Investigation of corrosion behaviour of friction rock stabilizers used in underground mines in Western Australia

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Abstract

Friction rock stabilizers are the most common steel-based ground reinforcement used in underground mines in Western Australia. The effect of corrosion is considered to be severe for this type of reinforcement due to the thin-wall tube construction and large surface area. Investigations have been carried out to determine the nature and extent of corrosion attacks and their influence on the ultimate tensile load-capacity of reinforcement.

KEYWORDS: Corrosion, friction rock stabilizer, ground water, underground mine, reinforcement, rock bolt.

Friction rock stabilizers (FRS) are the most commonly used ground reinforcement in underground mines in Western Australia. There are several advantages of FRS including the ease of installation, immediate effectiveness, and economy, and because of these advantages, FRS have become more popular than any other ground reinforcement currently available within the mining industry. A survey conducted by the Department of Minerals and Energy of Western Australia (DME; Ranasooriya, 1993) has shown that over 93% of the underground mines in Western Australia use them as a method of ground control.

The application of FRS exposes them to a wide range of mine-water, mineralogical, and atmospheric conditions. Mine-water and atmospheric conditions often change with variations in climate and changes in mining activities. Operating experience has shown that FRS corrode with time due to

their interaction with the physical and chemical characteristics of the environment. Corrosion reduces their integrity and load-bearing capacity, leading to unexpected rock falls, which may cause potentially fatal accidents.

Corrosion of ground reinforcement and other steel and iron products has been a widely known problem in underground mines throughout the world. Studies have been carried out on the corrosiveness of underground mine waters (Rawat, 1976; Higginson and White, 1983), and corrosion behaviour of mild steel in underground mine waters in general (Subramanyam and Hoey, 1975; Mursolo et al., 1988). Sundholm (1987) and Dahl (1989) reported comparative studies of the corrosion behaviour of different ground-reinforcement types used in underground mines. Because of their thin-wall tube construction and large surface area, the effect of corrosion is considered to be more severe for FRS than other reinforcements made of solid steel bars. Sundholm (1987) demonstrated that FRS corrode over their entire length,

and over 58% of their wall thickness can be lost in just one year after installation. Tilman et al. (1984, 1985) and Jolly and Neumeier (1987) investigated the corrosion problem relevant to a single type of FRS in selected mine waters; however, the corrosion behaviour of a range of FRS in varied underground mining environments so far is not fully understood.

The obvious safety problems that may result from corrosion have led both regulatory and industry personnel to raise concerns regarding the longevity of FRS in underground mining environments in Western Australia. In response to these concerns a research project was initiated by DME, with assistance from the mining industry and suppliers of FRS used in Western Australia. The research project was undertaken by chemists and metallurgists from the Chemistry Centre of Western Australia and geotechnical engineers from the Engineering Geology Section of the Geological Survey of Western Australia.

The research project was aimed at investigating the following:

(a) corrosiveness of underground mining environments in Western Australia;

(b) the nature and extent of corrosion of FRS;

(c) the effects of corrosion on the load-bearing capacity of FRS;

(d) the methods of predicting the potential longevity of FRS in underground mining environments.

This paper presents the results of the investigations carried out as part of this research work.

Types of friction rock stabilizers

Three types of FRS were available at the commencement of the study. They are known by the proprietary names of Split Set, Cotter Pin, and Swellex, and were supplied by Ingersol Rand, Hardie Drilling Supplies, and Atlas Copco respectively. Plain steel (ungalvanized) and galvanized or coated varieties are available from each type.
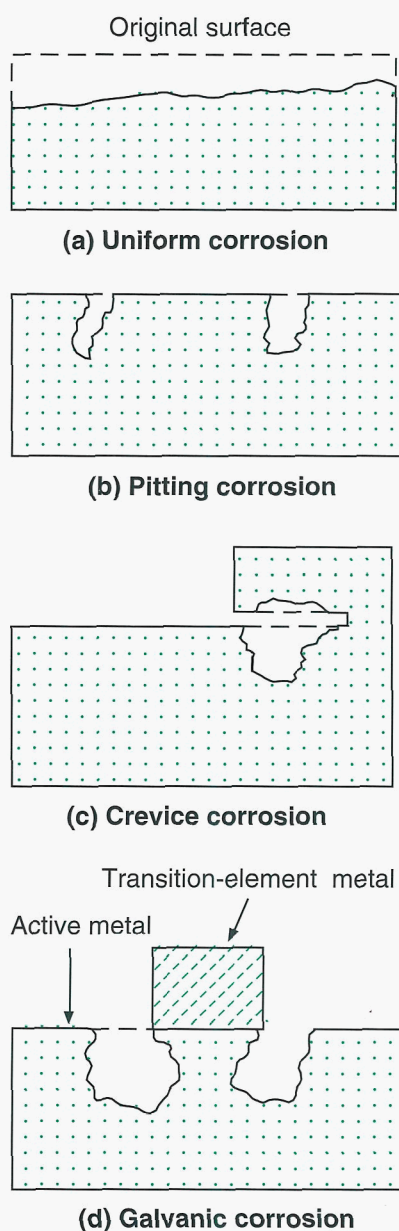
A Split Set is a steel tube of 3 mm nominal wall thickness, with a slot running its full length. The end of the Split Set that is inserted into the rock is tapered, whereas the outer end has a ring flange to hold an end plate. To install, the Split Set is forced into a slightly smaller-diameter hole drilled in the rock. Split Sets are available at various lengths with diameters of 33, 39, and 46 mm.

