An Investigation of the Corrosive Impact of Groundwater on Rock Bolts in Underground Coalmines

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ABSTRACT

Premature failure of rock bolts has been recorded at twelve underground coalmines over the past 15 years in Australia. Over the last four years, UNSW Australia has been conducting an Australian Research Council (ARC) and Industry funded linkage research project into premature failure of rock bolts. The extent of the problem was investigated by underground surveys of mines with known prematurely failed bolts using visual mapping, non-destructive load and ultrasound testing. A major component of this project was to define the environmental factors responsible for corrosion of rock bolts. The environment to which a rock bolt is exposed will include groundwater chemistry, the mineralogy of the strata, atmosphere within the drill hole and even microbial activity. This paper focuses on the groundwater survey and analysis findings to date along with in-hole bolt corrosion coupons installed into field sites. Corrosivity classification systems exist for general corrosion but do not apply to the rock bolt stress corrosion cracking (SCC) problem found in Australian underground coal. The method of *in situ* investigations is leading towards the building of a corrosivity classification model to assist mines in prediction of premature rock bolt failure. An 'in-hole bolt corrosion coupon' development by the project may have multiple benefits of:

- helping quantify any corrosivity classification system
- providing an *in situ* ground support corrosion monitoring tool
- for testing possible corrosion protection solutions.

INTRODUCTION

The problem of premature rock bolt failure in Australian coalmines was first identified by an Australian Coal Association Research Program (ACARP) funded project C8008 completed in 2002, with further findings from ACARP project C12014 reported in 2004. Many of the 50 broken bolts collected from five mine sites were determined to have failed from stress corrosion cracking (SCC). The majority of the broken bolts examined from 1999 to 2002 had steel Charpy impact toughness values of 4–7 J (Crosky *et al*, 2004). Fracture mechanics predicts that an increase in steel impact toughness will increase the length of the crack before sudden brittle failure. In the final report of 2004, anecdotal evidence from one coalmine indicated that the problem may be eliminated in some environments by a change to steel grades with higher Charpy impact values of ~16 (Crosky *et al*, 2004).

A 2003 laboratory study by Gamboa and Atrens on four Australian rock bolt steel grades in various electrolyte solutions had found SCC failures only occur within pH <2.1, which was much lower than sampled groundwater from underground hard rock mines and one coalmine of pH 6.8–8.3 (Gamboa and Atrens, 2003). There was no correlation of steel grade performance between the laboratory studies and coalmine rock bolt service history (Crosky *et al*, 2004).

Between 2004 and 2010, many Australian coalmines had reported further SCC premature rock bolt failures and these now included the higher Charpy impact toughness steels of ~16 J In 2010, the current UNSW Australian Research Council (ARC) and industry funded linkage project LP100200238 commenced with significantly more resources than previous projects.

The UNSW ARC linkage project has three main areas of investigation towards achieving its aims:

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1. laboratory bolt corrosion experiments aimed at reproducing SCC failures
2. metallurgical examinations aimed at defining the causes and mechanisms of coalmine SCC
3. coalmine data collection to identify the extent and environmental contributors to the problem.

This paper discussed the coalmine data collection and analysis to date.

EXTENT OF BROKEN BOLTS

Since 2010, approximately 200 broken rock bolts have been collected from 12 Australian coalmines and received into UNSW laboratories for various analyses. All of the rock bolts are 22 mm core diameter, 'X' grade steel, which is typically >600 MPa yield and >840 MPa UTS. Three main failure modes are visually evident as shown in Figure 1 and are generally described as:

1. rebar SCC
2. localised pitting corrosion
3. thread SCC.

It was obvious from mine sites with an adequate number of samples that both SCC and localised pitting corrosion occur within the same environments. Mine sites included in the study have had their name replaced with an allocated project identification number. Table 1 details the quantity and type of broken bolts at each mine site. It was clear that Mine 1 and Mine 3 have the most number of premature failures, and underground surveys were conducted to help further define the extent of the problem.

TABLE 1
Recovered broken bolts database.

Mine site – project identification number	Rebar stress corrosion cracking failures	Localised pitting failures	Thread stress corrosion cracking failures	Total recovered broken bolts
1	26	14	0	40
3	88	31	3	122
24	1	0	0	1
25	1	2	0	3
11	2	0	0	2
10	1	1	0	2
12	0	3	0	3
9	3	3	0	6
22	1	0	0	1
23	0	4	0	4
7	0	0	9	9
21	0	0	2	2
Totals	123	58	14	195

Mine site 1

Mine 1 is a coalmine operating in New South Wales within a 7 m thick coal seam(s) at a working depth of 300–430 m. The working section is within the bottom 3 m and the primary rock bolted horizon is predominantly lower quality coal with 3–4 claystone bands varying from 20–300 mm thick. The horizontal stress direction is near perpendicular to the longwall gate roads, resulting in higher rock bolt loading conditions in gate road roadways and in 'mains' cut-throughs. Mine 1 has predominantly bolts made from steel with Charpy impact toughness values ~16 J, and interestingly shares it lease boundary with a mine which previously claimed (Crosky, 2004) to have anecdotally eliminated premature bolt failures by moving from bolts of impact toughness 4–7 J to the bolts of ~16 J. The location of broken bolts was segregated into mains roadways inbye a lithological change and current longwall gate roads.

