

An acidic water corrosive environment and ground support strategies at the Grasberg Block Cave mine, Indonesia

JPE Hamman *PT Freeport Indonesia, Indonesia*

REP Belseran *PT Freeport Indonesia, Indonesia*

B Kriska *PT Freeport Indonesia, Indonesia*

T Ramadhan *PT Freeport Indonesia, Indonesia*

AY Sugiyanto *PT Freeport Indonesia, Indonesia*

H Banda *PT Freeport Indonesia, Indonesia*

Abstract

The Grasberg Block Cave (GBC) mine is below the Grasberg open pit at PT Freeport Indonesia (PTFI). The production and infrastructure levels are predominantly in the Grasberg Igneous Complex (GIC) and less so in the surrounding sedimentary rocks of the Waripi and Faumai formations. Development of the production levels in the GBC Production Block 2 South started in 2016, and undercutting commenced in 2018.

A prominent mineralised zone – the heavy sulphide zone (HSZ) with 10–75% pyrite and pyrrhotite – forms the outer boundary of the GIC along the country rock. High levels of oxidation and subsequent corrosion associated with the HSZ were identified within the first two years of development. Corrosion rates indicated an aggressive corrosive environment with pH levels of less than 4 (identified as a potential hazard) that could lead to support deterioration and excavation instability in the production and mine infrastructure levels.

A corrosion assessment based on the presence of sulphides, water volumes and water chemistry was conducted to determine the corrosivity of the groundwater. Corrosion maps were developed in the initial stages of development and followed up by actual corrosion mapping to determine the accuracy and severity of the expected corrosion zones. During this study, it became clear the parameters that played an important role in determining the corrosivity of the acidic groundwater in the GBC differ greatly from the saline-dominated corrosive environments identified in Australia and other areas of the mining industry.

Numerous groundwater datasets, laboratory analysis and measured ground support corrosion rates formed the basis of this study to determine the relationship between the pH, sulphate ions, electric conductivity and corrosion rates. Factors that increase and delay the corrosion rates were observed and documented. Various corrosive resistant ground support types were evaluated to determine their effectiveness in acidic environments.

This paper briefly describes the derivation of an acid-dominated aqueous corrosion design table that could be used in the industry to determine potential corrosion rates. Corrosion of ground support, as well as the management of corrosion, are also discussed.

Keywords: *corrosion, acidic environments, sulphides, corrosion rates, pH levels, ground support strategies*

1 Introduction

During operation of the Grasberg open pit, the heavy sulphide zone (HSZ) was stockpiled, which, over time oxidised and exhibited exothermic reactions and associated acid water formation. This resulted in an acid rock drainage strategy that involved the placement of limestone to neutralise the low-pH acid water. Silaen & Budiman (2017) recognised that this phenomenon also could develop in underground drifts that were excavated in the HSZ.

Detailed evaluation of the corrosive conditions at PTFI over the last four years indicated an acidic-dominated corrosive environment, which is directly related to the distribution of sulphides and groundwater. Apart from the aqueous corrosive environment, two more corrosive environments were identified: atmospheric and dust hybrid. The atmospheric environment is related to gas (SO_2), humidity and air temperatures and is present in exhaust levels, whereas the dust hybrid is related to sulphide-rich dust and humidity and is mostly present in the ore flow and conveyor belt drifts.

Corrosion can materially degrade surface and tendon supports, so that the support system no longer meets the required acceptance criteria for safe working conditions. Corrosion rates, based on the corrosive environment, play a major role in the decision-making process – where and when to implement preventative support maintenance or rehabilitation of ground support. Although the corrosive environments could be delineated accurately from the geological sulphide, groundwater maps and water chemistry data, the actual corrosion does not occur uniformly within these boundaries but in patches and streaks as the pH levels in the water can vary significantly between ground support holes (Figure 1). This phenomenon was also evident in areas where friction bolts (FB) support were installed, and failures occurred in an erratic pattern.