A Cotter Pin is a steel tube of 2 mm nominal wall thickness with a longitudinal inwards fold along its entire length. The inner end is tapered and the outer end has a welded ring flange to hold an end-plate. The installation process for Cotter Pins is similar to that for Split Sets. Cotter Pins are available at various lengths with diameters of 39 and 46 mm.

A Swellex FRS is a steel tube with a diameter of 41 mm and with a 2 mm nominal wall thickness, that has been reshaped to 25.5 mm diameter by folding longitudinally inwards along its length. Bushes are pressed onto each end and sealed by welding. A valve is fitted to the outer bush to allow injection of water into the Swellex tube. To install, the Swellex tube is inserted into a hole with a diameter less than 41 mm drilled in the rock. The Swellex tube is expanded by injecting water using a high-pressure water pump.

Types of corrosion

Corrosion is defined as a gradual wearing away or alteration of metal by a chemical or electrochemical oxidizing process. The process requires the combined presence of an electrolyte and oxygen. The damage resulting from the oxidizing

(a) Uniform corrosion

(b) Pitting corrosion

(c) Crevice corrosion

(d) Galvanic corrosion

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Figure 1.   Types of corrosion that may influence the longevity of FRS

process can take various different forms depending on the conditions of the surrounding environment and the quality of the metal itself. Types of corrosion which may destroy FRS are illustrated in Figure 1 and are discussed below.

Uniform corrosion

Uniform or general corrosion is characterized by an even, regular loss of metal from the corroding surface without appreciable

localization of attack (Fig. 1a). FRS which suffer this type of corrosion are radially thinned from inside or outside (or both) depending on the nature of the corrosive environment. The process of metal wastage is uniform around the entire circumference at a relatively linear rate with time.

Localized corrosion

Localized corrosion occurs at discrete, isolated locations on the surface of the metal. Two forms of localized corrosion are common: pitting corrosion and crevice corrosion.

Pitting corrosion (Fig. 1b) is the most common of all types of corrosion in the samples analyzed. Pitting may occur on either surface of the FRS where the surface is metallurgically non-homogeneous or under deposits of foreign matter. Localized variations in the mineralogical conditions of the ground in contact with the surface of the FRS can also create conditions that promote pitting corrosion. Once initiated, pitting corrosion continues until perforation of the FRS results. FRS may become unserviceable because of localized weakening by pitting, even though only a small percentage of the total metal has been lost.

Crevice corrosion (Fig. 1c) is a particular form of pitting corrosion which occurs on confined, closely spaced metal surfaces. In FRS the interface between the collar and the end-plate provides conditions suitable for crevice corrosion. This type of corrosion may lead to the loss of support provided by the end-plate, even though the bulk of the FRS may still be sound.

Galvanic corrosion

Galvanic or bimetallic corrosion (Fig. 1d) occurs when dissimilar metals are in contact in the presence of an electrolyte. The intensity of corrosion resulting from galvanic coupling depends primarily on the difference in solution potential between the metals. Galvanic corrosion of FRS occurs when they are electrically coupled to less reactive metals in the ground such as copper and nickel.

Underground corrosive environments

Corrosion is a chemical or electro-chemical process that requires the presence of an electrolyte and oxygen. In underground mines, water is the most common electro-lyte associated with corrosion. Oxygen is generally available from the air. In well-ventilated areas of an underground mine the oxygen supply is considered to be constant.