Mains

Figure 2 shows a schematic of Mine 1 main roadways with respect to some major features. The two headings on the far right of the drivage direction were reported by mine site personnel to contain the most broken rock bolts. These two headings and adjoining cut-throughs (c/t) were walked and visually inspected to note the location of missing bolts from the roof support pattern. This equated to approximately 6 km at 6 bolts per metre, equaling 36 000 rock bolts.

Figure 3 graphically represents the number of broken bolts per location along the two main heading roadways. The immediate finding is that age of the headings is not strongly related to the frequency of broken bolts in the mains. A total of 226 broken bolts were discovered, with the cut-throughs accounting for 60 per cent of the failed bolts and heading #5 on the far right accounting for 30 per cent of the failed bolts. Where possible, a tape measure was placed into drill holes where bolts were missing and the distance to the break location measured. The mine records had shown an increase in resin capsule length to improve bolt encapsulation in heading #5 from 89 c/t onwards. The bolt break lengths were averaged before and after 89 c/t, and found to be 290 mm before increasing resin encapsulation and 166 mm after increasing encapsulation. The number of broken bolts in heading #5 in the ~2 km before 89 c/t accounted for 40 per cent of broken bolts, whilst the ~1 km of heading #5 driven with the longer resin capsules accounted for 60 per cent of broken bolts. Strong conclusions cannot be made about the effect of bolt encapsulation as it will be shown that groundwater flow rates had a big impact on the number of broken bolts inbye of 89 c/t.

Considering the location of the roof bolts across the section of the roadway, it was evident that >95 per cent of the broken

FIG 1 – (A) Rebar stress corrosion cracking; (B) localised pitting corrosion; (C) thread stress corrosion cracking.

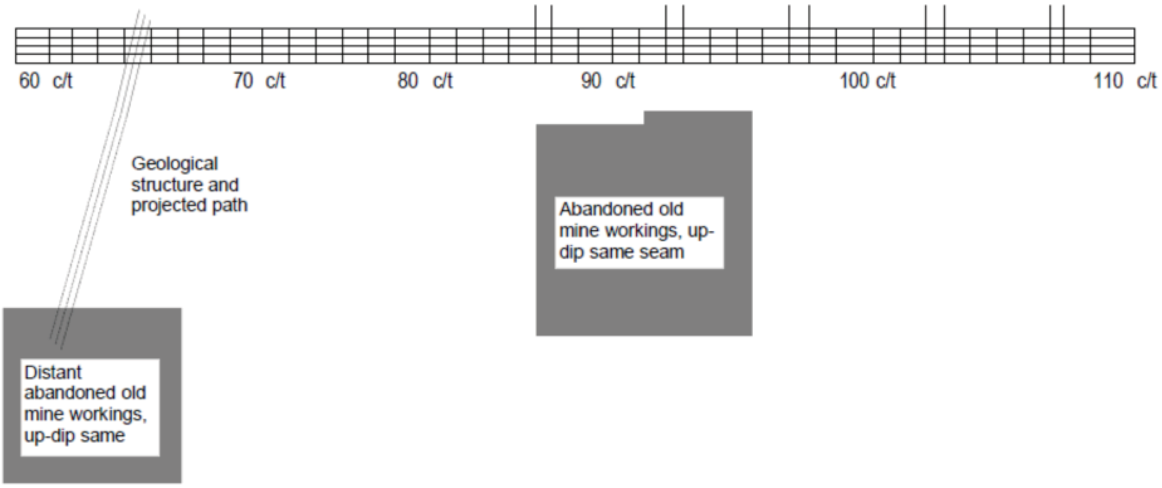

FIG 2 – Sketch of Mine 1 main roadways and associated features.

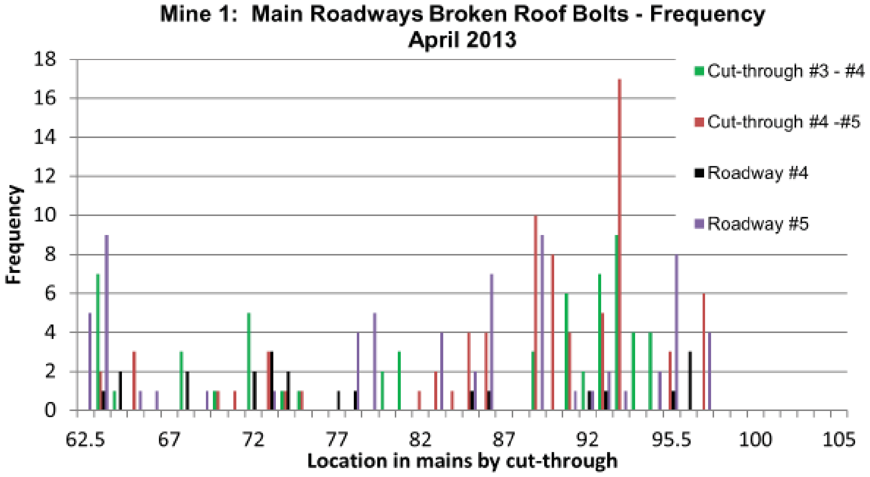

FIG 3 – Mine 1 'mains': underground survey of broken Bolts.

bolts occurred closest to the corner with the rib/wall. In terms of movement of laminated strata in a rectangular coalmine roadway, there is a concentration of horizontal stresses and lateral movement nearest the corners. It is postulated that the bending forces on the rock bolts nearest the roadway corners provide the increased 'stress' contributing to the stress corrosion cracking failure of bolts. There was also a higher instance of broken bolts in cut-throughs and nearest intersections in the roadways which matched the increased horizontal stress locations. The mine site had also completed geological structure and hazard mapping of the main roadways. It was found that many clusters of broken bolts coincided with areas of increased horizontal stress associated with geological structure locations and orientations.

