Investigations Into the Corrosive Environments Contributing to Premature Failure of Australian Coal Mine Rock Bolts

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ABSTRACT

The University of New South Wales (UNSW Australia) had been involved in the study of premature failure of rock bolts in Australian coal mines from the initial identification of the problem in 1999 (Crosky et al 2002). Rock bolt steel changes over the last decade appear to have not reduced the incidence of failures. A broadened UNSW research project funded by the Australian Research Council (ARC) and Industry has targeted finding the environmental causes through extensive field and laboratory experiments. This paper describes the field studies conducted in underground coal mines, in particular attempts to measure the contribution to corrosion from groundwater, mineralogy and microbial activity. Various underground survey techniques were used to determine the extent of broken bolts, with the presence of both stress corrosion cracking (SCC) and localized deep pitting making no single technique suitable on their own. Groundwater found dripping from bolts across various coalfields in Australia were found to be not aggressive and known groundwater corrosivity classification systems did not correlate to where broken bolts were found. In-hole coupon bolts placed in roof strata containing claystone bands confirmed the clay as being a major contributor to corrosion. Microbes capable of contributing to steel corrosion were found to be present in groundwater, and culturing of the microbes taken from in-situ coupon bolts proved that the bacteria was present on the bolt surface. An 'in-hole bolt corrosion coupon' development by the project may have multiple benefits of 1) helping quantify newly developed corrosivity classification systems, 2) providing an in-situ ground support corrosion monitoring tool, and 3) for testing possible corrosion protection solutions.

INTRODUCTION

The problem of premature rock bolt failure in Australian coal mines was published in 2002 and 2004 by UNSW Australia from Australian Coal Association Research Program (ACARP) funded projects. The majority of the broken bolts examined had steel Charpy impact toughness values of 4 – 7 Joules, and the failure mechanism was most often stress corrosion cracking (SCC). Steel fracture mechanics predicts that an increase in impact toughness will increase the length of the crack before sudden brittle failure. In the final report of 2004, anecdotal evidence from one coal mine 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, 2002 and 2004)

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

The UNSW ARC linkage project had three main areas of investigation towards achieving its aims; 1) Laboratory bolt corrosion experiments aimed at re-producing SCC failures, 2) Metallurgical examinations aimed at defining the causes and mechanisms of coal mine SCC, and 3) Coal mine data collection to identify the extent and environmental contributors to the problem. This paper discusses the coal mine data collection and analysis on environmental contributors to bolt corrosion.

BROKEN BOLT DATABASE

Approximately 200 broken rock bolts have been collected from twelve Australian coal mines and received into UNSW laboratories for various analyses. All of the rock bolts were 21.7mm (0.854") core diameter, "X" grade steel which is typically >600MPa (~87,000 psi) yield and >840 MPa (~122,000 psi) UTS. Three main failure modes are visually evident as shown in Figure 1a, Figure 1b, and Figure 1c. Rebar SCC represented 63% of the broken bolts, localized pitting corrosion represented 30% and thread SCC was 7%. It was obvious from mine sites with an adequate number of samples that both SCC and localized pitting corrosion occur within the same environments. Two mines, "Mine 1" and "Mine 3", represented 83% of the broken bolts and underground surveys were conducted to further define the extent of the problem.

BROKEN BOLT IN-SITU SURVEYS

Mine 1

Mine 1 represented 20% of the bolts within the broken bolt database at UNSW Australia. The portion of main roadways visually inspected for broken bolts is schematically shown in

Figure 1a. Rebar SCC.

Figure 1b. Localised pitting corrosion.

Figure 1c. Thread SCC.

Figure 2 with respect to some major features. The support pattern included 2.1m (7') rock bolts and a mixture of 4m (13') and 8m (26') long cable bolts. The right hand side of the main roadways was known to contain the majority of broken bolts, and heading #5 was known to have water dripping from many of the roof and cable bolts. A total of 226 broken bolts were discovered, with the higher stress cut-throughs accounting for 60% of the broken bolts and heading #5 on the far right accounting for 30% of the broken bolts. Horizontal stresses are typically most concentrated at the edge of the roadway, and this bolt location accounted for 95% of the broken bolts even when the roof showed very little visual deformation or plate loading on the bolts.