The rate of corrosion is accelerated by the acidity and electrical conductivity of the groundwater. Rapid corrosion may take place when the metal is surrounded by water; however, a film of water deposited on the surface of the metal from the moisture in the air also permits appreciable corrosion to take place. The corrosion resulting from moisture in the air can be accelerated by the presence of dust and other impurities, such as sulfur oxide and nitrogen oxide gases.

Mine-water analyses

Groundwater samples were collected from 21 underground mines in Western Australia. The majority of the samples were 25 L in volume. Up to six samples were collected from some mines where groundwater quality was suspected to be variable within the mine itself. Sample temperature, dissolved oxygen content, and pH were recorded on site.

The groundwater samples were analyzed for Na, K, Ca, Mg, Zn, Mn, Al, Fe, Ni, Cu, P, Si, chloride, sulfate, bicarbonate, and nitrate ions, and pH and total alkalinity. The results of the analyses indicate that only Na, K, Ca, and Mg cations, and chloride and sulfate anions, are present in significant concentrations, with wide variations from site to site. Other ions are present only in comparably small concentrations. More importantly, the results show that there is a wide range in the nature and concentration of dissolved salts in the samples collected. For example, the sodium content, which is indicative of the salinity of the groundwater, ranges from 180 to 99 400 ppm; the combined calcium and magnesium concentration, which is indicative of the hardness, ranges from 80 to 35 400 ppm.

Dissolved-salt content is generally considered to be an indicator of the salt-induced corrosiveness of groundwater; however, a low salt content does not necessarily mean that the environment is less corrosive, as severe corrosion can still take place depending on the mineralogical and atmospheric conditions of the site. Table 1 is a summary of selected chemical analyses of the samples collected in this study.

Rock mineralogy

The majority of rock-forming minerals are relatively chemically inert, and when in contact with steel will have little or no effect on the corrosion of the metal. Nevertheless, some water-soluble minerals such as sulfides, chlorides, and carbonates can significantly influence the corrosion of steel when in contact with it in the presence of aqueous solutions. Water-soluble minerals change the acidity and salinity of water, leading to a change in the corrosiveness of the water. Such minerals (e.g. pyrite) are generally found in orebodies mined by underground methods.

Table 1. Selected chemical analyses of mine waters

Mine no.	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}
			Parts per million			
1	1 080	360	620	5	110	100
2	1 300	300	670	30	50	180
3	1 520	630	1 020	10	115	100
4	32 500	5 200	16 700	115	580	3 060
5	75 000	1 860	36 300	180	8 000	130
6	347 – 607	390 – 765	180 – 466	11 – 20	38 – 153	36 – 42
7	400 – 2 500	nd	450 – 450	25	175 – 180	85 – 85
8	1 510 – 134 000	320 – 1 470	950 – 72 300	12 – 930	160 – 8 460	90 – 7 080
9	4 450 – 7 010	1 860 – 3 750	2 440 – 2 756	42 – 48	245 – 1 140	450 – 1 440
10	4 660 – 197 000	480 – 4 200	2 750 – 87 600	60 – 1 730	1 060 – 20 900	500 – 14 500
11	9 860 – 13 100	450 – 10 900	55 000 – 71 300	410 – 690	780 – 940	6 070 – 8 470
12	13 000 – 137 000	3 990 – 4 170	7 800 – 7 860	60 – 67	290 – 320	1 320 – 1 380
13	16 500 – 44 800	2 010 – 2 710	8 290 – 15 300	124 – 310	610 – 6 640	1 600 – 3 540
14	22 700 – 29 500	4 920 – 5 970	11 700 – 13 600	120 – 260	380 – 1 560	2 300 – 3 980
15	26 400 – 34 200	4 530 – 5 640	15 900 – 21 090	270 – 390	980 – 1 000	1 640 – 1 730
16	32 300 – 43 000	4 220 – 6 040	16 100 – 19 600	91 – 300	720 – 1 140	3 180 – 3 500
17	32 900 – 81 000	4 950 – 9 120	17 900 – 39 700	160 – 620	1 500 – 2 400	1 920 – 5 700
18	36 500 – 125 000	1 110 – 2 250	19 200 – 63 000	50 – 150	2 000 – 13 000	2 100 – 2 300
19	80 400 – 133 000	2 010 – 19 700	48 490 – 75 500	390 – 870	590 – 5 350	5 100 – 12 300
20	160 000 – 162 000	2 670 – 6 540	79 700 – 84 500	1 080 – 1 200	1 570 – 3 380	8 900 – 9 900
21	168 000 – 185 000	24 300 – 284 000	86 100 – 99 400	1 130 – 1 250	330 – 440	14 800 – 16 800