The service age from installation of the broken bolts in the mains was greater than seven years. The older broken bolts near the start of the outbye lithological change had been in service for 13 years.

Gate roads

Mine 1 gate roads comprise of around 28 pillars of 110 m long × 40 m wide, and as mentioned the headings are driven in the unfavourable direction to the regional horizontal stress. Reports of broken bolts in the active mining area of a recently completed gate road were investigated by visual inspection in August 2013. The bolts in the gate road were within two years of service life and there were 98 broken roof bolts, with all the broken bolts found within the headings and nil found in the cut-throughs. Broken bolts were particularly clustered in the headings between 10–12 c/t, 14–15 c/t and 18–19 c/t, with these areas accounting for 78 per cent of the broken bolts in the gate road. These locations coincided with elevated horizontal stress, and all of the broken bolts had failed from the rebar SCC, as shown previously in Figure 1.

Across both mains and gate roads at Mine 1, a total of 324 broken bolts were discovered during underground inspection, whereas previously only 40 broken bolts had been recovered and taken into the UNSW laboratories representing only 12 per cent of the actual extent of the problem found underground.

Mine site 3

Whereas Mine 1 had a fairly simple mine plan with one set of mains and all the gate roads off to the left in the same direction, Mine 3 is much more complex. Mine 3 has six different sets of main headings all in different directions to the regional horizontal stress, and the first development drivage commenced in 2003 making the majority of rock bolts less than ten years old.

Although in a completely different coalfield to Mine 1, Mine 3 had some similar overall characteristics. Mine 3 is operating in New South Wales within a 6–8 m thick coal seam(s) at a depth of 200–400 m. The working section is within the bottom 3 m of the seam and the primary rock bolted horizon is predominantly lower quality coal with three to four claystone bands varying from 10–100 mm thick. Mine 3 had older areas supported with bolts made from steel of impact toughness 4–6 J, but the far majority of workings are supported with bolts made from steel with Charpy impact toughness values ~16 J. The underground investigations focused on four areas, including two main headings, a gate road in an active mining area and a very old tailgate that remains accessible. The mine site personnel have mapped the extensive areas and ranked by areas of concern. The four areas selected were some of the worst affected locations and resources were allocated to allow load testing of old bolts combined with ultrasonic non-destructive testing (NDT) within these areas. To prevent damage to the ground support, load applied when testing of in-pattern support bolt is limited to 75 per cent of steel yield, and if any higher the bolt is replaced. The ultrasonic NDT device was a crack detector with specifically selected probes to suit very long thin shafts as represented by the rock bolts. Signal reflections off surfaces such as cracks or the end of the bolt are represented by a peak in the signal at the specific location on the screen representing the distance along the bolt. The surveys were conducted in the first quarter of 2014, and results summary of the load testing and NDT inspection of these four areas are shown in Table 2.

Mains

The first set of main roadways consisted predominantly of the bolt type with impact toughness of ~16 J, these were between eight and ten years old. There were 65 recorded broken bolts from the first mains in the UNSW laboratory, but locations were scattered over 3 km. The second set of mains were 100 per cent of the bolt type with impact toughness of ~16 J, and these were seven to eight years old. There were 21 broken bolts from the second mains in the UNSW laboratory.

The selected worst case areas of the first mains resulted in five from 98 visually intact rock bolts (five per cent) failing the load tests. Three of the failures were between 14–17 t and when pulled completely from the roof a bolt was suffering loss cross-section due to localised pitting, this bolt is shown in Figure 4. Prior to load testing, these failed bolts did not produce signal reflection by the ultrasonic NDT as the sound waves would have been deflected at the reduced cross-section rather than reflected back to the probe. These findings raise the possibility of bolts passing the 18 t load test yet being seriously compromised by loss of cross-section.

The NDT used in the first mains gave small crack reflection signals on three bolts, and a very large crack reflection on the fourth bolt. The first three passed the 18 t load test, but the fourth bolt failed and pulled out at 6 t. The failure surface was a perpendicular SCC crack, which explained the strong reflection. The other three bolts with indicated cracks on the NDT passed the 18 t load test but were likely broken far enough into the intact resin column that the resin bond below the crack held the load. Both non-destructive load test and ultrasound methods have limitations. The area of the second mains tested all passed the NDT and load testing.

A limited number of overcores were performed, but outside the surveyed areas. The recovered bolts showed small amounts of localised pitting corrosion. There are plans in place to overcore bolts within the worst affected areas when the equipment is available for those locations.

Old tailgate

Mine 3 has ready access to an old tailgate roadway which is around eight years old and has been subject to longwall abutment stress. The old tailgate heading is within the same mining area as the first and second mains, and a total of 22 broken bolts from the old tailgate were logged at the UNSW laboratories. The number of bolts was high considering it was a single heading compared to the mains which were two and three headings. A 100 m length of the old tailgate selected for survey which visually was potentially the worst affected location in the mine. A total of 60 bolts (ten per cent) were visually broken from the 600 bolts visually inspected, and load testing to 18 t of 42 visually intact bolts resulted in ten failures (24 per cent). The ultrasound NDT indicated seven bolts were cracked from 27 bolts tested. Two of the seven bolts failed the load test at 2 t, whilst the other five passed the 18 t load test.