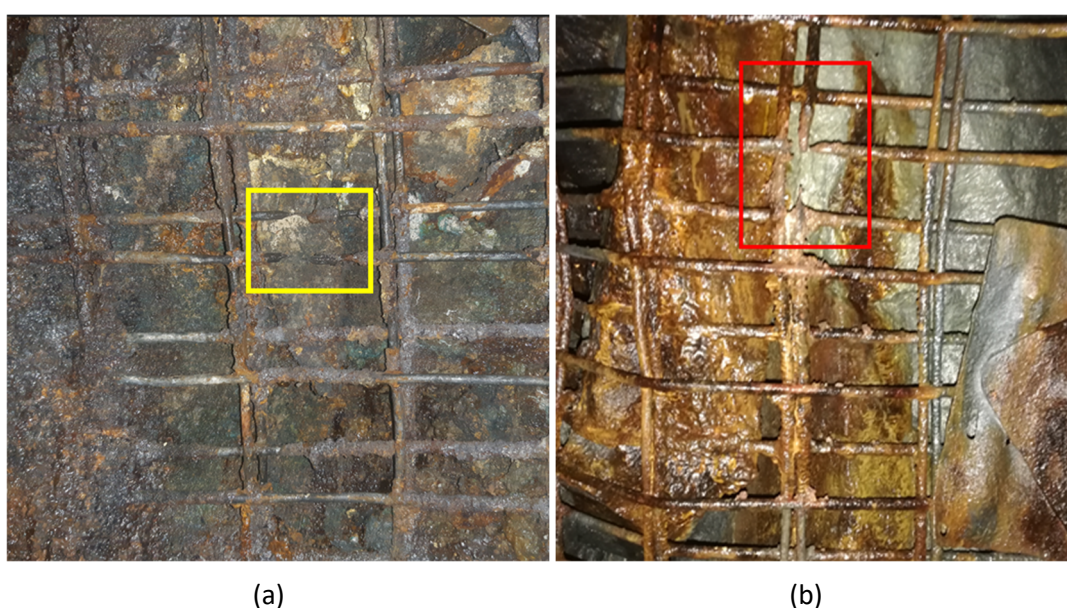


Figure 1 Aqueous corrosion on unprotected (a) 5.6 mm mild steel mesh (yellow square) and (b) 5.6 mm mild steel (red square) showing completed corroded areas next to no- to low-corrosion areas in GBC PB1S EL. Low-corrosion areas were covered by oxidation and corrosion by-products. Acidic corrosion is highly sporadic and less than 5% of the mesh has been corroded in the potential corrosion zones

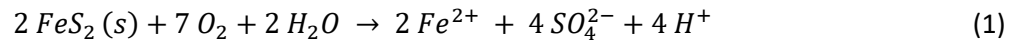
Sulphate attack on cementitious products, such as shotcrete and to a lesser extent concrete, is another method of ground support deterioration because groundwater contains sulphate ions. These ions are present in dolomitic water which is alkaline, as well as in acidic water due to the oxidation of sulphides.

Iron, sulphide and acid bacteria have been found in groundwater as well as in X-ray diffraction results (University of Indonesia 2021) on corrosion by-products from various areas at PTFI. The current bacteria levels are low and are not considered to contribute to the corrosive environment at PTFI.

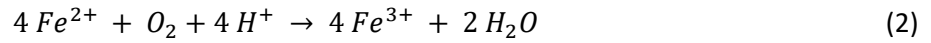
2 Factors contributing to an acidic corrosive environment

Corrosion is the process of destruction of metals by means of chemical reactions (electrochemical cell), and the formation of acidic water (sulphuric acid) is part of the oxidation process of sulphides (Equations 1–4). The oxidation of the sulphides in the HSZ is an exothermic reaction, resulting in environmental hazards such as sulphuric acid ($\text{pH} < 4$), sulphur dioxide (SO_2) gas and heat that increases the mine water and muck temperatures to a range of 15 to 150°C (Loomis et al. 2008).

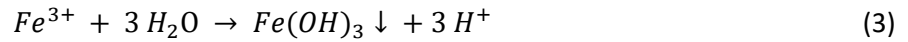
The oxidation process of sulphides is described by Jennings et al. (2008) as follows:



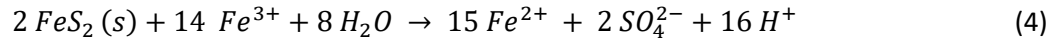
The Fe^{2+} can be further oxidised to Fe^{3+} :



The Fe^{3+} produced can be precipitated as the hydroxide or hydrous iron oxide:



The iron (III) ion (ferric iron) can also oxidise pyrite:



Due to the complexity of corrosion, the evaluation process required contributions from various departments within the GeoEngineering Division at PTFI, including geology, hydrology, QA/QC, corrosion and geotechnical engineering. The mineralisation data, especially the presence of pyrite and pyrrhotite (Figure 2a), and the distribution and volumes of groundwater levels data (Figure 2b), was identified as the most important information to develop potential corrosion maps.