nd – not determined

The presence of certain transition-element metals that may be otherwise relatively inert in the ground, such as copper and nickel, provide ideal conditions for galvanic or bimetallic corrosion when in contact with steel in the presence of aqueous solutions. The concentration of these metals in underground mines in Western Australia is generally very small (obvious exceptions include nickel and copper mines) but can vary from site to site as well as within a mine. Nonetheless, as galvanic corrosion primarily depends on the difference in solution potential between the metals (or alloys), small concentrations of these metals are sufficient to initiate this type of corrosion. Transition-element metals are commonly present in ore zones, although this depends on the type of ore being mined.

Quantification of corrosion rates

Two approaches were used to quantify the rates of corrosion of FRS. They were:

(a) assessment of the extent of corrosion of samples of FRS of known history collected from mine sites, and

(b) laboratory-based experimental corrosion of samples of unused FRS in simulated mining environments using ground-water and rock samples collected from mine sites.

In-mine corrosion of installed friction rock stabilizers

The preferred method of assessing the in-mine corrosion damage is to retrieve installed FRS by overcoring and then measure the extent of corrosion using laboratory techniques. Formal requests were made to all mine operators who use FRS in their underground mines to provide retrieved FRS of known history. Several mining companies expressed interest in overcoring FRS from their underground mines. Three companies agreed to install pairs of FRS at three-monthly intervals at a site set aside for this study and to retrieve them all by overcoring after 12 months from the first installation. Nonetheless, retrieval of FRS by overcoring is yet

to be performed at any of the underground mines in Western Australia.

An alternative approach taken to obtain samples of installed FRS from underground mines was to cut and remove the lower ends of FRS which were protruding from the rock, as a result of re-scaling, small rock falls, or poor installation. This approach was found to be relatively successful. A total of 133 such samples were collected from 12 underground mines. These included samples from three major rock-fall sites where accidents have occurred.

The age of the samples collected ranges from 3 to 77 months. This was estimated by mine site personnel from mine records and from manufacturer's product code stamps on the FRS.

The ground conditions at the sampling sites varied significantly from site to site in terms of lithology and mineralogy. The groundwater conditions ranged from completely dry to wet. In addition, where water was present, the groundwater chemistry differed from mine to mine. Therefore, the samples collected represent a wide range of mining environments; however, as sample collection was largely governed by the accessibility of the sites, they do not necessarily represent the extreme conditions that may be present in underground mines. The 133 samples were all plain steel (ungalvanized) Split Sets. Two samples of galvanized Split Sets were also received separately. This sampling bias is mainly due to the widespread use of Split Sets in underground mines in Western Australia.

All three styles of corrosion described above have been identified from the samples of FRS collected from mine sites. The extent of corrosion differed significantly depending on the type of attack, and any given sample may have suffered more than one type over its length. As a result, neither the area nor the depth of attack was found to be suitable for quantifying the extent of corrosion; therefore, mass loss as a percentage of the original mass was developed as a suitable common measure of the extent of corrosion of field samples.

The samples collected from mine sites were divided into two groups based on FRS length. Group 1 comprises samples with lengths from 500 mm to 1800 mm, whereas Group 2 comprises samples with lengths from 200 to 300 mm.

The samples were analyzed for 'average mass loss'. Three sections were tested from each sample of Group 1, each with a nominal length of 75 mm, and were taken from the two ends and the centre to represent the full length of a sample. The mass loss determined from the three sections was averaged to give a representative mass loss for each sample. For Group 2 samples, mass loss was determined for the entire sample.

Pitting (localized corrosion) was the most common form of corrosion in the samples collected. Pitting results in the localized perforation and weakening of FRS. The extent of localized corrosion may be quantified by estimating the localized mass loss, rather than the average mass loss; therefore, the 'localized mass loss' is defined for the Group 1 samples, which is the maximum value of the mass-loss measurements from the three 75 mm sections of a field sample. For Group 2 samples, localized mass loss could not be determined.

Laboratory-based experimental corrosion

Six laboratory-based corrosion experiments were set up to determine corrosion rates under various simulated mining environments:

1. A static-immersion corrosion test was designed to simulate corrosion under stagnant water or non-changing wet conditions where mining activity decreases or stops.