Active gate road

During June 2012, Mine 3 had reported several random broken bolts in a new mining area gate road during development where bolts were less than six months old. An underground visit was made and groundwater collected at the freshly exposed development heading at the continuous miner. It was noted at the time that water drippers were slow at 30 mL/min,

TABLE 2

Mine 3 – results summary from load testing and non-destructive testing in the first and second set of main roadways.

Location	Load testing			NDT Testing		
	Total tested	Pass	Fail	Total tested	Cracked bolts detected	Load test result on cracked bolts
First mains	98	93	5	93	4	1 failed
Second mains	35	35	0	35	0	-
Old tailgate	42	32	10	27	7	2 failed
Active gate road	17	15	2	nil	-	-

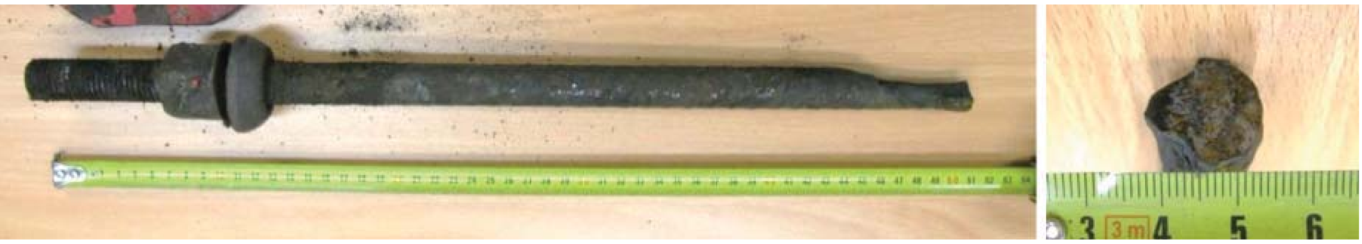

FIG 4 – Mine 3: bolt broken at 15 t during load test.

and that roof bolt drippers typically ceased flowing between 50 m and 100 m behind the advancing roadway.

A visual survey and load testing of bolts was conducted over 200 m of roadway at the same location in April 2014, after the roadway had been subjected to longwall retreat abutment stresses. There were 11 broken bolts during visual inspection and ten of these roof bolts had services pipes hanging from them which would have created vibration and small lateral loads. Load tests were conducted on 17 visually intact bolts and produced two failures (12 per cent).

GROUNDWATER

Thirty-eight groundwater specimens have been collected from 12 Australian coalmines, covering eight different coal seams across five coalfields. Each water collection was conducted by a member of the research team following a procedure of collection, storage and transport back to an accredited laboratory within 48 hours. All groundwater samples were taken from drippers coming out of rock bolts or cable bolts in the mines roof.

The groundwater analyses were compared for all mines, and also against other published corrosivity studies to build a relevant database which could be used for a future Australian coalmine corrosivity classification.

The variability of groundwater chemistry and flow rate across Mine 1 was investigated to check correlation against location of premature bolt failures.

Groundwater database

Early literature on corrosivity of mine water from Indian coalfields (Rawat, 1976; Singh, 1988) and South African gold mines (Higginson and White, 1983) were mostly concerned with pump out water and the effect on mild steel pipes carrying the water. These studies both found that the Langlier saturation index (LSI) which predicts the deposition of protective scale on the steel surface as not applicable to mine waters due to the presence of aggressive ions such as chlorides and sulfates.

More recent literature has investigated corrosion of rebar and cable bolts. Satola and Aromaa (2003) and Hassal *et al* (2004) investigated the application of the German Standard DIN 50929 for corrosion of metals in soils to the corrosion of metals in hard rock mines groundwaters of Finland and Australia respectively. Both found that the DIN corrosivity classification did not correlate to corrosion in mining applications. Dorion, Hadjigeorgiou and Ghali (2009) completed steel coupon testing in mine groundwaters of Canadian and Villaescusa, Hassell and Thompson (2008) in Australian hard rock mines respectively, with the aim of correlating groundwater characteristics to the general corrosion rate in millimetres per year. The coupons were carefully prepared specimens to the ASTM standard G4 as shown in Figure 5, with the surface mill scale removed. Australian coalmine rock bolts are rebar with mill scale attached, and are suffering from localised pitting corrosion and SCC which are different mechanism compared to general corrosion of coupons.

The UNSW coalmine groundwater data was also checked against the existing corrosivity classification systems and the known presence of premature rock bolt failures from particular mines.

Mine groundwater corrosivity

Corrosivity studies typically focus on a limited number of groundwater features including pH, alkalinity, total dissolved solids (TDS), aggressive anions (Cl^- and SO_4^{2-}), dissolved oxygen (DO) and temperature. The 12 Australian coalmine rock bolt dripper waters analysed were in general near neutral pH and low concentrations of aggressive ions.

FIG 5 – ASTM Standard G4 coupons (Dorion, Hadjogeorgiou and Ghali, 2009).

Figure 6 graphically represents the LSI rating for the Australian coalmine bolt dripper groundwater analysed by the project to date, on a mine by mine basis. It is clear that the LSI does not correlate as Mines 3, 9 and 11 are showing possible protective scale, but these mines have had numerous corroded bolts within the groundwater sampling locations. The LSI is not useful for Australian coalmine groundwater corrosivity due to the Cl^- concentrations exceeding 25 ppm at nine of the 12 mines (Sastra *et al*, 1994), which was also the finding from the Western Australia School of Mines (WASM) study into Australian Hard rock mine water conducted by Villaescusa, Hassell and Thompson (2008). As shown in Table 3, the Australian coalmine groundwater had very small amounts of aggressive chloride and sulfate compared to the WASM Australian Hard rock groundwater study.