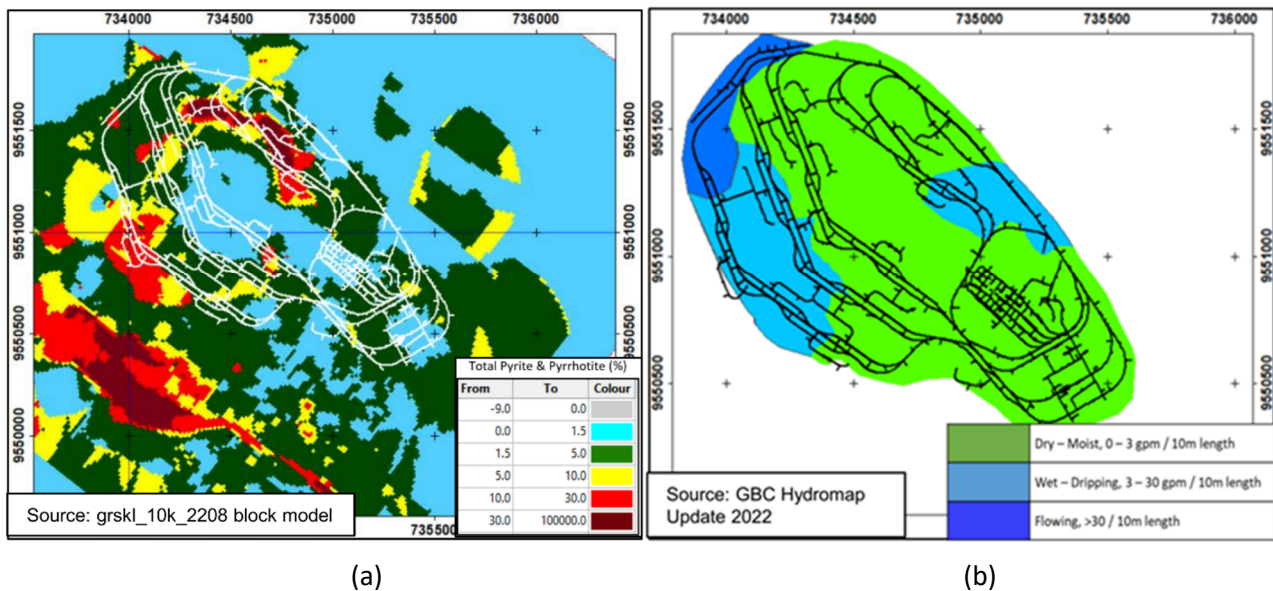


Figure 2 The main contributors to determining the acidic corrosion potential is the sulphide percentages and groundwater volumes. (a) Combined sulphide percentage maps for pyrite and pyrrhotite; (b) Groundwater levels (Bieniawski 1989)

2.1 Water chemistry

A detailed water chemistry analysis provided data on the important chemical relationships in the varying corrosive environments. The hydrogeological group was responsible for the collection of water samples, where the initial data in the field was collected with a Pro DSS multiparameter digital quality instrument testing pH, temperature (T), total dissolved solids (TDS), dissolved oxygen (DO) and electric conductivity (EC) on a monthly to quarterly basis. This field data was used to determine trends between the various collected parameters, especially in the extraction level and rail loop in the GBC.

Detailed analysis was conducted by Sucofindo; an independent laboratory in Timika, Indonesia (Table 1). This data indicated that the groundwater at the GBC is considered fresh with chloride (saline) levels of < 500 mg/L. Sulphate (SO_4) accounts for almost 65% of all the TDS, which could also be an indication of the presence of sulphuric acid.

Table 1 An example of the detailed water chemical analysis by Sucofindo Laboratories

Sample code		P26 DP16S	P21 DP48S	P19 DP46N	P31 DP36S	P26 DP26S	P27 DP26N
pH	Field	1.61	2.7	3.47	4.4	5.4	6.5
T	Field °C	31	19	17	12	12	11
TDS	Field mg/L	13,593	1,396	1,844	1,534	2,910	2,440
DO	Field mg/L	4.26	6.44	7.04	6.85	6.36	6.4
EC	Field µS/cm	13,783	2,530	1,786	2,760	5,180	4,390
pH	Lab	1.67	3.25	3.41	4.41	7.54	6.88
Electro conductivity	Lab µS/cm	18,200	2,700	3,440	2,890	3,810	4,500
Total suspended solids	Lab mg/L	34	120	298	5	15	2000
Turbidity	Lab NTU	7.80	65.4	60.6	4.28	1.05	138
CO ₃ alkalinity	Lab mg/L	NA	NA	NA	NA	0	0
HCO ₃ alkalinity	Lab mg/L	NA	NA	NA	NA	43	49
Dissolved alkalinity	Lab mg/L	NA	NA	NA	NA	43	49
Total alkalinity as CaCO ₃	Lab mg/L	NA	NA	NA	NA	45	63
Total acidity as CaCO ₃	Lab mg/L	15,900	225	274	93	9	14
Total hardness as CaCO ₃	Lab mg/L	2000	1,630	1,610	1,640	1,620	1,650
Total dissolved solids	Lab mg/L	20,500	2,610	3,050	2,710	3,380	3,940
Chloride (Cl)	Lab mg/L	37.1	11.1	101	92	175	333
Nitrite (NO ₂ -N)	Lab mg/L	0.501	<0.005	0.027	0.031	0.297	0.859
Nitrate (NO ₃ -N)	Lab mg/L	<0.005	0.54	1.92	1.73	9.33	19.5
Sulphate (SO ₄)	Lab mg/L	14,100	1,660	1990	1,740	1970	2050
Dissolved aluminium (Al)	Lab mg/L	223	6.47	13.2	6.24	0.029	0.088
Dissolved calcium (Ca)	Lab mg/L	674	593	490	533	508	534
Dissolved copper (Cu)	Lab mg/L	106	40.6	29.3	19.9	0.228	0.072
Dissolved iron (Fe)	Lab mg/L	4,730	12.3	14.1	0.0345	0.0091	0.0408
Dissolved magnesium (Mg)	Lab mg/L	78.1	37.1	94.2	76.3	85.2	76.9
Dissolved manganese (Mn)	Lab mg/L	29.2	10.2	8.49	10.4	4.4	6.66
Dissolved nickel (Ni)	Lab mg/L	0.262	0.114	0.114	0.036	0.004	0.005
Dissolved potassium (K)	Lab mg/L	5.85	11.1	18.6	13.9	49.8	36.3
Dissolved selenium (Se)	Lab mg/L	NA	NA	NA	<0.005	0.017	0.011
Dissolved sodium (Na)	Lab mg/L	38.2	20.5	175	99.2	600	458
Dissolved zinc (Zn)	Lab mg/L	12.2	10.2	8.72	6.75	0.75	0.282

Water samples from the underground were evaluated and plotted to determine relationships between pH, TDS, EC and DO as indicate in Figure 3a, b and c. Very good relationships were identified between pH, TDS and EC. The relationship between pH and DO indicates that, unlike for saline environments (Hassell 2008), the DO has no influence on the pH and little to no effect on the corrosion rate in an acidic corrosion environment.

