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ROCK BOLT CORROSION - AN EXPERIMENTAL STUDY

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ABSTRACT: The effect of long term exposure of full size bolts to corrosive environments is presented. A special test rig was used to test four bolts under different loading conditions. Four, X-grade identical profile bolts, each of 21.7 mm core diameter (23.7 mm full diameter) were subjected to prolong corrosion testing using acid sulphate water. The pH value of the circulated water varied between 3.4 and 4.3. The corrosion exposure test period lasted three and half years. Two bolts were axially loaded to 10 and 20 t force respectively, the third bolt was subjected to a 360 Nm torsion load and the fourth bolt was left unstressed to act as a reference bolt. After the test period ended, the bolts were stripped of their corroded coatings and weighted for weight loss. The diameter of each bolt was subsequently measured, and the loaded bolt samples were first tested non-destructively for tensile cracks and then tested for tensile failure. No cracks were found on post corrosion bolts tested non-destructively. The failure strength reduction on all four post-corroded bolts was significant, varying between 21% and 39%. The onset of corrosion was not confined to the targeted mid-section length of the bolt, however, the severest corrosion occurred at the anchored ends of the bolts.

INTRODUCTION

Corrosion is a physical alteration of a material from electrochemical reaction with its environment that often results in reduction of the mechanical properties of that material. Roof bolts are particularly susceptible to corrosion as they can be exposed in their working environment to ground water. Corrosion increases markedly in sulphide ore bodies due to acid runoff. Table 1 shows different types of corrosion that a rock bolt is likely to undergo when used for ground reinforcement. Of all the types of corrosion, pitting is particularly dangerous as it removes capacity for the bolt to deform with strata movements. Sudden failure of a bolt is likely to occur when pitting corrosion is experienced. The type and nature of corrosion depend on the nature of the ground condition and bolt encapsulation. Generally, the type of corrosion and severity of the corrosion varies along the bolt.

Historically the subject of steel corrosion has been of interest to civil and construction engineering. In mining, the interest in the topic is relatively new and following the introduction of bolting for ground support in mines and tunnelling. According to Baxter (1996) the early corrosion studies on rock bolting were carried out by Swedish and Finish researchers. Various publications include: Tuutti, 1982; Sundholm, 1990; Helfrich, 1990; Moving, 1994; Sundholm and Forsen, 1995; Satola and Aromaa, 2005. In the Australian context, the interest in bolt corrosion began in earnest in late 1990s, and the paper by Gray (1998) in which an emphasis was given to the Stress Corrosion Cracking (SCC). An ACARP project was initiated in 1999 to address the observed phenomenon of premature failure of rock bolts in a number of Australian coal mines, and with a particular focus on the problem of SCC in rock bolts (Hebblewhite, *et al.,* 2002, 2003a, and 2003b). Other Australian publications on corrosion include Gamboa and Atrens (2003), Hassell, *et al.*, (2005), and Vandermaat, *et al.,* (2012). The latter developed an apparatus to study stress corrosion cracking in full sized bolt specimens.

The rate of steel bolt corrosion is influenced by ground water composition, flow rates, water pH, temperature, CO_2 content, surface condition, presence of corrosion inhibitors, applied stresses, residual stresses (from workings, forming or welding operations) and any hydrogen sulphide concentrations (Henthorne, 1972; Spearing, 2010). Accordingly, a specialised test rig was constructed to study the effect of long term exposure on full size bolts, which are of current use in Australian mines. The study was undertaken in an environmentally controlled laboratory under different bolt loading conditions.

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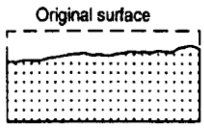
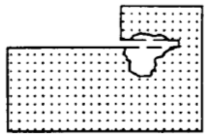
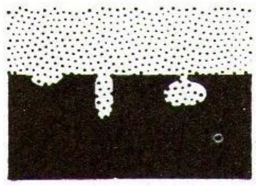
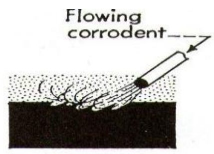
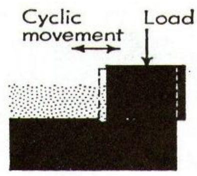
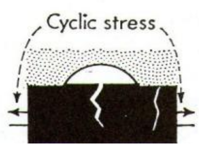
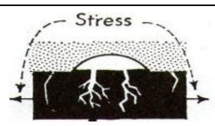
Table 1 - Types of corrosion in steel