2. Dynamic corrosion test 1 was designed to simulate an underground mine environment where groundwater with a relatively low dissolved-salt content (less than 1%) is freely flowing over the FRS.

3. Dynamic corrosion test 2 was designed to simulate an underground mine environment where groundwater with a relatively high dissolved-salt

content (approximately 24%) is freely flowing over the FRS.

4. Dynamic corrosion test 3 was designed to simulate an under-ground environment where water vapour is transported as a fine mist by ventilation, and deposited on the FRS. The dissolved-salt content for this test was approximately 24%.

5. An electrochemical corrosion test was designed to determine the corrosiveness of selected mine water from four mines where the broad spectrum of groundwater qualities is represented. Electro-chemical tests were also conducted to determine the effect of pH, salt content, and increased oxygen supply.

6. The salt spray test (ASTM[2] B117) is a standard test designed to compare the corrosion resistance of the three types of FRS under a continuous salt fog of 5% sodium chloride at 35°C for 500 hours.

Specimens used for laboratory experiments under simulated mining environments were commonly 75 mm in length. In order to be able to compare with in-mine corrosion rates, mass loss was again used as the common measure of corrosion. Measurements obtained from electrochemical tests were converted to mass loss for comparison.

Results of corrosion analyses

In-mine corrosion rates

Figure 2 is a log–log plot of installed age versus average mass loss of samples collected from mine sites. The graph shows that the average mass loss can vary significantly for a given length of time of installation. This large variation is considered to be a function of differing conditions in the mines. Nonetheless, on the basis of data available, ungalvanized FRS can be given upper and lower limits of average mass loss as shown by curves A and B respectively on Figure 2. As a preliminary guideline, the upper limit (curve A) may be used to predict the maximum corrosion damage that may be expected in an underground mine.
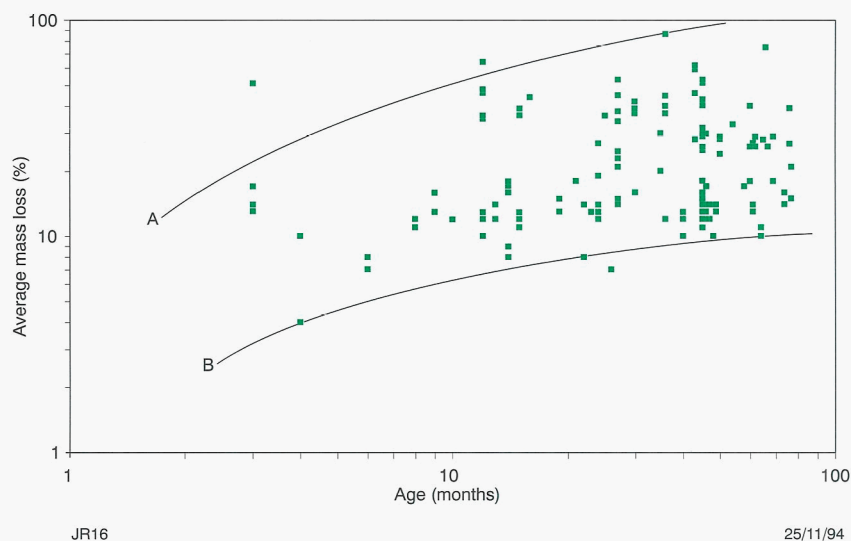
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[2] American Society for Testing and Materials.

Figure 2. Age versus average mass-loss of samples of FRS collected from mine sites

Figure 3 is a log–log plot of age versus localized mass loss determined from the Group 1 specimens of 75 mm nominal length. This figure shows that more than 10% of local mass loss can be lost within 8 months due to localized corrosion. Moreover, the maximum localized mass loss is up to 80% in just over 10 months.

Effect of rock type on in-mine corrosion

Of the field samples analysed, 55 were collected from a single mine where groundwater quality was considered to be uniform. Rock type and degree of wetness of each sampling location was recorded for all 55 samples. The samples were recovered from four rock types: basalt, ultramafic rock, porphyry, and massive sulfide. The massive sulfides correspond to the nickel-bearing ore zone; ultramafic rocks and porphyry occur in the footwall and hanging wall to the ore zone; and the surrounding country rock is basalt.