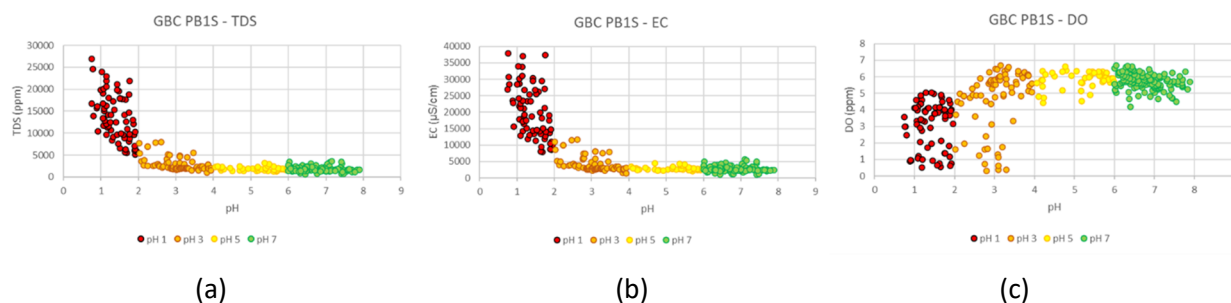


Figure 3 The main chemical relationships from water collected in GBC PB1S and analysed during field tests

2.2 Acidic environment corrosion design table

Different approaches were followed to determine the contributing effects of the various parameters on the corrosion rate. Silaen & Budiman (2017) indicated that corrosion was found to be correlated to the pH levels of the groundwater, which was related to the oxidation process of the sulphides. It also became evident through inspection that the groundwater temperatures were higher in drifts developed in the HSZ, especially in the extraction levels (EL) that were connected to the cave through joints, fractures or zones of low RQD. These high groundwater temperatures in the EL drifts were measured to be 20°C higher than the drifts outside of the HSZ. Roberge (2000) indicated that there is an exponential relationship between water temperature, pH and corrosion rate (Figure 4a). Data collected in the GBC PB1S also indicated good relationships between sulphide percentage, pH, water temperatures and associated corrosion rates, as indicated in Figure 4b.

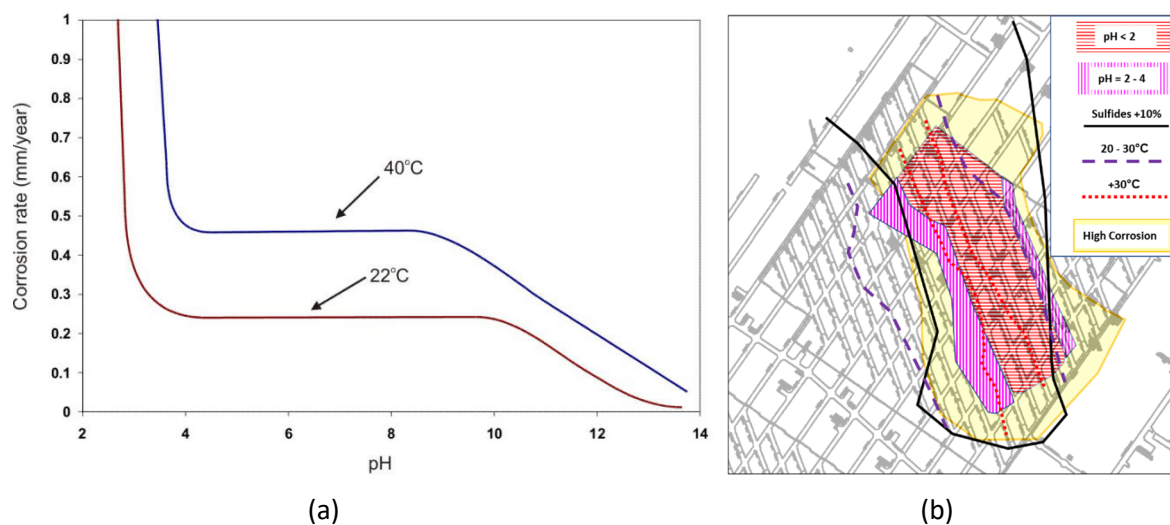


Figure 4 (a) Relationship between groundwater temperatures, pH and corrosion rates (Roberge 2000); (b) Relationship between sulphide percentage, pH and water temperatures in GBC PB1S

Various groundwater datasets, corrosion rates (coupons, unprotected mesh and un-grouted cables), as well as visual observations of actual corrosion indicated that parameters such as pH, TDS (sulphate), T (°C) and EC were used as the basis to develop a corrosion table for acid corrosion environments (Figure 5).

