Australian Rock Bolt Steel Chemistry and Stress Corrosion Cracking

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ABSTRACT

It's long been suspected that there has been an increase in the incidence of premature failure of rock bolts in underground coal mines over the past ten years. As far back as 2002 a study found a possible contributor to such premature failure in some Australian coal mines might be linked to stress corrosion cracking (SCC) (Crosky *et al*, 2002). That study suggested the low impact toughness could be a major influence on the susceptibility to SCC of different steel compositions. A subsequent study involving laboratory corrosion tests however failed to confirm any link with metallurgical factors (Villalba and Atrens, 2007), a finding that is at odds with field experience.

Some mine sites today are still reporting prematurely failed rock bolts to the rock bolt manufacturers; the failures are being identified at SCC induced.

To this end a research project has recently been commissioned at University of New South Wales (UNSW), which aims to identify the environmental factors causing SCC, through field test sites and simulating the conditions within an accelerated corrosion laboratory. This paper outlines the methodology that will be used in this study.

INTRODUCTION

Rock bolts were pioneered in Australia and first used on a large-scale in the Snowy Mountains Hydroelectric Scheme and later adopted in mining as a means of contributing to a stable underground excavation. The current design approach to rock bolting in Australian coal mines is to minimise the resin or grout annulus so as to maximise the load transfer between the deforming rock mass and the steel rock bolt. In recent years increasingly higher strength grades of steel have been used to meet the increasingly demanding requirements placed on the rock bolts.

The grade of steel used for rock bolts in Australian coal mines has gradually moved to increasingly higher strengths since the introduction of the technology in the 1970s. The current 'X' grade rock bolt that are used in the far majority of coal mines today typically have a yield strength of approximately 600 MPa and an Ultimate Tensile Strength of 850 MPa. Various chemical compositions are used by steel manufacturers to achieve these high strength requirements of the 'X' grade rock bolt.

Premature failure of rock bolts was increasingly being reported by mines in different coalfields throughout Australia by 1999 (Hebblewhite, Fabjanczyk and Gray, 2003). In 2002 an Australian Coal Association Research Project (ACARP) funded study revealed that premature failures were most often occurring by SCC, but the impact of different mining environments and type of rock bolt steels were not assessed under the limited scope of that original study.

A new project being undertaken at the School of Mining Engineering, UNSW has recently received ARC funding with the aim to determine the factors responsible for SCC of rock bolts so as to develop novel and innovative strategies for producing rock bolts resistant to this form of failure.

OVERVIEW OF STRESS CORROSION CRACKING IN ROCK BOLTS

Characteristics

The typical failure surface of a rock bolt that has been subjected to SCC is shown in Figure 1. The figure illustrates typical brittle failure of a rock bolt, which was initiated from a small crack at the bottom of the bolt; as evident by the lines radiating from crack. The failure surface is essentially flat and at right angles to the applied stress.

Failed rock bolts often indicate only limited plastic deformation. Typically the rock bolts have been subjected to brittle failure due to the growth of cracks associated with corrosion as indicated in Figure 2. Figure 2a shows cracks as revealed by magnetic particle impregnation (MPI) on a rock bolt: note that cracks usually initiate at stress raisers such as the base of ribs on a hot rolled bar. Figure 2b indicates the SCC, which developed at the base of a rib on a hot rolled rock bolt. This would cause a drastic reduction in bolt strength and probably led to brittle failure of the bolt: note the steel bar is white and the rib extends up to the top right hand corner (Crosky *et al*, 2002).

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FIG 1 - View showing evidence of brittle failure of a rock bolt (Crosky *et al*, 2002).

