Quantifying the rate of corrosion in selected underground mines

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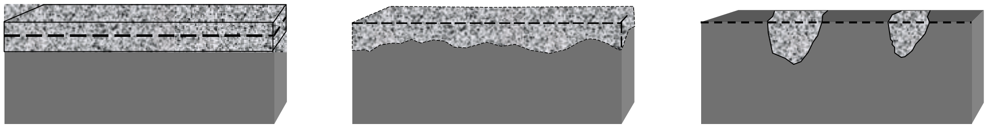
ABSTRACT: This paper presents the results of on-going investigations on the performance of support systems in Québec underground mines. The focus of these investigations is on site observations complemented by laboratory investigations. Of particular interest is deducing the corrosion rate, at selected mine sites, as determined by the installation of monitoring coupons.

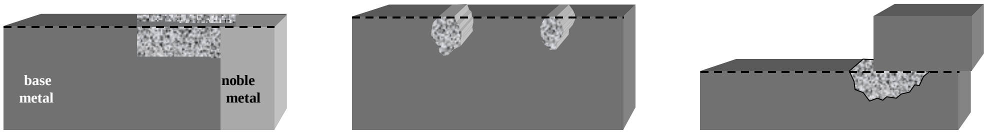
1 INTRODUCTION

Corrosion of support systems can be a major safety and economic concern in underground hard rock mines. An improved insight on the factors that contribute to the corrosion of support systems can aid in the selection of appropriate support strategies and a reliable assessment of the predicted useful life of a support system.

There are several ways to respond to corrosion issues of support systems. Quite often a corrosion investigation is part of a failure analysis of support systems. In this context a support system is considered failed when it no longer provides the support it was designed for. Support systems are susceptible to different types of corrosion processes as illustrated in Figure 1, after Hadjigeorgiou et al (2002).



(a) Uniform corrosion (b) Semi-uniform corrosion (c) Localized corrosion



(d) Bimetallic corrosion (e) Pitting (f) Crevice corrosion

Figure 1. Types of corrosion that may attack rock bolts, modified from Dillon after Hadjigeorgiou et al (2002).

Fundamental investigations aim to help us understand the corrosion phenomena and can lead to protective coatings to increase the resistance to corrosion of support systems. Of particular interest would be the development of a classification system that would identify areas more susceptible to corrosion. This information can eventually be used that would result in corrosion resistant support systems.

This paper presents the preliminary results of on-going investigations in selected Québec underground hard rock mines. These involve the use of a corrosion classification system based on visual observations. This was complemented by a comprehensive testing program where aqueous and atmospheric corrosion were monitored at selected mine sites. This involved direct measurements using corrosion coupons, as well as electrical and analytical methods.

2 GROUNDWATER AND AQUEOUS CORROSION

Investigations on the influence of aqueous corrosion on support systems focused on collecting water samples from reference sites at six mines. This has been on-going since 2007. The employed methodology is described by Dorion & Hadjigeorgiou (2008) and Hadjigeorgiou et al (2008). The in-situ analysis determined the following critical parameters:

- Conductivity. This is a measure of the ability of a solution to transport current. As the conductivity of a solution increases, in most cases, so does the corrosion of immersed metals. It is recorded in Siemens per meter (S/m) in S.I. units or as microohm per cm (μΩ/cm) in the United States. As a reference, drinking water has a conductivity of 0.005 – 0.05 S/m.
- Acidity or alkalinity. This is measured by a pH value defined as $-\log(H^+)$. Alkaline environments are characterized by high pH values with acidic solutions having low pH values. Acidic solutions are more corrosive and attack metals.
- Solubility. This 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 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 ^{0}C. Typically corrosion rates increase as temperatures increase.

Subsequent chemical analysis of collected water samples provided comprehensive information on the presence of selected ions. This information is summarized in Table 1. A correct interpretation of these data is only possible, however, with reference 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^{0}C higher. The increased temperature is a factor that accentuates the susceptibility of the support to corrosion. It is of note that only mines #4 and #5 were recorded as acidic environments the rest of the mines characterized as weak alkaline or normal environments. The pH values of the water samples varied from 3.4 to 8.0. 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^-. Samples from Mine #1 were characterized by high Cl^- concentrations ranging from 1938 to 5701 ppm. The higher SO_4^{2-} concentrations were recorded in samples from Mine #6 (2737-18053 ppm) and Mine #4 (19029-45757 ppm). Aggressive ions in a solution attack the thin protective film that forms on the surface of metals, making them more vulnerable to corrosion. In practical terms 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 Quebec underground mines.