Forms	Categories	Description	
Uniform	Atmospheric	Corrosion of material exposed to air and its pollutants.	
	Galvanic	Corrosion due to electrolysis	
Localised	Crevice	Localised corrosion occurring on confined, closely spaced metal to metal or non metal to metal component surfaces. It is localised corrosion occurring in small areas of stagnant solution in crevices on joints. Crevice corrosion can also occur as a result of differential aeration mechanisms.	
	Pitting	Highly localized corrosion occurring on a metal surface. Pitting is marked by the development of sharply defined holes "pits". Occurs as a process where the metal loss is accelerated by the presence of a small anode and a large cathode. A dangerous form of corrosion as it can cause failure where only small weight loss of metal is observed	
Mechanically Assisted Degradation	Erosion	The removal of a metal surface material by the action of numerous individual impacts of solid or liquid particles.	
	Fretting	Occurs as the combined wear and corrosion between contacting surfaces, when the motion between the surfaces is restricted to very small amplitude oscillations. Oxidation is the most common element in the fretting process.	
Environmentally Assisted Degradation	Corrosion Fatigue	The process in which a metal fractures prematurely under conditions of simultaneous and repeated cyclic stress loading. This is likely to occur at lower stress levels with fewer cycles than would be required in the absence of the corrosive environment.	
	Stress Corrosion Cracking	This is a progressive development and growth of brittle cracks in a metal due to the combined effects from localised corrosion and tensile stress.	
	Hydrogen Embrittlement	This results from the combined action of hydrogen and residual or tensile stress. This type of failure occurs in quenched and tempered high-strength steels. The presence of hydrogen in steel reduces the tensile ductility of the material	
	Bacterial Corrosion	Sulphate reducing bacteria (SRB) metabolising sulphate in anaerobic conditions produce the most common form of attack. The sulphate ions, as the waste product of such metabolism, react with the metal to give metal sulphides. A deposit of black iron sulphides results when iron is corroded in sulphate bearing water-saturated ground.	

EXPERIMENTAL PROCEDURE

The laboratory experiment involved four X-grade roof bolts subjected to similar environmental conditions to provide data on the effects of corrosion. The testing period lasted three and half years.

During the testing period the bolts were subjected to a corrosive environment using acid sulphate soil water with corrosive characteristics significantly greater than that can be found in most mine environments. This was necessary in order to speed up the corrosion process. The method adopted to study corrosion under various bolt loading conditions was as follows:

- Corrosion testing of a bolt axially loaded to 10 t force,
- Corrosion testing of a bolt axially loaded to 20 t force,
- Corrosion testing of a bolt subjected to torsion of 350 Nm, and
- Corrosion testing of a bolt section without loading as a reference bolt.

Factors such as pH, temperature, conductivity and salinity of the corrosive medium were constantly monitored and recorded. Water was sourced from acidic ground water drainage channels that flow into the Shoalhaven River in the South Coast of NSW, Australia. The acidity of the water was thus attributed to the regional acid sulphate soils

Test equipment

The corrosion testing apparatus consisted of a header tank which fed water to all test bolts as shown schematically in Figure 1. Figure 2 shows the laboratory experimental test rig. The dispersion of water on each tested bolt used 13 drippers spaced at 40 mm along a 720 mm long 100 mm diameter PVC manifold tubing, giving each bolt a wetting exposure length of between 520-540 mm. Water in the PVC manifild tubes was supplied from the main reserviour tank, placed about 500 mm above the PVC water manifold tubings. The length of each bolt loading frame was 770 mm. The dripped water was collected in plastic drip trays placed beneath each tested bolt and returned to the header tank for recirculation.

Bolt tensioning

Bolt tensioning was carried out using three strong Parallel Flanged Channel (PFC) steel frames, which allowed axial loading of two bolts to the predetermined loads of 10 and 20 t, and torsion of the third bolt. The 9.5 mm thick steel tensioning PFC frames consisted of two 150 mm x 75 mm sections. Two 150 mm square, 10 mm steel plates welded the two PFC steel channels together and were painted to protect and prevent them from influencing the bolt corrosion. The end-plates were drilled with 25 mm diameter holes to allow the bolt to pass through and sit between the beams spaced at 50 mm. The strength of the end-plates allowed the applied tension to be held by an interlocking nut against the sides of the frames as shown in the Figure 2 inset. The PFC section frames were designed to allow the water, that drip on to the bolts, to be collected in plastic trays placed underneath bolt mounted rigs. The reference bolt (non-tensioned) rested on top of the plastic drip tray, and the dripper tube was supported on a small plastic stand, just above the bolt. Figure 3 shows the procedure adopted for tensioning the bolt axially.