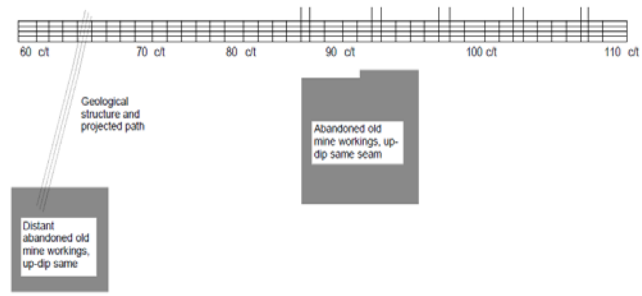

Figure 2. Schematic Mine 1 main roadways and associated features.

To obtain groundwater flow rate trends, each bolt/cable with water flowing (dripper) had flow measured at every intersection and mid-pillar over a selected 3m (10') length of roadway and then added together. The flow rate and frequency of broken bolts is plotted in Figure 3 showing a good correlation between groundwater flow rate in heading#5 and the number of broken bolts, especially in the cut-throughs (c/t). 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 200m (650') away up-dip within the seam. Resin capsule length used with the roof bolts was increased from 1400mm (4'6") to 1700mm (5'6") at 89 c/t. The distance into the roof at which the bolts broke were found to average 290mm before increasing resin encapsulation and 166mm after increasing encapsulation. The number of broken bolts in heading#5 before 89c/t accounted for 40% of broken bolts, whilst after increasing resin capsule length accounted for 60% of broken bolts.

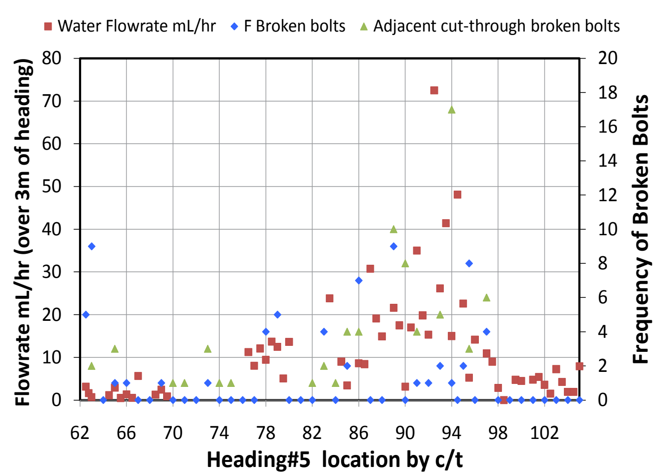

Figure 3. Mine 1 survey of broken bolts and dripper flowrates.

The mine 1 longwall gateroad under development had reported premature failure of rock bolts, but did not have reported groundwater drippers. A visual inspection found 98 broken roof bolts, with all the broken bolts found within the higher stress headings and nil found in the cut-throughs. Clusters of prematurely failed bolts coincided with structure induced elevated horizontal stress, and all of the broken bolts had failed from SCC.

The conclusions from the mine 1 in-situ survey were;

- Higher levels of horizontal stress caused a higher incidence of premature bolt failure
- An increased presence of groundwater drippers can lead to increased incidence of broken bolts
- 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

Mine 3

The mine site personnel had mapped extensive areas of the mine and ranked by areas of concern for frequency of broken bolts. Areas were selected for non-destructive load testing combined with ultrasonic non-destructive testing (NDT) of intact rock bolts. To prevent damage to existing ground support, load applied when testing was limited to 75% of steel yield which in this case was 18 tonne. 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.

