The solubility of oxygen is an important influence on the corrosion rate. In this investigation the recorded values ranged from 5.9 to 9.0 ppm. The recorded conductivity is directly related to the presence of solids.

Table II summarizes the results obtained from the analysis of the collected water samples at the investigated sites. The corrosivity of an environment is influenced by the degree of ionization in the solution. Of particular significance in this investigation was the recorded high concentration of

Table I

***In situ* analysis of water samples**

Parameters	Niobec			Mouska			GéantDormant		Doyon			LaRonde	
	1150-GA-17	1150 ventilation 1-E	1450-GA-34-PS44	Level 8-access shaft 2	Level 8-drilling bay	Level 11-drilling west	60-8-275-PS105	60-3-370-PS134	8-2(8-3)-principal ventilation access	9-4-access-2.08	10-0-access - 1.33	158-20-57	203-20-52
Temperature (°C)	13.5	15.0°	14.2	9.7	9.0	11.6	8.0	7.9	15.7	14.6	16.8	27.0	28.4
pH	7.8	8.0	7.7	7.6	7.6	6.9	7.2	7.1	2.9	4.0	5.9	3.4	4.4
Dissolved Oxygen (ppm)	7.4	8.8	8.7	8.2	9.0	5.9	11.2	9.3	8.0	8.8	9.0	6.5	7.4
Salinity (ppt)	6.7	-	10.1	0.2	0.6	4.9	2.2	1.0	3.5	8.2	1.9	17.9	5.0
Conductivity (μS)	9150	6530	13630	282	860	6540	2743	1301	5240	11250	3045	30800	9650

Table II

Water analysis of the investigated sites

Parameters (ppm)	Niobec			Mouska			GéantDormant		Doyon			LaRonde	
	1150-GA-17	1150 ventilation 1-E	1450-GA-34-PS44	Level 8-access shaft 2	Level 8-drilling bay 6450E	Level 11-drilling bay (waste)	60-8-275-PS105	60-3-370-PS134	8-2(8-3)-principal ventilation access	9-4-access-2.08	10-0-access - 1.33	158-20-57	203-20-52
Ca	296	151	470	67	159	1370	290	182	424	381	610	404	449
Cu	-	-	-	-	-	-	-	-	14.1	-	-	154.0	0.4
Fe	-	-	-	-	-	-	0,5	0,4	334	2170	103	589	32,6
K	48.9	29.0	51.8	2.3	3.5	2.7	12.2	4.7	7.1	14.4	18.4	17.4	117.0
Mg	97.2	49.4	149.0	7.6	13.3	1.4	45.8	29.1	380.0	446.0	191.0	591.0	187.0
Mn	-	-	0.2	0.3	-	0.2	-	0.2	50.4	53.0	14.5	72.1	66.5
Na	2020	1010	3070	3.1	53.7	425	416	136	132	63.1	35.5	821	859
Ni	-	-	-	-	-	-	-	-	0,8	2.5	-	7.7	0.8
Pb	-	-	-	-	-	-	-	-	-	-	-	2.2	3.7
Zn	-	-	-	-	-	-	7.2	1.6	9.8	4.3	-	14000	13000
Si	7.9	5.1	5.9	6.4	7.5	3.7	4.0	6.4	46.8	13.1	6.3	100.0	25.9
F	-	-	-	-	-	-	-	-	40	61	-	440	61
Cl	4432	1938	5701	9	171	3128	1450	49	50	140	19	368	789
NO_2	-	-	-	-	-	-	-	-	-	-	-	-	-
Br	-	-	-	18	-	-	10	-	-	-	15	-	-
NO_3	348	21	-	-	9663	-	-	-	93	-	158	-	1696
SO_4	78	182	247	56	323	733	67	84	5128	18053	2737	45757	19029

aggressive ions such as Cl^- and SO_4^-. Niobec is an example of high Cl^- concentrations ranging from 1938 to 5701 ppm while the higher SO_4 concentrations are associated with Doyon (2737–18053) and LaRonde (19029–45757 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. On the other hand, certain ions such as CO_3^{-2} and HCO_3^- as well as Ca^{2+} act as inhibitors.

Atmospheric corrosion

The most important factors influencing the rate of atmospheric corrosion are moisture and heat. It should be recognized that as mines operate deeper then the ambient, heat will not only affect workers but also will have a direct impact on the resistance to corrosion of support systems. It is generally accepted that corrosion activity will double for each 10°C rise in temperature.