Test water

Water was sourced from Shoalhaven River (NSW, Australia) inlets. The Shoalhaven groundwater was acidic, with variable low pH value ranging between 3.4 to 4.3. The variation in the quality of the water was seasonal and at times the water was collected from two separate locations within a two square kilometre area. Due to the weathering of pyrites forming acid sulphate soil in this area, the water quality was of sulphuric acid concentration. The flow rate of dripping water to each bolt surface was kept between 3 - 5 L/h. Water in the circulation was regularly topped-up with fresh supplies, because of the losses occurring from spillage and evaporation.

Recycling of the water through the rig system was achieved using a small submersible pump with a float switch. Constant monitoring of the condition of the water was recorded as well as a titration analysis on four water samples at different times, spanning about three years of the experimental study. Table 2 shows the major chemicals present in the water and properties such as pH levels and conductivity. Figure

4 show the graph of PH level variations with time. Table 2 shows four water samples chemical analysis. Samples one to three were collected form Shoalhaven River inlet while sample four was from water from a local mine.

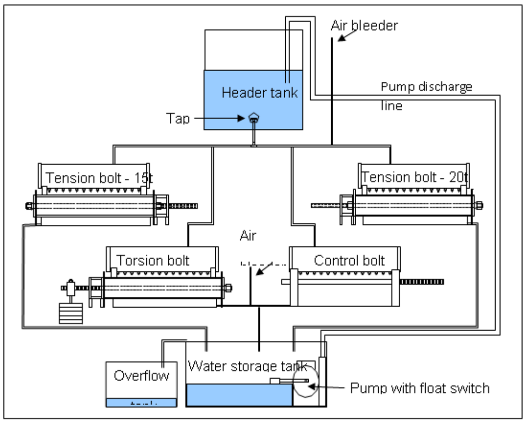


Figure 1 - The general layout of the bolt corrosion rig

Figure 2 - Corrosion testing rig

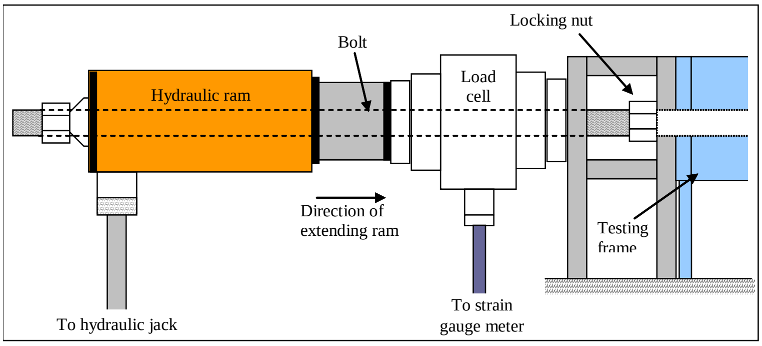


Figure 3 - Axial tensioning of bolts installed in the tension rig

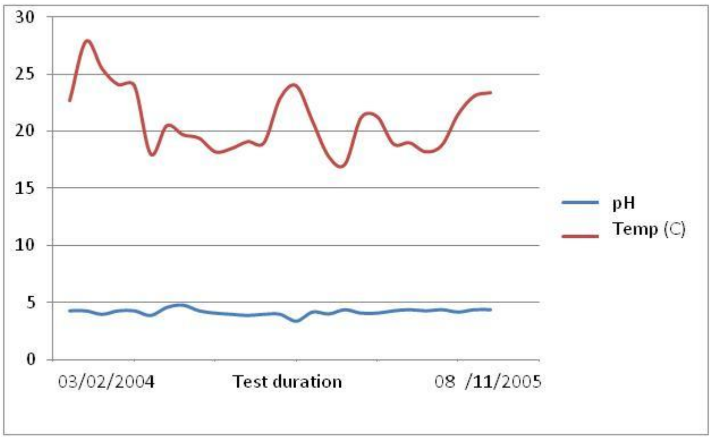


Figure 4 - Laboratory room temperature fluctuation and water Ph value

Table 2 shows the analysis of the water quality from Shoalhaven River and water quality of mine water collected from one mine in the southern coal field if Sydney Basin. It is clear from Table 2 and graphs in Figure 4, that the test water from Shoalhaven River was an aggressive solution that was suited to corrosion reactions in comparison from a typical mine water sample shown in Table 2. High concentrations of chloride ions as well as low pH level suggest that the solution was acidic. The large proportions of sulphates reinforced the weathering of the pyrite from the water origin, which assisted in decreasing any resistance to corrosion such as the formation of oxide layers. The sample solutions also show that the water had low dissolved oxygen content, which is not favoured in corrosive reactions;

however this was not thought to hinder corrosion in this test as oxygen was available to the metal surface from the atmosphere and the solution had a low pH and was not dependent on oxygen.