There were 86 recorded broken bolts from the main roadways in the UNSW laboratory. The selected worst case areas resulted in 5 from 98 visually intact rock bolts (5%) failing the load tests. Three of the failures were between 14 – 17 tonne and when pulled completely from the roof a bolt was suffering loss cross section due to localized pitting 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 tonne load test yet being seriously compromised by loss of cross section. The NDT gave small crack reflection signals on 3 bolts, and a very large crack reflection on the fourth bolt. The first 3 passed the 18 tonne load test, but the fourth bolt failed and pulled out at 6 tonne. 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 tonne load test but were likely broken far enough into the intact resin column that the resin bond below the crack held the load. Overcoring of 2.4m (8’) rock bolts was proven possible in the main roadways but the location of the bolting rig was not in an area suffering from premature failures. The mine intends to carry out overcoring of bolts with detected cracks in the near future.

An old tailgate heading within the same mining area as the tested mains represented a total of 22 broken bolts at the UNSW laboratories. A 100m (328’) length of the old tailgate was selected for survey and was visually the worst affected location in the mine. Visual inspection found 60 bolts (10%) were visually broken, and load testing to 18 tonne of 42 visually intact bolts resulted in 10 failures (24%). The ultrasound NDT indicated 7 bolts were cracked from 27 bolts tested. Two of the 7 bolts failed the load test at 2 tonne, whilst the other five passed the 18 tonne load test.

Figure 4. Severe localised pitting corrosion on load tested bolt.

The conclusions from Mine 3 survey were;

- Both non-destructive load test and ultrasound methods have limitations in detecting SCC and severe pitting corrosion damage in visually intact bolts
- An area containing 10% broken bolts by visual survey can have 24% of the remaining intact bolts damaged to the point of supporting less than 75% of steel yield, near half ultimate capacity.

GROUNDWATER

Thirty eight rock bolt dripper groundwater specimens have been collected across twelve Australian coal mines, spread across eight coal seams and five coalfields. Six of the mines had recorded premature rock bolt failure due to corrosion related mechanisms. 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 groundwater analyses were input into known corrosivity classification system to determine their relevance for a future Australian coal mine 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 Corrosivity Classifications

Early literature on corrosivity of mine water from Indian coal fields (Rawat, 1976 and 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 sulphates. It was found that the LSI corrosivity index did not correlate with the incidence of corrosion across Australian coal mines, and again the reasoning is most likely the Chloride levels exceeding 25 ppm in the majority of groundwaters sampled.

More recent hardrock mining corrosion literature from Finland by Satola and Aromaa (2003), and then from Australia by Hassal et al (2004) investigated the use of German Standard DIN 50929, which is a corrosivity classification for corrosion of metals in soils. Both studies found that the DIN corrosivity classification did not correlate to corrosion in hard rock mining applications. The DIN 50929 corrosivity classification of the Australian coal mine 'bolt dripper' groundwater is graphically represented in Figure 5, and it can be seen that no strong correlation exist with known corrosion of rock bolts in Australian coal mines. The DIN classification focusses on aggressive ions and will not be discounted at this stage in the project due to some correlation with mines 6, 9, 10 and 11.

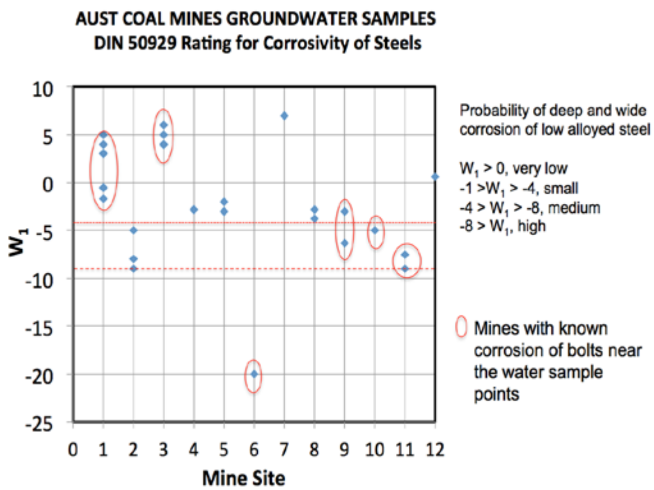

Figure 5. DIN corrosion rating.