Average mass loss was determined for each of the 55 samples as out-lined above. The results of the
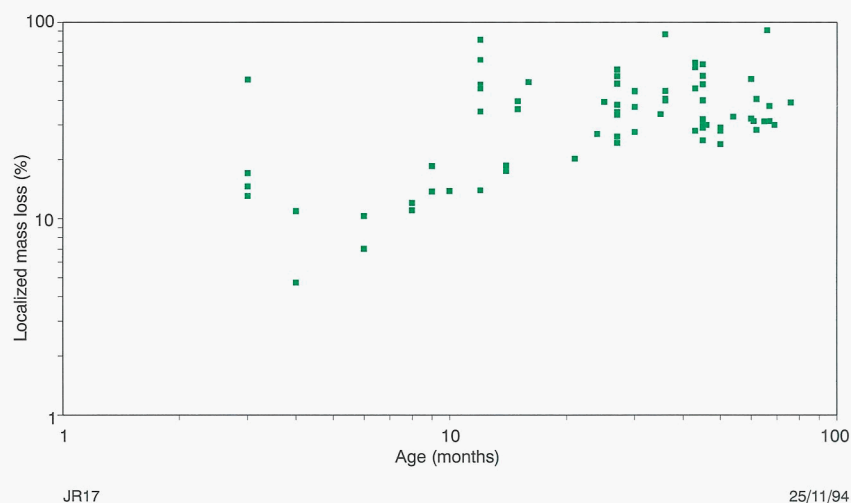

Figure 3. Age versus localized mass-loss of samples of FRS collected from mine sites

Table 2. Influence of rock type on rate of corrosion

Rock type	Wetness	Mass loss per month (%)
Basalt	dry	0.2 – 0.6
Basalt	wet	0.3 – 0.8
Basalt	damp	0.3 – 0.7
Ultramafic	dry	0.5 – 1.2
Ultramafic	wet	0.9 – 1.2
Porphyry	dry	0.4 – 1.4
Massive sulfide	dry	0.3 – 1.5

analyses are presented as mass loss per month (corrosion rate) in Table 2. Although a direct correlation between the corrosion rate and the rock type is not possible at this stage, the results suggest that the extent of corrosion may have been influenced by rock type. The lowest minimum and the lowest maximum rates of corrosion were found to be associated with basalt country rock, where soluble minerals and transition-element metal concentrations are significantly low compared to the ore zone. The highest maximum rate of corrosion was associated with massive-sulfide ore zones.

Laboratory experiments

Static immersion tests

Static immersion tests were conducted on samples of Split Set, Cotter Pin, and Swellex FRS. Both galvanized and ungalvanized samples were tested. Water with a chloride content of 66 200 ppm (which is twice the salinity of sea water) was used in these tests. Corrosion rates were determined at 95 and 209 days after the first immersion. The results (Table 3) indicate that the corrosion rate of ungalvanized samples was relatively uniform over the whole time of immersion. In contrast, galvanized samples initially corroded faster. The corrosion rate of galvanized samples at 95 days was 3 to 4 times higher than that of the ungalvanized samples. While a reduction in the rate of corrosion of galvanized samples was clearly evident at 209 days,

rates were still observed to be higher than for ungalvanized samples.

Dynamic tests

Results of the three dynamic tests are also presented in Table 3. The three tests represented free-flowing water with low dissolved salts (less than 1%; Test 1), free-flowing water with high dissolved salts (approximately 24%; Test 2), and mist conditions (Test 3). The results indicate that ungalvanized samples corroded at a faster rate than galvanized samples in the presence of a low concentration of dissolved salts. Under conditions of high salt concentration, galvanized samples corroded faster than ungalvanized samples. This is, however, expected to reverse with time. Further testing is under way to examine long-term trends.

As galvanizing is applied only on the outer surface of Swellex FRS, the experimental procedure is not necessarily applicable to Swellex. The rate of corrosion of galvanized Swellex under the dynamic tests should be treated with caution, as this represents the corrosion of both ungalvanized and galvanized sides of the specimen.

The results of dynamic tests on ungalvanized samples of FRS have shown the following:

• Corrosion rates of all three types of FRS are higher in water with a low concentration of dissolved salts. Under the conditions used for the dynamic tests, a tenfold

difference in the rates of corrosion was observed.

• Corrosion rates were similar for each type of FRS under Dynamic Tests 2 and 3. This indicates that under a high concentration of dissolved salts, both free-flowing water over FRS and moisture deposited on FRS have a similar influence on the rate of corrosion.