		Mine #1					Mine #2			Mine #3	
Parameter	Units	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	1370	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	2020	1010	3070	65	4	425	13	12
Zn	mg/L	-	-	-	-	-	-	-	-	-	-
Cl	mg/L	1933	2230	4432	1938	5701	20	7	3128	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	1968	4510	9150	6530	13630	439	282	6540	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

		Mine #4				Mine #5				Mine #6	
Parameter	Units	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	2170	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	14000	13000	3	2	10	4	7	2
Cl	mg/L	78	80	368	789	10	19	50	140	1450	49
NO_3	mg/L	NA	NA	-	1696	6	519	93	-	-	-
SO_4	mg/L	NA	NA	45757	19029	88	NA	5128	18053	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	1614	1400	30800	9650	2894	3106	5240	11250	2743	1301
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

- : Undetected; NA : Not analyzed

An operating mine is a dynamic environment where conditions and access are subject to production constraints. This can make long time observations difficult. The same precise location investigated in preliminary corrosion studies in 2007 at Mine #2 was also accessible in 2008. Of interest was the absence of significant variations in the water analysis for this time period, Table 2. Further site visits are scheduled for 2009. Should the site conditions remain constant over time it may be possible to develop reliable corrosion rate predictions for the installed support systems.

Table 2. Analysis of water for Mine #2 at site #2

Year	Ca	K	Mg	Mn	Na	Si	Cl	SO_4	pH	Conductivity	Salinity	Dissolved Oxygen	Temp.
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		µS	ppt	ppm	°C
2008	65,0	2,0	6,9	0,3	5,0	6,0	5,4	7,9	7,1	282	0,2	13,9	10,9
2007	66,6	2,3	7,6	0,3	3,1	6,4	9,0	56,0	7,6	282	0,2	8,2	9,7

3 ATMOSPHERIC CORROSION

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 vapor 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 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. A summary of corroding-steel susceptibilities to the presence of atmospheric corrodants is summarized in Table 3.

Table 3. Steel sensitivities to atmospheric corrodants (Leygraf & Graedel, 2000).

Corrodant	Steel Sensitivity
CO_2/CO_3^{2-}	Moderate
NH_3/NH_4^+	Low
NO_2/NO_3^-	Moderate
H_2S	Low
SO_2/SO_4^{2-}	High
HCl/Cl^-	High
$RCOOH/COOH^-$	Moderate
O_3	Moderate

Table 4 provides a summary of atmospheric observations recorded during the mine visits. Most sites were characterized by high relative humidity that contributes to corrosion. This information is still analyzed and will be cross referenced with the coupon monitoring results presented in the subsequent section.

Table 4. Average atmospheric data at selected sites between July 2008 and January 2009.

Parameter	Mine #1			Mine #2			Mine #3		
	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	76,0
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)	45000	132500	47000	0	42000	0	88000	52000	262000
Air quality	Fresh	Fresh	Operation	Stagnant	Fresh	Stagnant	70% recycled	Fresh	Exhaust

Parameters	Mine #4			Mine #5		
	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)	120950	80400	34000	330000	33000	0
Air quality	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Stagnant

4 DETERMINATION OF CORROSION RATES BY TESTING OF COUPONS

4.1 *Coupon testing*

A corrosion coupon testing program was designed to evaluate the type and rate of corrosion in diverse underground mining environments. Coupon testing is a simple method of corrosion monitoring that provides the opportunity to test different environments over a certain period of time. It can be used to establish the average corrosion rate over a known exposure period by weight loss or gain. Coupons were used by Villaescusa et al (2008) to measure corrosion rates in several Australian underground mines. A sufficient number of coupons were prepared to be installed at five mine sites.

4.2 *Preparation and identification of corrosion coupons*

Each rectangular specimen was 100 x 15 x1.5 mm. Three small holes were drilled in each coupon so that they could be attached in situ and with an identification tag, Figure 2. In all, 60 coupons were installed at every mine, with 12 coupons at each location. At predetermined time intervals (~ 3, 6 and 12 months) 4 coupons are recovered, three made of steel and one galvanized. The coupons are made of hot rolled steel, ASTM A1011 Type B.