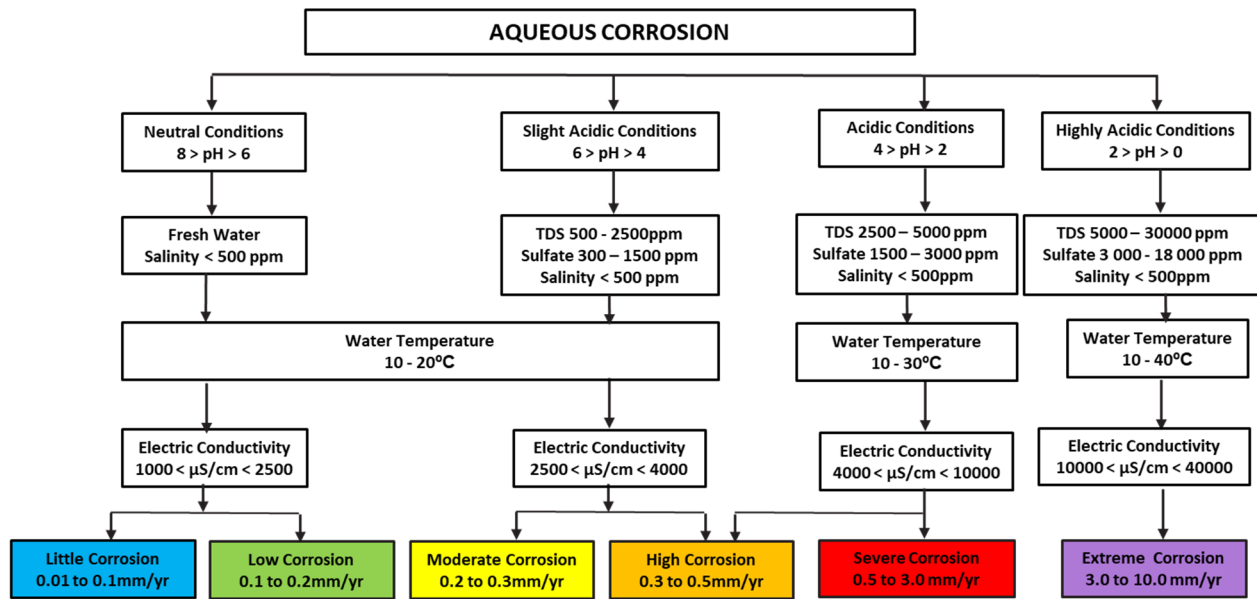


Figure 5 Aqueous corrosion rates related to pH, TDS, water temperature and electric conductivity

Coupons were found not to be effective in determining the corrosion rates due to numerous factors, e.g. location, water flow conditions, surface deposits and water flow variations. Also, the method of corrosion rate calculation is based on volumetric methods and not relevant to tendon support, which is vulnerable to diametrical corrosion.

3 Corrosion of ground support

Corrosion of ground support is a complex process and could vary depending on the parameters that influence the corrosion rates. Ground support products behave differently in an acidic aqueous corrosion environment, and therefore some products, e.g. FB, are more susceptible to corrosion. Tomory et al. (1998) highlighted the useful life span as a major concern. FB are susceptible to corrosion and in some severely corrosive groundwater conditions, they can become ineffective after a period of seven or eight months or even as little as two months. In less corrosive environments, life spans of two to six years are common.

Villaescusa et al. (2007) established that FB suffer from two modes of failure because of corrosion: (a) the loss of frictional resistance and (b) the loss of tensile strength. A large decrease (50%) of pull-out strength due to a relatively small reduction (20%) in wall thickness was measured. The loss of tensile strength is mostly related to the level of pitting corrosion, which is a rapid penetration of corrosion at discrete locations.

3.1 Process of corrosion

Observations of an acidic corrosive environment at PTFI indicated that corrosion does not occur as a blanket type of pattern but corrodes in patches and streaks and causes corrosion-related failures in approximately 5% of all installed support in high to severe corrosion areas. Groundwater infiltrates through single open joints, fractures, zones of low RQD values or open support holes (Figures 6a and b). Open support holes are one of the reasons why FB corrodes faster than other grout-filled support types because the acidic water follows the open route and corrodes the FB from the inside out as well as at the FB neck and plate interface.

3.2 Deterioration in ground support systems

Ground support systems at the GBC are normally made up of fibre-reinforced shotcrete (FRS) with an internal layer of mesh, as well as bolts and cables. The FRS forms an alkaline barrier which neutralises the acidic water. This can be compared to a sulphate attack resulting in the FRS increasing in volume and eventually losing strength. If the acidic water with a low pH continues to enter the excavation, the resultant water pH levels

could be low enough to start a corrosion process in the steel products. The result is dripping groundwater with a low pH that causes patchy or streaky corrosion patterns on the surface support.