Figure 7 graphically represents the DIN corrosivity rating for the Australian coalmine bolt dripper groundwater sample analysed by the project to date, on a mine by mine basis. The DIN classification will not be discounted at this stage in the project due to good correlation with Mines 6, 9, 10 and 11. Mines 1 and 3 which do not correlate have significant clay bands in the bolted horizon, which may have a greater impact on corrosion than the groundwater alone.

Mine 1 groundwater field study

Mine 1 heading #5 and adjacent cut-throughs were mapped for broken bolt locations. It was found that water was flowing and dripping from a large number of rock and cable bolts in heading #5. The adjacent cut-throughs and headings were damp but did not have water flowing or dripping from many bolts. The groundwater in heading #5 was sampled for chemical analysis every ~10 cut-throughs, and the flow rate was measured every intersection and mid-pillar for over 50 pillars. The support pattern included 2.1 m rock bolts and a mixture of 4 m and 8 m long cable bolts. To obtain a representative sample a 3 m length of the 5 m wide roadway was selected at each sampling point. The flow rate of each individual dripper was measured and then added together to obtain the total flow rate in millilitres per hour for that 3 m length of roadway.

Mine 1 groundwater flow rate

The flow rate from Mine 1 heading #5 is plotted in Figure 8 along with the frequency of broken bolt in heading #5 and

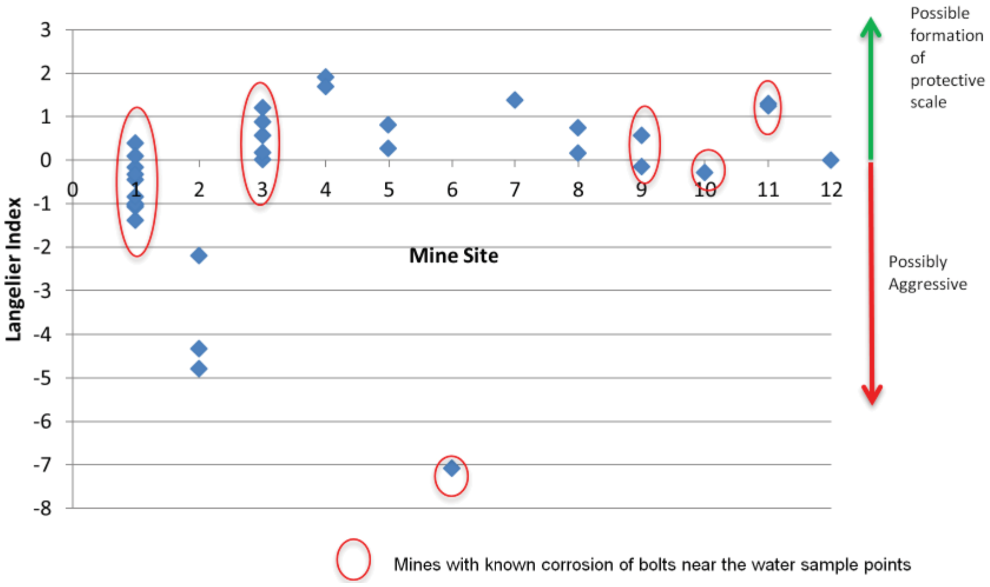

FIG 6 – Australian coalmine groundwater: Langlier saturation index and known corrosion of rock bolts.

TABLE 3

Groundwater total dissolved, Cl$^-$ and SO$_4^{2-}$ differences between Australian hard rock and coalmines.

	Total dissolved solids (mg/L)			Chloride (mg/L)			Sulfate (mg/L)		
	Min	Max	Av	Min	Max	Av	Min	Max	Av
Australian coalmines 'rock bolt drippers'	100	10 000	1400	6	1500	140	0	700	70
Australian hard rock mines (Villaescusa, Hassel and Thompson, 2008)	4000	230 000	70 000	27	180 000	22 000	2	24 000	3000

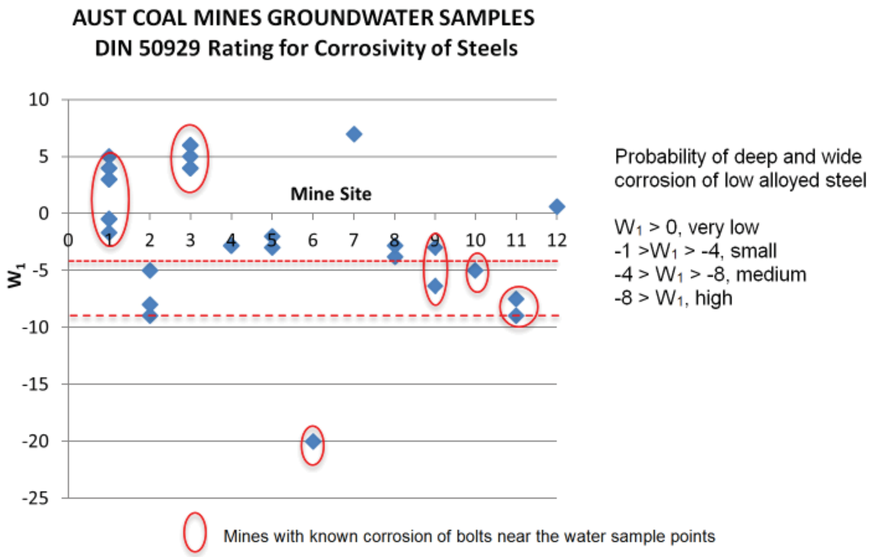

FIG 7 – Australian coalmine groundwater: DIN rating and known corrosion of rock bolts.