Mine 1 Groundwater Chemistry Survey

Mine 1 rock bolt dripper groundwater was sampled and analyzed every 10 pillars along the main headings from 60 – 115 c/t which also had an extensive survey of broken bolts. The groundwater was slightly alkaline at pH 7.5 – pH 8.5, and aggressive ions were at very low levels as also indicated in the DIN classification show in Figure 5. The groundwater chemistry showed only slight variation along the 55 cut-throughs and showed no correlation between aggressive ions and frequency of broken bolts.

The mine site had completed surface to seam boreholes in 2003 with the intention of assessing the risk of water ingress from abandoned flooded mine working shown in Figure 1. Surface boreholes were drilled into the area between the planned main headings and the old workings, 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 from rock bolt drippers sampled in 2012 – 2014 were compared to water sampled in 2003 from boreholes in close proximity to the now completed 94 c/t area of the mains and from the old flooded mine. Figure 6 shows the groundwater analysis from the surface boreholes intersecting the virgin coal seam in 2003 gave similar results to rock bolt drippers after the mains headings were developed many years later. The up-dip 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 flooded mine sampled from in 2003 are very different to the flowing rock bolt drippers ~200m (650') 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 which would eventually contact the rock bolts upon development.

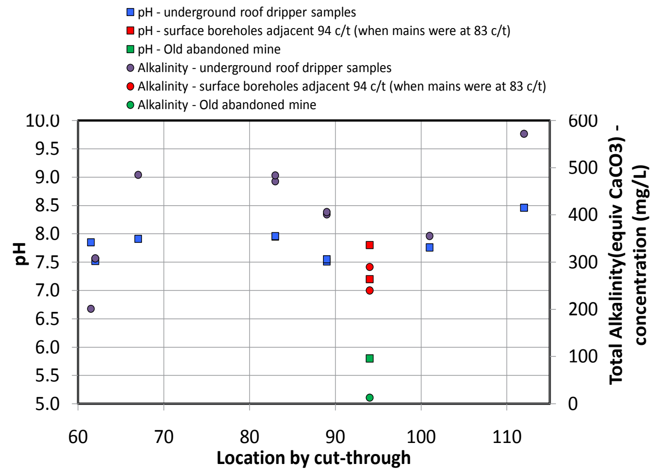

Figure 6. Mine 1 variation in groundwater chemistry mains headings.

CORROSION COUPONS

Dorion, Hadjigeorgiou and Ghali (2009) completed steel coupon testing in mine groundwater's of Canadian and Villaescusa, Hassell and Thompson (2008) in Australian hardrock 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 7, with the surface mill scale removed. These carefully prepared steel coupons have been essential in building successful corrosivity classification systems based on uniform corrosion rates. Australian coal mine rock bolts are rebar with mill scale attached, and are suffering from localized pitting corrosion and SCC which are different mechanisms compared to general corrosion.

Satola and Aromaa (2003) and then Spearing, Mondal and Bylapudi (2010) immersed complete rebar and cable bolts in mine water within 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 (2012a) have successfully produced SCC failures in complete rock bolts in acidic solution. The aforementioned laboratory experiments and the underground coupons described in Vandermaat et al (2012b) have not produced SCC or localized 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.

Figure 7. G4 coupons (Dorion, 2009).

To develop a corrosivity classification system for Australia coal mines, a database would be required comparing rock bolt SCC and localized pitting corrosion to the environmental conditions those rock bolts are exposed. An "in-hole" rock bolt coupon has been developed by the UNSW project team aimed at enabling a correlation between environments and rock bolt corrosion found in Australia.