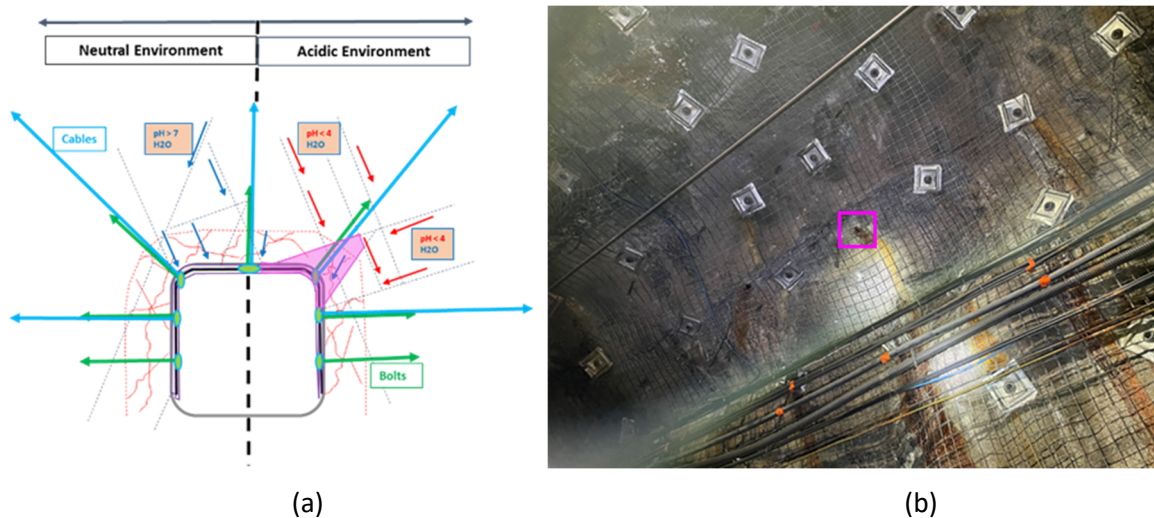


Figure 6 (a) Schematic representation to indicate potential causes of a patchy corrosion pattern; (b) Observed patchy corrosion patterns in GBC PB1S (Corrosion failures $\pm 5\%$ of all installed support elements in high to severe corrosion areas)

In the situation where groundwater reaches encapsulated bolts (resin) or cables (cement), a similar process could be started. If a bolt is completely encapsulated in resin, corrosion is expected to be minimal except for the bolt zones which are not completely encapsulated such as the plates and tension heads. The same is expected to take place for cables in cement grout, although the cement grout will delay the corrosion rate (Hassell 2008) in similar fashion as the FRS. The deterioration of the cement grout, through a sulphate attack, is at a much slower rate than the FRS, because the cement grout is much denser and less permeable.

Deterioration of support systems will occur in patches or streaks that will cause minor sections of surface support to corrode or suffer sulphate attack or cause single bolts or cables to lose support capacity that could lead to failures. These failures could be observed visually or through ZF scan monitoring as 1–4 m² areas that deforms for approximately 100 mm.

3.3 Ground support capacity loss

Cable and mesh are the main support items to control unravelling and minor falls of ground (mesh) or large falls of ground including wedge or beam failures (cables). PTFI went through a process of evaluating laboratory results, like Dorion & Hadjigeorgiou (2013), to determine a method to calculate the loss in support capacity because of the effect of corrosion (Figure 7). The process includes plotting the corroded data against the uncorroded technical data of the product to determine the confidence of the results and the residual capacity of the support at a reduced diameter. Results from mesh testing indicated that the load was approximately 10% less than the minimum load as per technical data, which was interpreted to be due to a pitting effect. This lower interpreted dataset was used to calculate the residual capacity of the mesh.

The capacity of the cable loads (Figure 8) were not directly downrated relative to the diameter of the cable, but the loads were subdivided according to the number and the diameter of the individual wires. It was assumed that the king-wire would not be corroded within 30–40% reduction in cable diameter. Cables will be replaced, depending on the rock type density and criticality of the excavation, between 55–65% of the remaining support capacity which is approximately equivalent to a reduction in cable diameter of 35%.

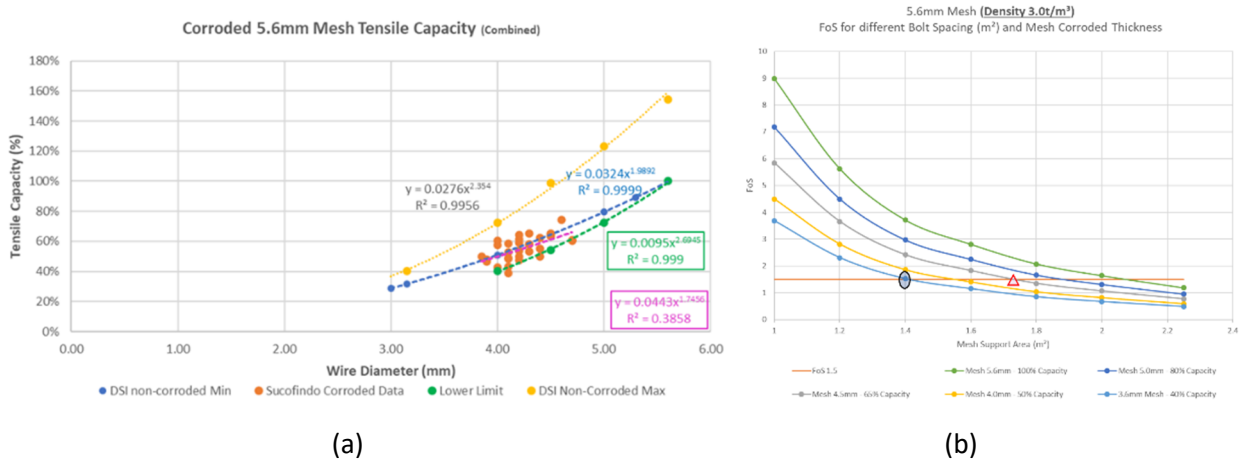


Figure 7 (a) Laboratory testing of corroded mesh samples; (b) Interpreted Factors of Safety per area of mesh support based on cable support spacing