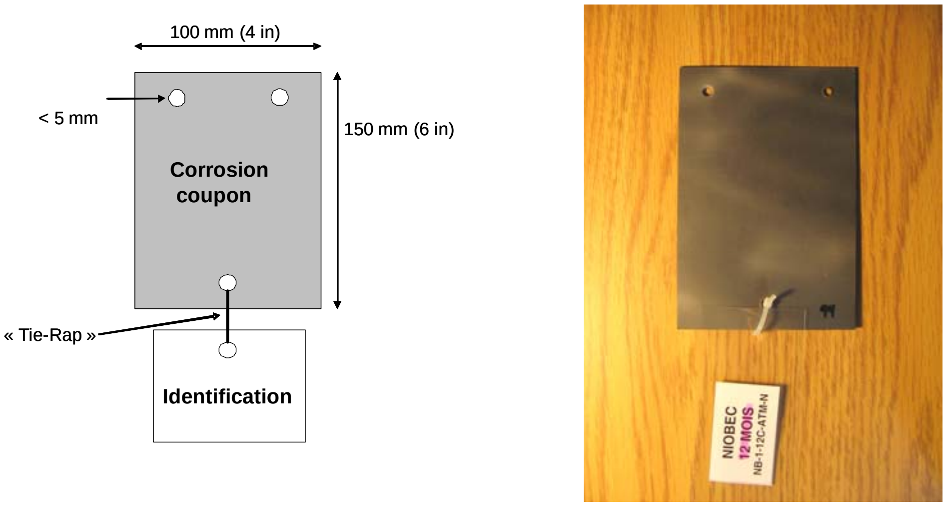


Figure 2. a) Configuration of the corrosion coupons with identification tag and b) corrosion coupon

The coupons were prepared and cleaned following the ASTM Standard G4. After been sandblasted, each coupon was cleaned using distilled water and acetone and dried on paper towels under hot air. Following the cleaning process, the coupons were measured and weighed. A plasticized identification tag was attached to each coupon with a tie-rap. The corrosion coupons were then placed in an airtight plastic bag to prevent any contact with ambient environment before their installation underground. Figure 3 illustrates installed coupons at two sites: a) in relatively dry conditions and b) in an area under direct water flow.

Figure 3. a) Corrosion coupons attached from the mine screen at the back of a drift; b) Coupons installed in flowing water along a drift wall

4.3 *Assessment of Corrosion Damage*

Once the coupons were recovered, after the pre-defined exposure (around 3 and 6 months), they were treated to remove corrosion products following the ASTM Standard G1. The first cleaning step of the coupon required the removal of corrosion products and crust using a smooth brush. Then they were placed in an acidic solution containing antimony trioxide and stannous chloride to remove any corrosion products. For the galvanized coupons, the cleaning product is reagent water containing ammonium persulfate.

The initial total surface area and the mass lost during the test are determined. The average corrosion rate (mm/year) was obtained by the following equation:

$$\text{Corrosion Rate} = \left(\frac{\text{K x W}}{\text{A x T x D}} \right) \tag{1}$$

where: K = 8.76 X 10^4 (for units in mm/y); T = time of exposure in hours; A = area in cm^2; W = mass loss of coupon in grams, and D = density of coupon in g/cm^3

The in situ characteristics of each site have already been presented in Tables 1 and 3. The resulting corrosion rate, calculated by the coupons, is summarized in Table 5. Based on the 2,5 month and 5,5 month readings the corrosion rate of steel is higher for aqueous corrosion as compared to atmospheric corrosion. As expected corrosion rates are lower for galvanized steel. The impact of humidity and condensation has not yet been completed. Some areas in the mines having high relative humidity exhibited low corrosion rate while other places with high humidity are corrosive. There are insufficient data to determine with confidence the impact of blasting gas and exhaust air in mine using diesel equipment. It should also be noted that typically corrosion rates decrease with time. This is the case since steel products corrode more rapidly at the beginning of exposure. The subsequent deposition of a corrosion crust results in a reduction in the corrosion rate. This observation has been reported by several authors including Hassell (2007), however, this may change the type or form of corrosion from uniform to non-uniform or localized corrosion.