In-hole Rock Bolt Corrosion Coupon

In-hole coupons constructed as shown in Figure 8 were installed in Mine 1 and Mine 3. Expanded 'stressed' sections are placed at ~200mm centers along the rock bolt and the entire 1.2m (4') bolt 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 'gateroad' conditions after 203 days. Upon installation, a groundwater dripper 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 liter 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 localized pitting and SCC. It was found that localized pitting corrosion was underway within the stressed section at the claystone horizon, 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 sub-critical stress corrosion crack on one of the stressed sections below the claystone, this section is pictured in Figure 9a, Figure 9b, and Figure 9c before and after inspection.

Similarly, an identical set of in-hole coupons were installed in Mine 3 and removed after 200 days. Upon installation, a groundwater dripper sample was taken for analysis. It was noted all coupon holes had groundwater dripping at installation, but upon removal they were no longer dripping and did not have any signs of puggy clay present as found in Mine 1. It was found that Mine 3

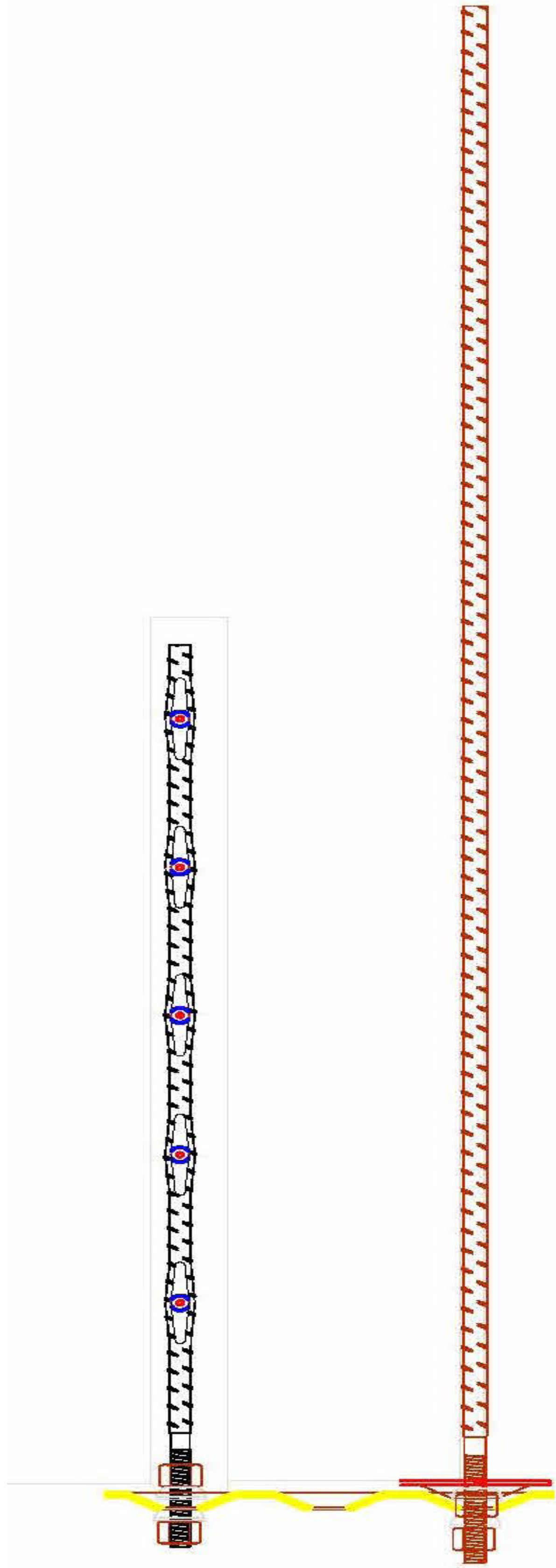

Figure 8. UNSW in-hole corrosion coupon.

Figure 9a. Stress section of coupon.

Figure 9b. Magnetic particle inspection revealing a crack.