Table 2- Chemical analysis of test solutions, 1- 3 collected from Shoalhaven River with the fourth sample from a mine

	Sample 1 June 2002	Sample 2 May 2005	Sample 3 April 2006	Sample 4 (Mine water)
K (mg/L)	7.41	8.65		134.4
Ca (mg/L)	2.61	2.16	115	431.0
Al (mg/L)	60.4	47.6		10.21
Fe (mg/L)	69	74.8		1.00
Mg (mg/L)	60	58.2	130.7	533.7
Na (mg/L)	107.85	208.09	910	2850
Cl (mg/L)	217.55	62		5230.10
SO_4 (mg/L)	1059.44	1500		2380.80
Na/Cl	0.5	3.36		0.55
Cl/SO_4	0.21	0.41		2.2
pH	2.85	2.98	3.97	3.8
Electrical Conductivity (μS)	2008	2359	5080	18000
Dissolved Oxygen (mg/L)	8.3	9.7		
Total Dissolved Solids (ppm)	2.75	2.89		

Test bolts

Four M24 (22.0 mm core diameter) X-grade (AX) bolts were selected for this investigation. The chemical analysis conducted on the bolts is shown below in Table 3 and indicates a high carbon manganese steel. The post test samples were stripped of the corroded deposit layer to bare metal surface and had their diameters measured. The average diameter of the four tested samples pre and post-test is shown in Table 4.

Table 3 - Chemical analysis of the test bolts (source: Bureau Veritas Australia, 2012)

Bolt	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Cu	B
Ref	0.43	0.73	0.010	0.027	0.22	0.10	0.16	0.03	0.002	0.002	0.30	0.0008
Tor	0.45	0.74	0.010	0.029	0.22	0.1	0.16	0.03	0.002	0.002	0.3	0.0008
T10	0.29	0.82	0.011	0.023	0.24	0.09	0.08	0.02	0.044	0.001	0.31	0.0007
T20	0.53	1.65	0.008	0.022	0.24	0.07	0.11	0.01	0.002	0.001	0.25	0.0011

NB: Ref; Reference bolt, Tor: torsion bolt; T10: 10 t tensioned bolt; T20; 20 t tensioned blt

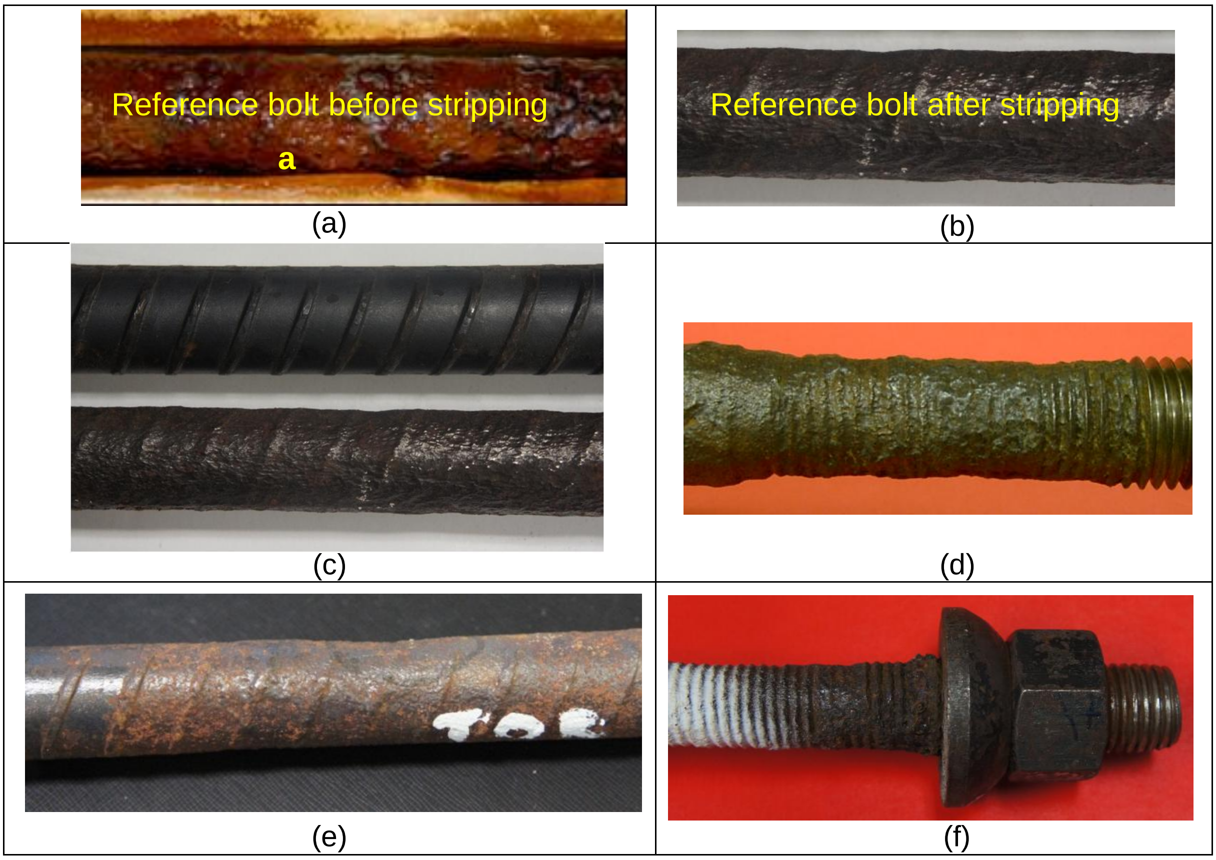
Table 4 - Yield and ultimate strength failure load of the tested bolts