• All three types of FRS corroded at similar rates under each of the dynamic test conditions. The rates of corrosion of ungalvanized FRS does not appear to be product-type dependant.

Electrochemical tests

Electrochemical tests were conducted using distilled water with sodium chloride concentrations of 0, 1, 3, 5, and 7%. All three types of ungalvanized FRS were tested. The results of these tests show that the maximum rate of corrosion occurs when the sodium chloride concentration is between 1 and 6%. These results are in agreement with the findings of Borgmann (1937) on the corrosion of cold-rolled steel, where the maximum corrosion rate was at a salt concentration of 2.9% sodium chloride.

Electrochemical tests were also conducted using mine water from four mines. The mine waters have dissolved-salt concentrations of 1.2, 4.8, 5.7, and 6.4%. The major components of dissolved salts in the four mine-water types are chlorides,

Table 3. Results of laboratory corrosion tests

Test	Corrosion rate (% mass loss per month)					
	Split Set		Cotter Pin		Swellex	
	Plain	Galvanized	Plain	Galvanized	Plain	Galvanized
Static	0.2	0.9 → 0.5	0.4	0.8 → 0.5	0.2	0.6 → 0.4
Dynamic 1	3.0	0.1	4.0	0.2	3.5	(a) 1.5
Dynamic 2	0.3	0.5	0.35	1.0	0.4	1.0
Dynamic 3	0.3	0.1	0.5	0.1	0.3	0.3
ASTM B117	11.0	9.0	11.0	9.0	10.0	8.0

Note: Rate of corrosion is calculated over the full time of immersion (209 days). Two rates are given for samples for which corrosion rates differed at 95 days compared with 209 days: the first is at 95 days and the second at 209 days.

(a) The experimental procedure is not necessarily applicable to Swellex because galvanizing is applied only on the outer surface.

sulfates, and bicarbonates. The concentrations of individual salt types differ from mine to mine, and do not directly represent the total salt concentration. The results of these tests have shown similar rates of corrosion for all three types of ungalvanized FRS. Galvanized samples were not included in the electrochemical tests reported here owing to sample preparation difficulties to suit the available apparatus. Galvanized samples are to be tested as part of further studies.

Salt spray tests

The results of the Salt Spray Test (ASTM B117) are also presented in Table 3. These results show that the rates of corrosion in water with a 5% sodium chloride salt concentration at 35°C are significantly higher than those determined from the three dynamic tests and the static immersion tests. The high rates of corrosion are considered to be due to the 10°C increase in temperature (compared with 25°C for dynamic tests) and the near-optimum salt concentration for high-corrosion effects. Although the corrosion rates are higher, all three types of ungalvanized FRS corroded at similar rates under ASTM B117 test conditions. Galvanized FRS corroded at marginally slower rates than ungalvanized FRS. Again rates were similar for all three types.

Reduction in tensile strength

Average mass-loss measurements of corroded field samples

Laboratory tensile tests were performed to determine the ultimate tensile load at failure for corroded samples collected from mine sites. The reduction in ultimate tensile strength was calculated as a percentage of the original ultimate tensile strength before corrosion. Prior to the tensile load testing, average mass loss was determined for corroded samples. A plot of mass loss versus reduction in ultimate tensile strength is shown in Figure 4.

A regression analysis of this data suggests that a linear relationship between average mass loss and reduction in ultimate tensile strength can be expressed as follows:
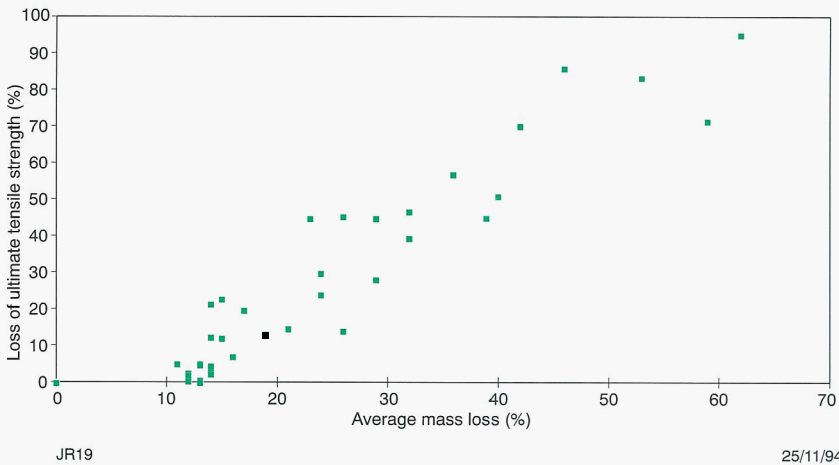

Figure 4. Average mass-loss versus reduction in ultimate tensile strength

$$L = 1.8M - 15.8$$

where: L = loss of ultimate tensile strength (%),
M = average mass loss (%) resulting from corrosion.