the adjacent cut-through. There is a good correlation between flow rate in heading #5 and the number of broken bolts, especially in the cut-throughs. The cut-throughs were noted as not having groundwater drip from bolts but these roadways are higher stresses due to the horizontal stress direction. With reference to Figure 2, the higher flow rates measured between ~85–95 c/t coincide with the proximity of the abandoned flooded old mine workings some 200 m away up-dip within the seam. The mine site had completed permeability testing in the area in 2003, and obtained an average of 4.98 L/min/m within the coal seam and was considerably more permeable than the surrounding rock strata.

Mine 1 groundwater chemistry

The mine site had completed surface to seam boreholes in 2003 with the intention of assessing the risk of water ingress from the old abandoned flooded mine as the main headings approached the area. Boreholes were drilled into the area between the planned main headings and the old working, along with a borehole intersecting the old flooded mine. The main headings had only extended to 83 c/t at the time of the surface to seam boreholes. Groundwater chemistry along the current main headings sampled in 2012–2014 from 60–115 c/t, was compared to water sampled in 2003 from boreholes in

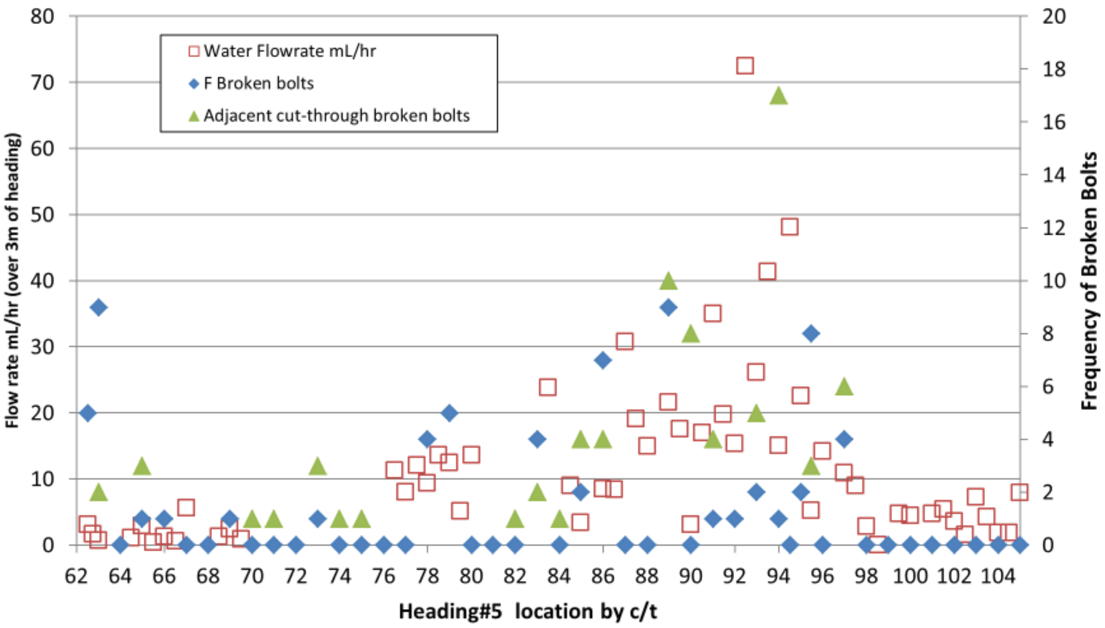

FIG 8 – Mine 1 'mains': roof 'dripper' flow rate in heading #5 correlation to broken bolt location.

close proximity to the now completed 94 c/t area of the mains and from the old flooded mine. Figure 9 shows generally that there is only minor variation of the groundwater coming from rock bolt drippers along the main headings. The groundwater analysis from the surface boreholes in 2003 gave similar results to rock bolt drippers after the mains headings were driven into that area many years later. The up-dip old abandoned flooded mine workings are the most likely source of the water as indicated by flow rate trends, but the chemical analysis of the assumed stagnant water sampled from the working in 2003 are very different to the flowing rock bolt drippers ~200 m down dip from the workings. In terms of corrosion, the pH 5.8 water from the old workings would have given a false indication of corrosion mechanism and severity compared to the surface borehole samples of pH 7.2–7.8, which proved to be closer to the actual groundwater coming into the roadways.