Relative humidity is the ratio of the quantity of water vapour present in the atmosphere to the saturation quantity at a given temperature. There exists a critical humidity, usually assumed over 60%, beyond which the corrosion rate increases. Atmospheric corrosion will be further influenced by the presence of pollutants. Table III provides a summary of information collected during the site visits. All investigated sites are characterized by high relative humidity that contributes to corrosion. Most mines do not operate the ventilation system continuously for all excavations. This is reflected in the reported variations in air flow summarized in Table III.

Table III

Atmospheric data at selected sites

Location	Niobec			Mouska			GéantDormant			Doyon			LaRonde		
	1150-GA-17	**1150 ventilation 1-E**	**1450-GA-34-PS44**	**Level 8-access shaft 2**	**Level 8-drilling bay - 6450E**	**Level 11-drilling bay west**	**60-30-292-PS43**	**60-8-275-PS105**	**60-3-370-PS134**	**8-2(8-3)-principal ventilation access**	**9-4-access-2.08**	**10-0-access - 1.33**	**149-20 west**	**158-20-57**	**203-20-52**
Depth (m)	350	350	442	435	435	610	605	605	605	460	500	635	1490	1580	2030
Temperature dry (°C)[1]	15.0	20.0	16.0	12.0	9.0	11.6	9.0	9.0	9.0	16.0	15.0	19.0	26.0	28.0	30.0
Temperature humid (°C)[1]	12.5	20.0	13.5	12.0	9.0	(11)	9.0	8.7	9.0	16.0	15.0	18.0	26.0	28.0	28.0
Relative humidity (%)[1]	70–80%	100%	79%	100%	100%	>80–100%	100%	95%	100%	100%	100%	90%	100%	100%	(85%)
Condensation point (°C)	11.2	20.0	11.5	12.0	9.0	10.5	9.0	8.5	9.0	16.0	15.0	17.5	26.0	28.0	27.0
Air flow (pcm)	45 000	65000–200000	47000	42000	0–20000	0–20000	500–16000	5000–22500	2000–12000	0–40000	0–25000	0–20000	0–50000	0–50000	0–50000

Note: [1]Recorded temperatures and humidity at the time of the site visits

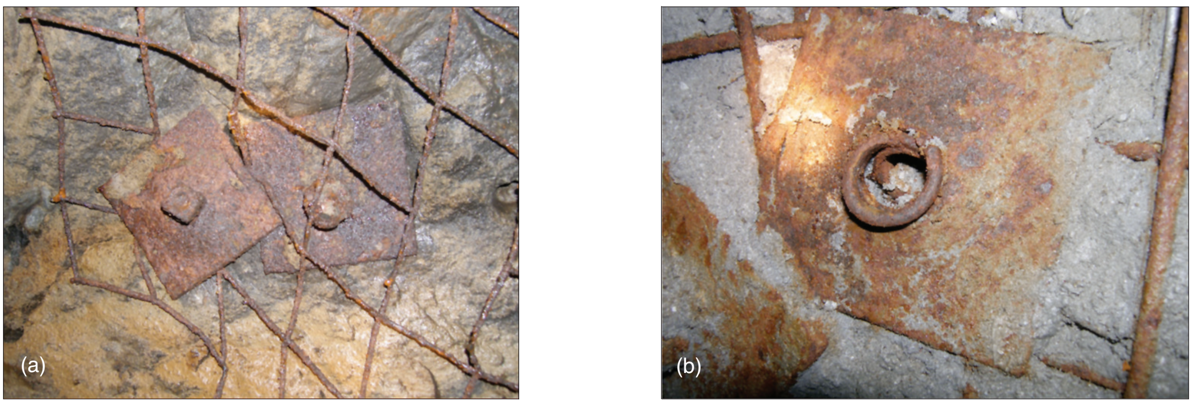


Figure 4—(a) Corroded plates with deteriorating screen; (b) corroded split set ring

Support systems

The mines that participated in this study use a variety of support systems to address ground control issues. Furthermore, the investigated sites at each mine were in varying ground conditions, and the time of installation varied from 3 to 180 months. None of the specific sampling sites had been witness to falls of grounds. These inherent variations accentuate the difficulty in developing some sort of mine specific corrosivity classification. Now it is recognized that there is a need for a much more comprehensive sampling programme before any comprehensive guidelines on corrosion based susceptibility zones are established. Nevertheless, it is felt that there is real value in trying to identify salient factors that may contribute to the corrosion of the support systems.