Note that this relationship is applicable only when the average mass loss is greater than 10%.

Samples with simulated localized mass loss

Tensile tests were also performed to simulate the effect of localized mass loss of FRS resulting from localized corrosion. Localized mass loss was simulated by drilling several holes, 10 to 15 mm in diameter, across new samples. A plot of localized

mass loss versus reduction in ultimate tensile strength is shown in Figure 5.

A regression analysis of this data shows that an approximate linear relationship between localized mass loss and reduction in ultimate tensile strength can be expressed as follows:

$$L = 1.4M + 20.5$$

where: L = loss of ultimate tensile strength (%),
M = localized mass loss (%) resulting from pitting-type corrosion.

This relationship indicates that a 10% loss in localized mass results in about 30% reduction in ultimate tensile strength.
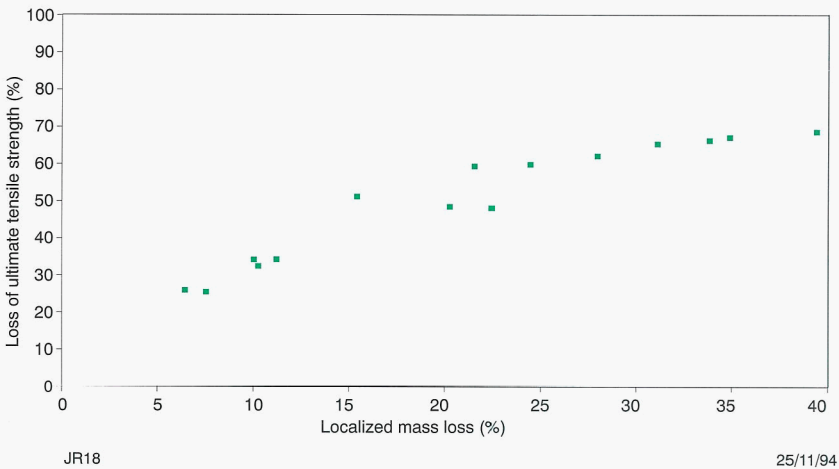

Figure 5. Localized mass-loss versus reduction in ultimate tensile strength

Discussion

This study has established that the quality of groundwater in underground mines in Western Australia is highly variable. The groundwater quality is variable even within single mines, possibly because of the use of water in mines from sources other than the mine itself. As a result, the corrosiveness of underground mining environments is extremely variable from site to site. This is evident from Figure 2.

An important outcome of the project is that for the first time in Western Australia operators and regulators will be able to quantitatively assess the extent and significance of corrosion of randomly collected samples of FRS.

One possible limitation of the study is that the samples were mostly collected from the protruding ends of Split Sets, which may not necessarily represent the conditions acting inside the ground; however, the maximum rate of mass loss recorded (81% in 11 months) was determined from a rock-fall site from a sample which was fully embedded in the ground before the failure.

Analyses of corroded samples have shown that three types of corrosion can damage the FRS in underground mining environments. They are uniform corrosion, localized corrosion, and galvanic corrosion. A linear relationship exists between average mass loss and the ultimate tensile strength. A second relationship also exists between simulated localized mass loss and the ultimate tensile strength. If the mass loss for a FRS can be predicted, then the loss of ultimate tensile strength in an underground mine can be predicted. This has ramifications for the safety of workers due to the progressive loss in holding power of the installed reinforcement.

It is important to note that the maximum initial load-bearing capacity or reinforcing effect available is governed by the maximum frictional resistance along the interface between the drillhole wall and the stabilizer itself. This aspect has not been studied as part of the present investigations. Sundholm (1987) observed that the residual holding force of FRS significantly decreases with time. Sundholm interpreted that the reduction in holding force was partly due to initial surface corrosion, which smooths down the surface roughness of the stabilizer; and corrosion products, which diminish the sliding friction between the stabilizer and the drillhole wall. In contrast, Ingersoll-Rand (1980) claim that initial surface corrosion increases the holding force. This aspect of FRS is still to be addressed in detail.

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