Bolt Status	Reduction in bolt diameter after corrosion test (%)	Reduction in bolt cross -section area (%)	Yield load (kN)	Change in yield load with respect to new bolt (%)	Failure load (kN)	Reduction in failure load bolt (%)
New bolt (P new) *	0	0	219.663		347.187	
20 t axially loaded (T_{20})	12.1	11.04	219.507	0	274.957	21
10 t axially loaded (T_{10})	12.5	11.40	150.518	31.5	211.354	39
300 Nm torsion Bolt (T_t)	9.65	8.81	126.930	42.2	211.518	39
Reference bolt (T_r)	12.6	11.50	128.119	41.6	222.164	36

* Initial bolt core diameter: 21. 7 mm; full diameter with ribs: 23.7 mm

Figure 5 shows pictures of various sections of pre and post-tested bolts. It is clear that there were some variations in the post-testing diameters along the length of each bolt. A noticeable and excessive corrosion occurred on the threaded bolt-ends section and at the sections of the bolts passing through the steel PFC end plate holes. These two sections were outside the direct water dripping zones. The threaded side of the bolt with maximum corrosion were for the purpose of bolt tensioning on the loading frame sides. Figure 5 d, e and f show corroded bolt surfaces located in the vicinity of the PFC bolt tightening hole. This type of crevice corrosion is most likely to be the result of differential aeration mechanism.

Figure 6 shows the load-displacement graphs of various corrosion tested bolts as well as a new bolt, which was not subjected to the corrosion test. Table 4 shows the various bolts load-displacement values at yield as well as the ultimate strength values as seen in column six in Table 4.



f

Figure 5 - Photos of parts of various corroded bolt sections compared with un- corroded section. Section (e) shows the evidence of crevice corrosion due to aeration at bolt end