		TDS	Independent Lab QA/QC	Design for UG
Yield Load (kN)	Min	311	321	328
	Typical	343	334	
UTS (kN)	Min	355	358	359
	Typical	360	362	
Elongation (%)	Min	3.5	4.7	5.2
	Typical	5.7	4.7	

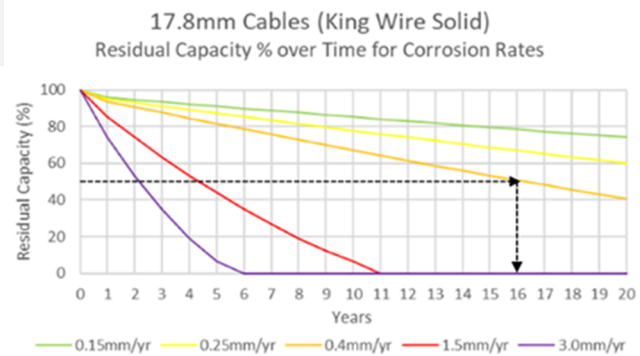


Figure 8 (a) Design data for 17.8 mm cables based on laboratory and underground data; (b) Residual capacity and years effective for cables at different corrosion rates

3.4 Additional factors that increase or delay the effect of corrosion

During studies by PTFI and laboratory investigations by the University of Indonesia, it has been found that under natural conditions, the corrosion rates and the effect of corrosion could be increased through pitting and bacteria, whereas a delay in corrosion is caused by the build-up of corrosion by-products, as well as changes in groundwater and water chemistry conditions. It has been found that in certain areas, the groundwater volume reduced significantly once the cave advanced over these areas.

Management strategies to reduce or delay the effect of corrosion includes galvanised or thermoplastic-coated support units, cement and resin-grouted bolts and cables, as well as pumpable resin sealing to reduce or eliminate water inflow and the application of thin sprayed liners and FRS to protect mesh, plates and bolt stick-outs.

4 Management of corrosion

The management of corrosion is addressed and guided through managerial and operational procedures. The foundation of the management of corrosion is based on but not restricted to the following processes:

- Identify potential corrosion environments through sulphide and groundwater assessments.
- Confirm actual corrosion environments through inspections and water sample laboratory tests.

- Develop corrosion forecast HAZMAPS based on best available corrosion rates and support residual capacity.
- Develop monitoring strategies including ZF scanning and corrosion instrumentation.
- Determine preventative support maintenance (PSM) and schedules.
- Train and share knowledge.

4.1 Corrosion maps

Various maps including potential, actual (Figure 9) and hazard are compiled to assist management in identifying and classifying the corrosion risk. Corrosion maps indicated the level of corrosion, as well as the projected corrosion rates and the expected year when PSM will be implemented.