Table 5. Corrosion at investigated sites (not all data are available at this time)

				Corrosion rate (mm/year)	
Mine	Location	Environment	Coupon	After 2,5 months	After 5,5 months
Mine #1	Site #1	Aqueous	Steel	0,32	0,18
			Galvanized	0,05	-
	Site #2	Aqueous	Steel	0,29	0,18
			Galvanized	0,09	-
	Site #3	Atmospheric	Steel	0,04	0,06
			Galvanized	0,03	0,01
	Site #4	Atmospheric	Steel	0,12	0,05
			Galvanized	0,03	0,01
	Site #5	Atmospheric	Steel	0,15	0,11
			Galvanized	0,05	0,03
Mine #2	Site #1	Atmospheric (condensation)	Steel	0,18	0,14
			Galvanized	-	0,02
	Site #1	Aqueous	Steel	0,27	-
	Site #2	Atmospheric (condensation)	Steel	0,11	0,03
			Galvanized	-	0,02
	Site #2	Aqueous	Steel	0,16	-
	Site #3	Atmospheric (condensation)	Steel	0,03	0,04
			Galvanized	-	0,02
Mine #3	Site #1	Atmospheric	Steel	0,10	0,05
			Galvanized	-	0,01
	Site #1	Aqueous	Steel	0,04	-
	Site #2	Atmospheric	Steel	0,05	0,06
			Galvanized	-	0,01
	Site #2	Aqueous	Steel	0,05	-
	Site #3	Atmospheric	Steel	0,04	0,04
			Galvanized	-	0,01
Mine #4	Site #1	Atmospheric (condensation)	Steel	0,09	-
			Galvanized	0,03	-
	Site #1	Aqueous	Steel	0,10	-
			Galvanized	0,13	-
	Site #2	Atmospheric (condensation)	Steel	0,01	-
			Galvanized	0,03	-
	Site #2	Aqueous	Steel	0,18	0,14
			Galvanized	0,16	-
	Site #5	Atmospheric	Steel	0,08	-
			Galvanized	0,03	-
Mine #5	Site #1	Atmospheric (condensation)	Steel	0,08	-
	Site #1	Aqueous	Steel	0,39	-
	Site #2	Atmospheric (splashing)	Steel	0,34	0,27
			Galvanized		0,06
	Site #2	Aqueous	Steel	0,37	-
	Site #3	Atmospheric (condensation)	Steel	0,11	0,05
			Galvanized		0,02

5 TENSILE STRENGTH OF COUPONS

It is recognized that corrosion can have a detrimental impact on the capacity of a support system. This investigation is exploring the correlation between the loss of strength of steel and the rate of corrosion. The designed testing program calls for a series of tests of recovered coupons. The corrosion coupons are tested in tension accordingly to ASTM E8 standards. These will be compared to the reference (non-corroded) samples. As more data become available it should be possible to establish useful correlations between corrosion coupon rates and material resistance.

Figure 4. a) Tensile sample from a coupon and b) sample after testing

The average tensile strength of the coupons is 358 MPa. Tests on corroded coupons exposed to water at Mine #4, site #2 characterised by a corrosion rate of 0.14 mm/y resulted in average tensile strength of 302 MPa. The recovered coupon was in flowing water at a temperature of 9.8^{0}C. The results of the chemical analysis, at this site, is presented in table 1. The test coupon was affected by pitting, Figure 5. A tested sample from this coupon is shown in Figure 6.

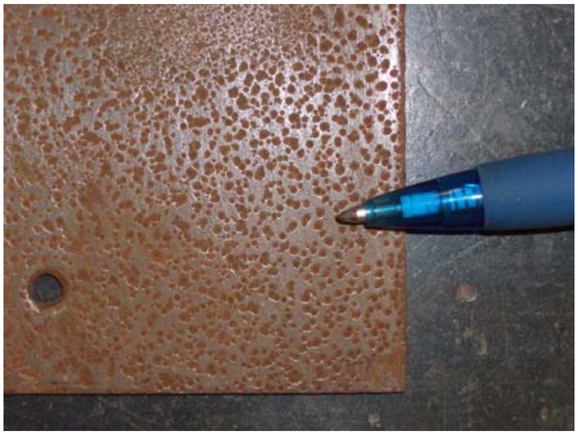


Figure 5. Coupon from Mine #4 site #2 showing pitting.

Figure 6. Coupon from Mine #4 site #2 after testing.

6 CONCLUSIONS

A comprehensive research program on support system performance in corrosive environments has been undertaken with the collaboration of 6 mines. This investigation aims to characterize and monitor the performance of support systems over time several environments. Preliminary results suggest that it is possible to quantify the performance of support systems under corrosion. This paper reports work in progress. As more data become available these relationships can lead to useful information on the choice of support systems and reliable estimates of their longevity.

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