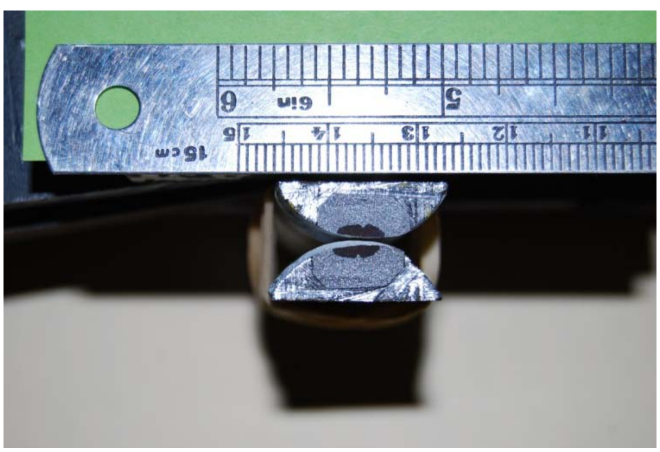

Figure 9c. Crack opened confirming SCC.

coal roof tends to drain over time and the clay content of the stone bands is much lower. The recovered coupons were taken to a microbiology laboratory for the bolt surface scrapings to be taken for fluorescence microscopy and DNA analysis. The coupons were also magnetic particle crack inspected with no SCC or localized pitting corrosion found. The bolt crust contained a sulfate reducing bacteria (SRB) cell concentration of 4.1×10^7 cells mL^{-1} of a total cell count of 6.1×10^9 cells mL^{-1}, such a concentration is likely to contribute to the corrosion process (Beckmann, 2015). Detailed microbiological testing is currently underway on another set of coupons removed from Mine 3 to further investigate the location and species of bacteria present along the coupon bolts.

The relative simplicity and low cost of the in-hole coupon will allow numerous other coupons to be installed into other coal mine 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 and provide a means of testing possible bolt anti-corrosion solutions in the future.

CONCLUSIONS

The current UNSW Australia study into premature failure of coal mine rock bolts has collected over 200 broken bolts from twelve Australian coal mines. An extensive underground survey revealed that the number of broken bolts collected and supplied to UNSW may represent only 12% of the total number visually found underground. Non-destructive load testing in the very worst affected roadway containing 10% visually broken bolts has revealed up to 24% premature failure rate of the remaining intact rock bolts. Non-destructive load testing is limited to 75% of steel yield and will likely give many ‘pass’ results for bolts that could have small stress corrosion cracks or localized 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. Both NDT methods have limitations in detecting SCC or severe localized pitting corrosion.

Increased horizontal stress on bolts and increased presence of groundwater has been correlated to an increase in premature rock bolt failures. The existing LSI and DIN groundwater corrosivity classifications typically aimed at general corrosion appear to not apply to the problem in Australian coal mines. The sometimes low probability of general corrosion from groundwater chemistry alone does not explain some increases in premature bolt failures. Groundwater from the twelve Australian coal mines sampled does vary, but in terms of aggressive ions typically associated with corrosion, it is relatively benign. Mine 1 and Mine 3 ranked very low in the aggressiveness of the groundwater ions and the development of a new in-hole corrosion coupon has directed researchers towards a cause of rock bolt corrosion in these two mines.

Interaction of groundwater with claystone bands was found with in-hole corrosion coupons to be a likely important factor to further explore, with localized pitting corrosion found to occur within puggy clay collapsing and contacting the rock bolt. In-hole corrosion coupons containing the steel and surface finish of typical rock bolts have proven to reproduce actual SCC which has been identified in field premature failures. The presence of SRB bacteria capable of creating localized corrosive conditions was confirmed within coupon bolt surface crust by fluorescence microscopy and DNA analysis. 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 ‘coal mine corrosivity classification system’ using ‘in-hole corrosion coupons’ to enable mine sites to predict and monitor corrosion of ground support.

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