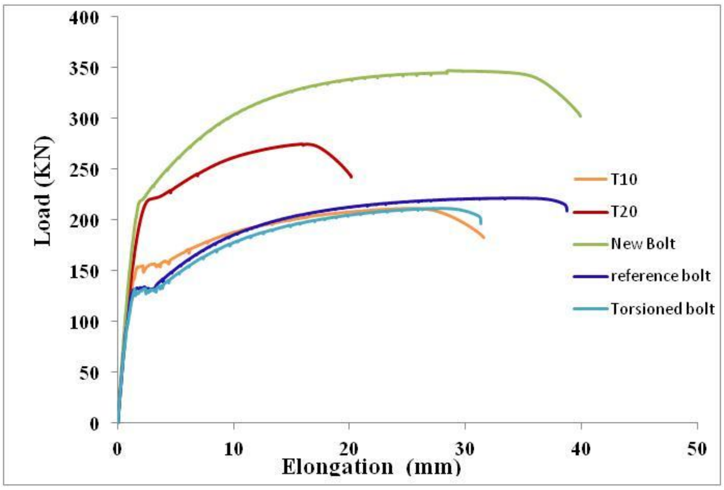


Figure 6 - Load displacement profiles of various bolts

One of the noticeable profiles of the load displacement graph was that the strength value of the 20 t tensioned bolt (T_{20}), was relatively greater than the other three bolts in the test. The peak load of P_{20} bolt was in the order of 274 kN (27.94 t). This level represented a reduction of around 21% in strength with respect to the failure strength of a similar new bolt with its tensile strength failure load of 347 kN (35.38 t). The 10 t (T_{10}) tensioned bolt achieved 39% reduction in strength, and the reduction in strength of the torsion bolt (P_t) was 39% and the reference bolt (T_r) was 36%. The unusually lower percentage reduction in the failure load of the 20 t bolt as compared to other corroded bolts is likely to be attributed to the steel composition of the bolt as shown in Table 4. It is clear that the carbon and manganese content of the T_{20} bolt was greater than with other three bolts.

The average reduction in borehole diameter of all four bolts due to three and half years of corrosion testing was in the order of 11.7%. This is equivalent to a cross-sectional area reduction of around 10.7%. This level of cross-sectional area reduction was significantly less than the percentage reduction of the bolt tensile strength.

The accuracy and reliability of the corroded bolt diameter measurement were affected by the level of bolt surface irregularity due to the bolt surface pitting as well as near total erosion or corrosion of bolt profiles around the bolt. This made it difficult to differentiate measurements between core and full diameter bolt cross-section.

The weight loss measurement, before and after the test, could not be related solely to the designated wetted section of the bolt. There was some further corrosion at the bolt ends that anchored the bolt ends to the PFC steel loading frame. Thus, two forms of corrosion were identified in this experimental study, pitting and crevice corrosion. Pitting corrosion was evident in the mid-sections of the bolt directly along the dripping zone as seen in Figure 5 a, b and c. Crevice corrosion on the other hand occurred at the bolt ends as demonstrated in Figure 5 d, e and f. The mounting of the torsion bolt on the PFC tension frame also generated crevice corrosion as one side of the bolt required no direct axial loading, just torsion, thus leaving a free flow of air through the bolt surface as shown in Figure 5e. Normally crevice corrosion occurs in the confined space as a result of differential aeration mechanism. Also the excessively crevice corroded zone shown in Figure 5e was not in direct contact with the dripper waters as the last drip nozzle was some 60-70 mm away from either side of the rig side holes housing the bolt ends. This sort of corrosion is most likely to be observed underground at the collar of the installed bolt in a hole with less encapsulation, thus leading to the onset of stress corrosion cracking, particularly when the protruding bolt end is subjected to external shear loading or impact. According to Gray (2006) this kind of corrosion was often found in their field observations particularly at Angus Place Mine, NSW, with severe corrosion taking place along the free length of the bolt, even though there was no apparent free water. A damp corrosive atmosphere is sufficient to cause corrosion and perhaps this is because of the greater presence of free oxygen in air rather than under water. Also the excessive surface area of the threaded section of the bolt also has an influence.

A non-destructive test was carried out on T20 bolt to determine whether there was an onset of stress corrosion cracking of the sample after it was subjected to 20 t tension force. Using magnetic particle inspection, repeated tests on the sample produced negative results which indicated no cracks were found.

CONCLUSIONS

Prolonged experimental study using high carbon manganese X-grade rock bolt showed that significant corrosion has occurred in an aggressive low pH groundwater. Both pitting and crevice corrosion was identified as the type of corrosion that is most likely to occur along the tested bolt length. Using low pH water to speed up the corrosion process was considered as acceptable and viable methods of conducting bolt corrosion testing in the laboratory environment.

The ultimate tensile strength of bolts subjected to prolonged corrosion tests was reduced by between 21%, for 20 t bolt, and 39% of the reference bolt, compared with the ultimate tensile strength of a new similar type bolt. Both T_{10} and torsion bolts had near equal ultimate tensile strength reduction of 31%. The abnormally high load displacement profile of the T_{20} bolt was attributed to different composition steel with high carbon and manganese content in comparison to other three tested bolts

The average reduction in borehole diameter of all four bolts over the period of three and half years of corrosion testing was in the order of 11.7 %. This level of diameter reduction was significantly less the percentage reduction of the bolt tensile strength of between 21 and 39%.

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