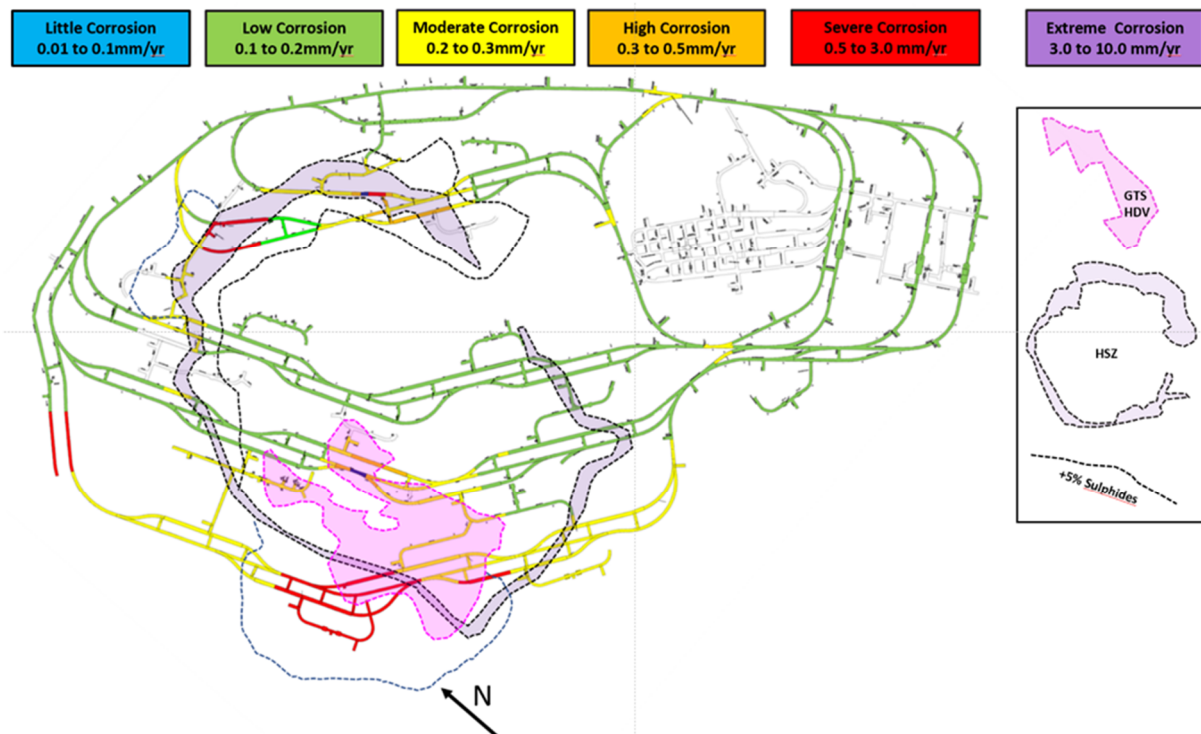


Figure 9 Potential and actual corrosion maps

4.2 Determine preventative support maintenance levels

PSM levels were assigned to the identified actual corrosion and corrosion rates information as indicated in the actual corrosion maps and HAZMAPS. A guideline for PSM is indicated in Table 2.

Table 2 Guideline for PSM levels in the rail loops

PSM rail loop and chute galleries			
Class	Normal	Abnormal	Abnormal
	Acceptable	Non-urgent	Urgent
	1	2	3
	Low	Moderate	High
pH	pH > 6	4 < pH < 6	pH < 4
Corrosion rate	<0.2 mm/yr	0.2–0.3 mm/yr	0.3–0.5 mm/yr
PSM type	PSM 1	PSM 2	PSM 3
Monitoring and actions	Visual monitoring	Increase data collection	Increase ZF scan monitoring
	Corrosion monitoring	Start ZF scan monitoring	PSM – support
	Water sampling	Quarterly – bi-annually	Monthly – quarterly
	Bi-annually – annually	Indicate expected time of PSM	Divided in areas to be re-supported in 1 shift

4.3 Training

Very often the assumption is made that the workforce understands the various hazardous conditions that prevail in an underground mine, but it is more likely that they have a different understanding of the situation. Information sessions indicated that a large group of the workforce interpreted any rust-coloured staining or sediment as corrosion, but these conditions only indicated the oxidation process. Clearing away this staining and sediment revealed uncorroded steel support items.

In many instances where corrosion did take place, the support did not need to be replaced nor the excavation need to be rehabilitated. Training and information sessions used photographs and practical examples to indicate the various levels of corrosion and explain the actual conditions.

5 Conclusion

Various groups within the PTFI GeoEngineering Division and independent Indonesian laboratories worked together over the last five years to determine the parameters that contribute to the acidic environment at the GBC. The severity of this acidic corrosive environment was classified according to the most relevant parameters that include the pH, sulphate, temperatures and EC levels. An acid-dominated aqueous corrosion design table, based on the above-mentioned parameters, was compiled that could be used in the GBC, as well as in the industry to determine potential corrosion rates.

It was observed that corrosion appeared in patches and streaks, which is related to the flow of acidic groundwater along structures and open ground support holes. Preliminary observation indicated that approximately 5% of installed ground support elements, in identified high to severe corrosion areas, will be corroded. At this stage, this reduction in the severity of corrosion can be attributed to the neutralising effect of the alkaline FRS, corrosion-protected ground support and natural contributors such as a change in groundwater volumes and water chemistry, as well as the deposits of corrosion by-products that protect the steel products.

PTFI have developed a management strategy for the corrosion hazard.

Acknowledgement

The authors thank PTFI and Freeport-McMoRan management for the opportunity to submit and present this work at Ground Support 2023.

References

- Bieniawski, ZT 1989, *Engineering Rock Mass Classifications*, Wiley, New York.
- Dorion, JF & Hadjigeorgiou, J 2013, 'Corrosion considerations in the design and operation of rock support systems', in Y Potvin & B Brady (eds), *Ground Support 2013: Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 497–509.
- Hassell, R 2008, *Corrosion of Rock Reinforcement in Underground Excavations*, PhD Thesis, Western Australian School of Mines, Perth.
- Jennings, SR, Neuman, DR & Blicher, PS 2008, *Acid Mine Drainage and Effects on Fish Health and Ecology: A Review*, Reclamation Research Group Publication, Bozeman.
- Loomis, IM, Hughes, S, Osborne, K, Basyuni, J & Samosir, E 2008, 'Control of a sulfide ore thermal event in a drawpoint at PT Freeport Indonesia's DOZ Mine, Papua, Indonesia', in KG Wallace (ed.), *Proceedings of the 12th U.S./North American Mine Ventilation Symposium*, University of Nevada Press, Reno.
- Roberge, PR 2000, *Handbook of Corrosion Engineering*, McGraw-Hill, New York.
- Silaen, H & Budiman, J 2017, *GBC Corrosion Potential Preliminary Study*, PT Freeport Indonesia, Jakarta, internal document.
- Tomory, PB, Grabinsky, MW & Curran, JH 1998, 'Factors influencing the effectiveness of Split Set friction stabilizer bolts', *CIM Bulletin*, vol. 91, no. 100, pp. 205–214.
- University of Indonesia 2021, *Identification of Bacteria through XRD Results*, University of Indonesia, West Java, internal report.
- Villaescusa, ER, Hassell, R & Thompson A 2007, *Corrosion of Rock Reinforcement in Underground Excavations*, MERIWA project 333, Western Australia School of Mines, Curtin University of Technology, Perth.