CORROSION COUPONS

Carefully prepared steel coupons such as those shown in Figure 5 have been essential in building successful corrosivity classification systems based on uniform corrosion rates. The problem in ground support is not typically uniform corrosion and other types of coupon tests have been tried by different researchers. Satola and Aromaa (2003) and then Spearing, Mondal and Bylapudi (2010) immersed complete rebar and cable bolts in mine water with laboratories, neither methods produced SCC or gave grounds for a corrosivity classification. To date the current project laboratory tests conducted at UNSW laboratories as described by Vandermaat *et al* (2012b) have successfully produced SCC failures in complete rock bolts in acidic solution. The aforementioned laboratory experiments and the underground coupons described in

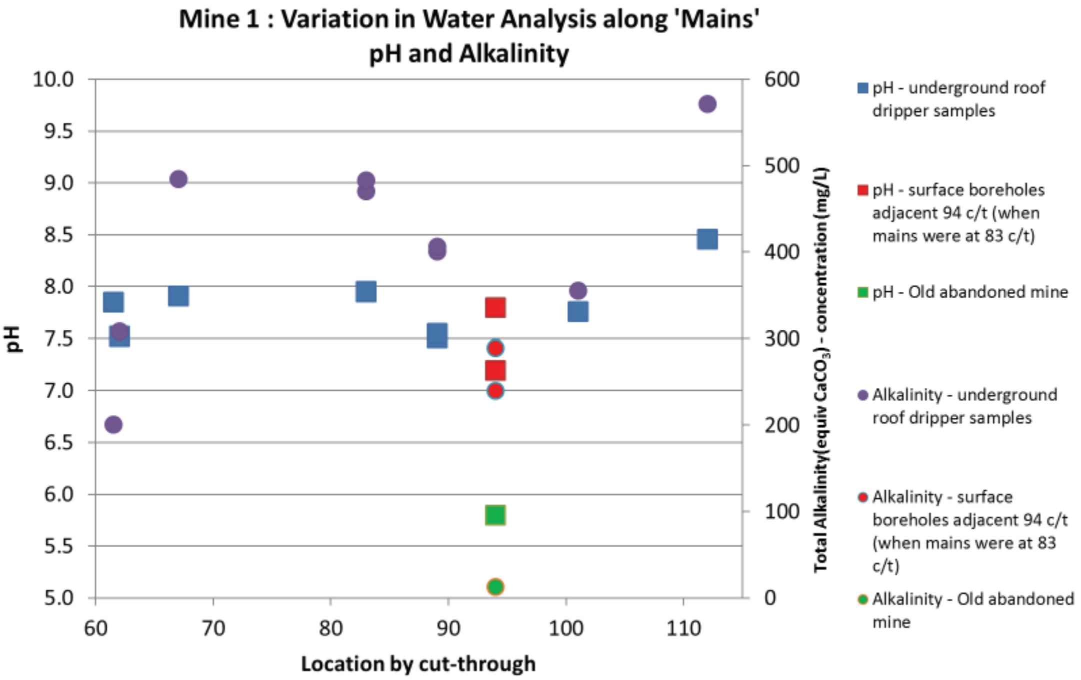

FIG 9 – Mine 1 comparison of groundwater properties.

Vandermaat *et al* (2012a) have not produced SCC or localised pitting corrosion in actual mine water.

The importance of conducting quantitative controlled experiments on bolt coupons containing the surface deformation profiles and mill scale were highlighted by Elias *et al* (2013). Microstructure analysis of SCC failed Australian coal rebar rock bolts has shown that cracks most often initiate at the stress concentration geometry of the ribs/deformations. It was also found that cracks within the surface mill scale can act as an initiation point for SCC to propagate down into the main steel microstructure.

To develop a corrosivity classification system for Australia coalmines, a database would be required comparing rock bolt SCC and localised pitting corrosion to the environmental conditions those rock bolts are exposed. A limited amount of data is available comparing the number of broken bolt in service to the environments, as significant numbers of broken bolts (+100) have only been found in two coalmines. An 'in-hole' rock bolt coupon has been developed by the UNSW project team with promising results to date.

In-hole rock bolt corrosion coupon

In-hole coupons constructed as shown in Figure 10 were installed in Mine 1 and Mine 3. Figure 10 shows the expanded stressed sections of rebar placed at ~200 mm centres and the entire coupon is inserted into an oversized drill hole. It is connected to an existing rock bolt to secure the coupon into the strata and to maintain connection to the existing steel mesh and adjacent bolts.

A set of five coupons made from different types of steel and surface finish were removed from Mine 1 gate road conditions after 203 days. Upon installation, a groundwater sample was taken for analysis and matched known areas of broken bolts for Mine 1. It was noted all coupon holes had groundwater dripping at installation, but at a 128 day interim inspection they were no longer dripping. Upon removal of the coupon from the drill holes, the top of the coupon contained puggy clay and approximately half a litre of groundwater above the clay plug which explains the drips ceasing over time. The coupon bolts were wrapped in plastic and transported to UNSW laboratories for cleaning and subsequent inspection for localised pitting and SCC. It was found that localised pitting corrosion was underway within the stressed section at the claystone, and in particular at points on the rebar where mill scale had been cracked from the expanded 'stressed' section. The most significant finding was a subcritical stress corrosion crack on one of the stressed sections below the claystone, this section is pictured in Figure 11 before and after inspection.

Three other sets of coupons will be removed from across Mines 1 and 3 during late 2014 to try and confirm the repeatability of the result. The relative simplicity and low cost of the in-hole coupon will also allow numerous other coupons to be installed into other coalmine sites across Australia. If successful, it is envisaged that the coupons will provide data towards building a quantitative corrosivity classification system. It also has potential to provide mines with a rock bolt corrosion monitoring system for different environments encountered across a mine.