All sites used a combination of screen and bolts to provide support. The reinforcement units included rebar bolts, split sets, Swellex bolts and mechanical bolts. A visual assessment of the observed degree of corrosion was undertaken at the locations where water and atmospheric measurements were recorded. Finally, support specimens were collected for metallographic analyses in the laboratory. Figures 4 and 5 illustrate examples of observed corrosion at different sites.

An example of atmospheric corrosion is illustrated in Figure 4a where surface corrosion is observed on the elements of the support system. A second example of atmospheric corrosion is presented in Figure 4b, clearly illustrating the damage to the ring of the split set. In this particular location the rock mass was weak and the excavation had converged significantly. At both sites the relative humidity of the atmosphere was 100%.

An example of heavily corroded support system is shown in Figure 5a. This was attributed to both the very high humidity but also to the presence of water infiltration in the back of the excavation. A closer inspection of the photograph shows the water droplets on the support as well as resulting metal laminations, Figure 5b). The analysis of the water samples, flowing through the rock fractures at this location, revealed a concentration of 1938 ppm of Cl^-. In this particular location the screen crumbled when squeezed by the fingers.

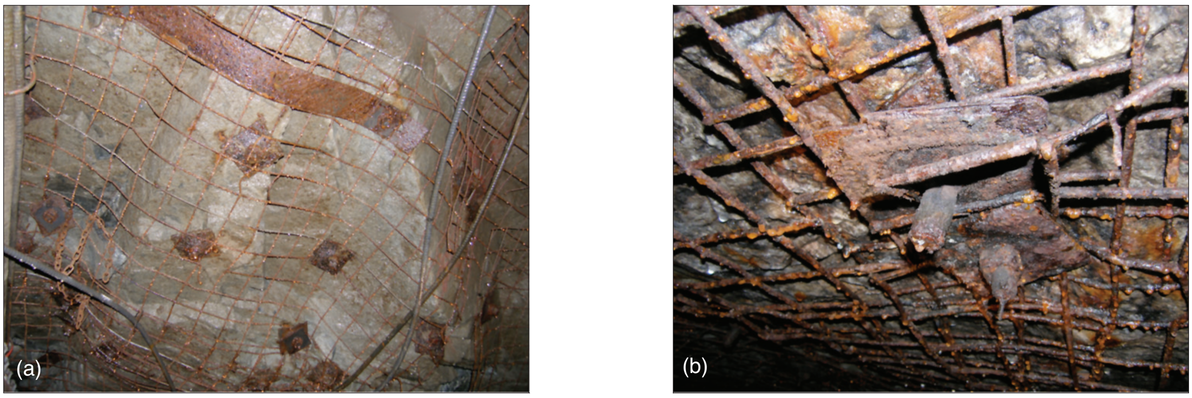


Figure 5—(a) Surface corrosion of support; (b) corroded screen

Table IV

Degree of corrosion at investigated mine sites

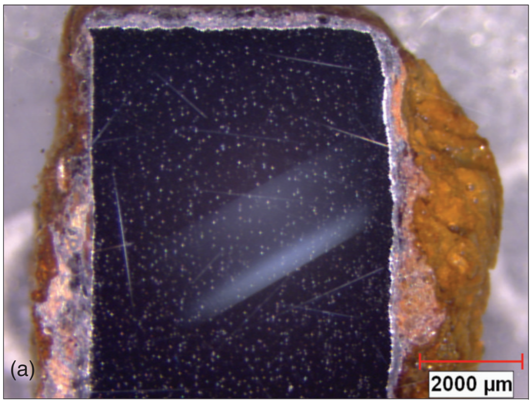
Location	Niobec			Mouska			GéantDormant			Doyon			LaRonde		
	1150-GA-17	1150 ventilation 1-E	1450-GA-34-PS44	Level 8-access shaft 2	Level 8-drilling bay - 6450E	Level 11-drilling bay west	60-30-292-PS43	60-8-275-PS105	60-3-370-PS134	8-2(8-3)-principal ventilation access	9-4-access-2.08	10-0-access - 1.33	149-20 west	158-20-57	203-20-52
Excavation age (months)	60	120	12	114	66	15	66	54	18	180	9	<3	84	3	12
Degree of corrosion (visual observation)	Advanced to very advanced	Advanced to very advanced	Corrosion with little penetration to advanced	Advanced corrosion when water is present	Localized staining to advanced corrosion (water)	Localized staining to advanced corrosion (water)	Localized staining to advanced corrosion (water)	Localized staining to advanced corrosion (water)	Localized staining	Advanced to very advanced	Localized staining to advanced corrosion (water)	Localized staining to advanced corrosion (water)	Localized staining to important degradation	Localized staining to advanced corrosion (water)	Advanced corrosion