CONCLUSIONS

Since 2010, the current study into premature failure of coalmine rock bolts has received ~200 broken bolts into the UNSW laboratories. Underground surveys at the two mine sites where 82 per cent of these broken bolts originated, revealed that broken bolts taken to the surface by site personnel may only represent 12 per cent of the extent of the problem underground. Non-destructive load testing in the very worst affected roadway containing ten per cent visually broken bolts has revealed up to 24 per cent premature failure rate of the remaining intact rock bolts. Non-destructive load testing is limited to 75 per cent of steel yield and will likely give many 'pass' results for bolts that could have small stress corrosion cracks or localised pitting. An ultrasonic non-destructive crack detector was used in conjunction with non-destructive load testing, and results to date indicate that ultrasound waves will reflect back of stress corrosion cracks but do not give signal reflections back off some large deep corrosion pits.

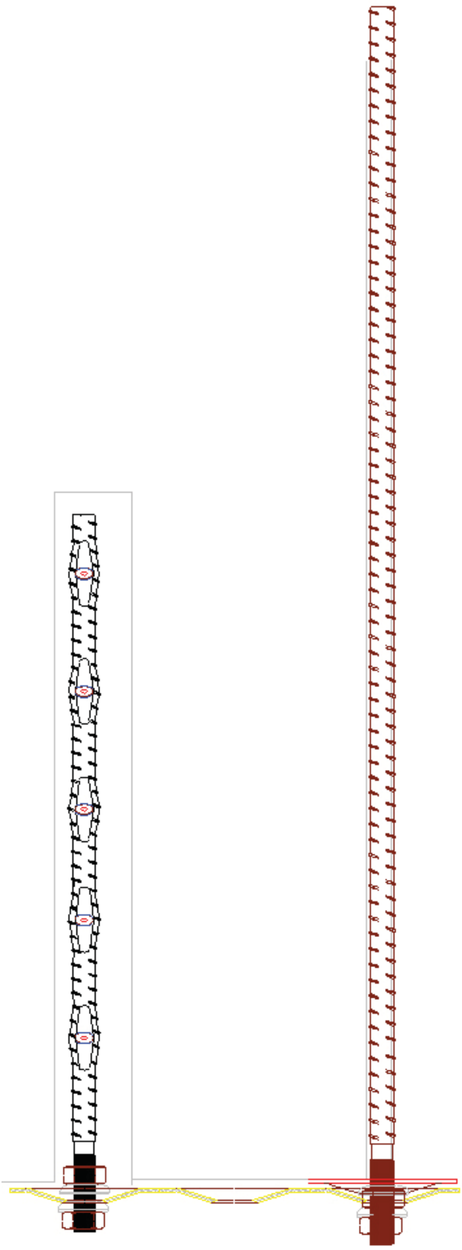

FIG 10 – In-hole corrosion coupon construction.

Increased presence of groundwater has been related to an increase in premature bolt failures. The existing groundwater corrosivity classifications typically aimed at general corrosion do not apply to the problem in Australian coalmines. The sometimes low probability of general corrosion from groundwater chemistry alone does not explain some increases in premature bolt failures. Interaction of groundwater with claystone bands was found with in-hole corrosion coupons to

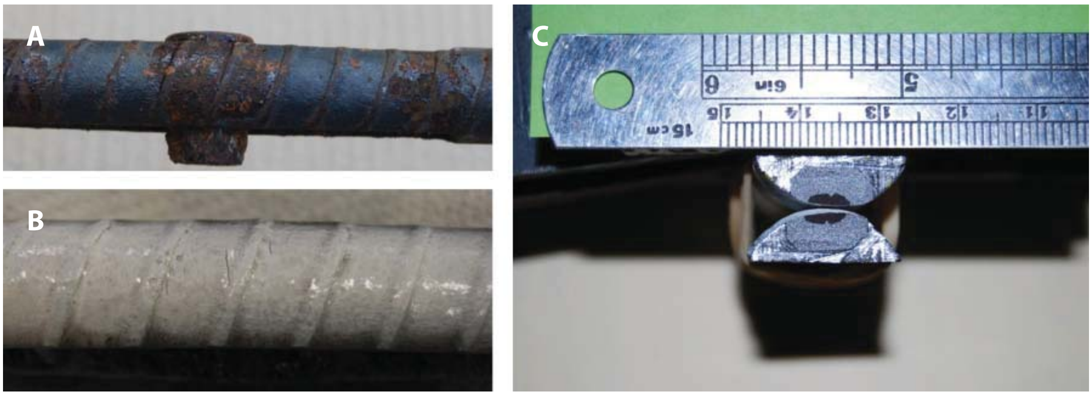

FIG 11 – In-hole coupon removal after ~200 days. (A)Stressed section of coupon after cleaning; (B) magnetic particle inspection revealing a crack; (C) crack opened confirming stress corrosion cracking.

be a likely important factor to further explore. Groundwater from the 12 Australian coalmines sampled does vary, but in terms of aggressive ions typically associated with corrosion, it is relatively benign compared to the very high chloride and sulfate type groundwater found in hard rock mines. Water analysis sampled from surface boreholes has closely matched water analysis from roof drippers in roadways driven near the boreholes many years later. Water sampled from adjacent old flooded mine workings did not represent the actual water coming from rock bolts just 200 m away in a roadway.

In-hole corrosion coupons containing the steel and surface finish of typical rock bolts have proven to reproduce the actual SCC and localised pitting corrosion which has been identified with premature failures. Future work will focus on placement of more in-hole corrosion coupons throughout different mine sites of known groundwater and rock type. A research target is towards a 'coalmine corrosivity classification system' to enable mine sites to predict and monitor corrosion of ground support.

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