In order to provide a reference point for this preliminary investigation, six levels of corrosion were identified. It is recognized that these will eventually be revised as the established database expands, and the laboratory investigations are completed. The first category was when no visible trace of corrosion was observed on the support systems. The second category was characterized by the presence of localized corrosion traces on the support. Surface corrosion with little penetration was the third category. Once corrosion penetrates a small surface it is considered to be in an advanced state. The next more aggressive state occurs when a penetration of a certain thickness is observed. Finally the last stage is typified with severe degradation or deterioration of the support unit. Table IV provides a summary of the observed degrees of corrosion recorded at the investigated sites. It is recognized that these results will have to be interpreted by recognizing the influence of excavation age, exposure to corrosion agents, type of support, ventilation, etc.

Although it is relatively early to draw firm conclusions, it was noted that in areas where galvanized screen was used it was relatively more resistant to corrosion than other elements of the local support system.

In this preliminary investigation, field observations, atmospheric and water analysis were complemented by fracture analysis of selected support specimens. Figure 6a shows a section of a rock bolt plate under 10X magnification. It is evident that the plate is subject to uniform corrosion over the full plate area. Based on SEM analysis it was noted that the corrosion layers were composed of iron oxides closer to the intact metal, whereas further away there were elements of rock dust including different mineral fragments. The nature of these minerals deposited on the rock bolt plate, particularly the presence of pyrite, may have an important role in the corrosion process under these environments of high humidity. Figure 6b is a section through a screen showing pitting corrosion.

The thickness or diameter of selected support elements collected during the site visits were determined. Using the nominal diameter or thickness and based on the date of installation, it was then possible to quantify the corrosion rate of different support components. These values, however, provide only an estimate and will be followed up with more



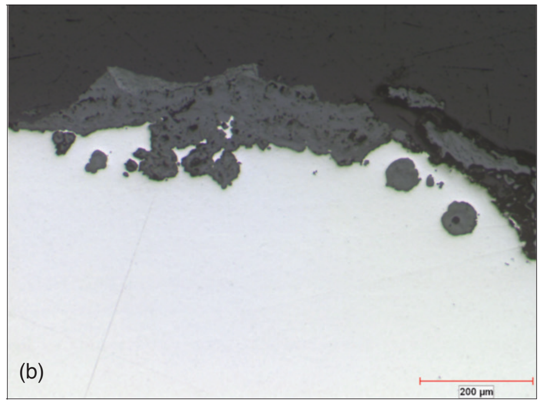


Figure 6—(a) Plate under 10X magnification; (b) Screen section showing corrosion products and pitting (100X magnification)

comprehensive investigations for the range of corrosion environments and support systems. Consideration will be given to parameters such as water and atmospheric properties, quality of steel, etc. The corrosion rates for screen and rock bolt plates varied from 0.07 to 1.40 mm/year (0.38 to 2.98 mm^2/year). It was also noted that mine sites rich in sulphates displayed higher corrosion rates of the support systems.

A good understanding of the expected corrosion rates and the design life of a support system can eventually allow the use of this information in the design of support systems. This will eventually contribute to quantifying the cost of support systems, the potential cost of rehabilitation and the development of an optimal support strategy.

Conclusions

Although corrosion of support systems in Canadian mines is recognized as a major problem, it has not been the topic of comprehensive investigations. Most operations seem to rely on some 'rules' to identify the longevity of support in corrosive environments. These rules do not seem to be based on documented case studies but at best reflect the opinion of particular mining personnel.

Furthermore, the loss of support capacity over time is not considered in the design methodology of support systems. On the contrary, it is recognized that in corrosive environments it is necessary to monitor support performance and if necessary initiate rehabilitation of affected excavations.

This paper presents a preliminary study aiming to eventually provide the framework for characterizing the corrosivity of mining environments in Canadian mines. The objective is to provide further aid in the selection of appropriate support systems and eventually provide reliable guidelines on the projected longevity of support systems.

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