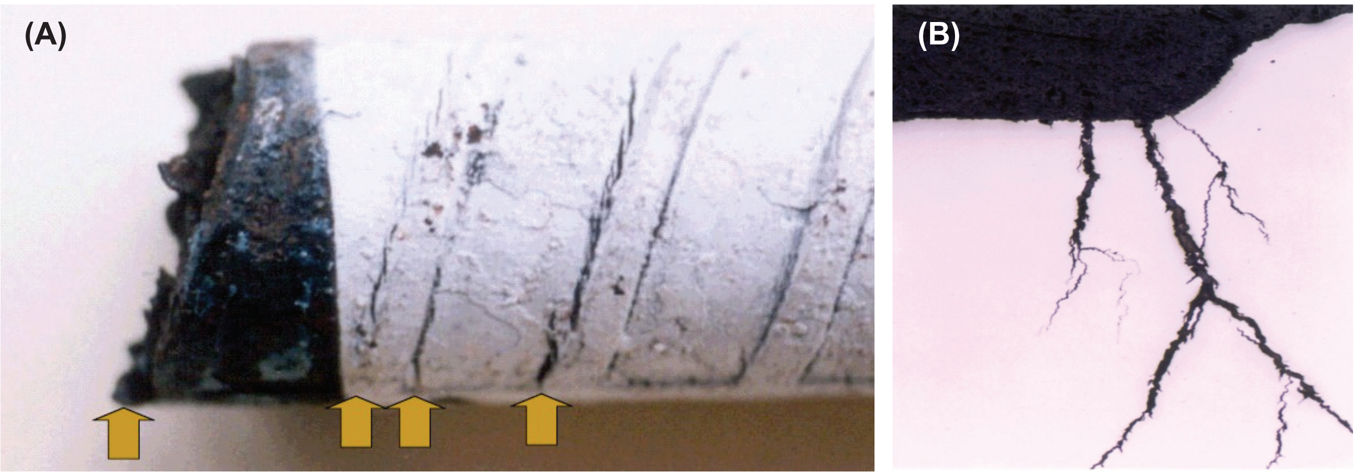

FIG 2 - (A) Cracks revealed by MPI on a rock bolt; and (B) indications of SCC that developed at the base of a rib on a hot rolled rock bolt (Crosky *et al*, 2002).

In Australian coal mining, strata control practise focuses on achieving a high bond strength between the rock bolt and borehole surface to create a stiff reinforced beam to support the immediate roof above the roadway. To achieve this stiff reinforcement the size of the resin bond annulus is minimised in an attempt to ensure the ribs of the rebar place the resin into compression against the sidewalls of the borehole. This approach has been adopted at all Australian underground coal mines. It is an approach though that contrasts with the hard rock mining and civil tunnelling sectors where they attempt to achieve a thicker annulus.

While contributing to a stiff member, the reduced resin annulus can increase the probability of water ingress through cracks in the resin and/or other pathway mechanisms to the rock bolt and hence increase the susceptibility of SCC. Traditional approaches to protection of ground anchors are reliant on encasement within a plastic sleeve. However, this tends to reduce bond strength and also requires a larger annulus.

A disadvantage of full-length resin bonded rock bolts is that it makes it more difficult to detect failed rock bolts. Currently, there is no reliable non-destructive test (NDT) method available that is in regular use; hence there is no means presently available to quantify the magnitude of the risk of roof failure in underground coal mines.

Consequently, one hazard stemming from SCC is a breakdown in the reinforcement member that can eventually lead to a fall of ground with the possible resultant outcomes of damage to infrastructure, lost production and death and injury of operators.

The risk of a roof fall is exacerbated in an active longwall roadway subject to high stresses associated with longwall extraction. Typically, the longwall face is accessed by two roadways, one for the conveyor belt and the other for operators and materials. A roof fall in either can result in a number of undesirable consequences especially for operators who travel along these roadways. If the fall of ground occurs on the main conveyor belt it can stop production. A fall can also block emergency exits or even general access to the underground workings of the mine as well as create many secondary risks of lost ventilation and power to the face.

The downtime with a fall of ground can equate to lost production from downtime of the longwall of up to A$ 1 M per day, requiring anywhere from three days to three months depending on the severity of the fall to recover access through the roadway not to speak of equipment damage.

PREVIOUS RESEARCH INTO STRESS CORROSION CRACKING OF ROCK BOLTS

ACARP Project 1999 - 2002

The earliest research in this area was conducted in the late 1990s and early part of this decade (Crosky *et al*, 2002). The project measured the incidence of prematurely failed rock bolts in Australian coal mines. It identified that the problem was not isolated to specific cases but more widespread and occurred to varying degrees in different geology, ground water and in different rock bolt steels. The study concluded that the factors that were likely to contribute to SCC were:

- roof lithology containing clay bands and thick coal sections,
- presence of groundwater,
- use of high tensile steels – approaching 1000 MPa tensile strength, and
- possibility of bacterial corrosion.

The project found that it was often difficult to identify prematurely failed rock bolts and therefore to quantify the scale of the problem. Trialling of non-destructive testing devices, many of which were still in development, was undertaken and highlighted the potential for ultrasonic testing of *in situ* steel bolts to identify failed rock bolts.

One particular focus of the study was steel composition and resulting mechanical properties. There was a high incidence of failed rock bolts that were of high carbon steels having low impact toughness.

Although useful in highlighting SCC as a potential issue in coal mines, the scope of the project was limited to considering only failure analysis of broken rock bolts that had been recovered from mine sites. The study did not address the possible environmental factors impacting on SCC.

The report suggested that seven critical issues needed to be addressed:

1. a comprehensive field evaluation of non-destructive test devices for rock bolts,
2. development of metallurgy and corrosion surface test procedures and database expansion,
3. an investigation and documentation of the properties of new steel products,
4. an investigation into the extent of potential bacterial corrosion of rock bolt steel and possible remedial actions,
5. development of industry guidelines to minimise SCC problems, including bolt and steel traceability,
6. documentation of the extent of brittle failures of rock bolts in threaded sections with regard to hanging structures from roof bolts, and
7. introduction of an Australian standard for rock bolts specifying a minimum toughness level.

United Kingdom Coal Project

Similar results were found with comparable steels in a study undertaken in the late 1990s in the UK coal mining environment (Shutter, Geary and Heyes, 2001).

In this case the study focused primarily on the metallurgical aspects of SCC. The failure mechanism associated with crack growth leading to sudden brittle failure was investigated. This led to the development of a British Standard that requires all high tensile rock bolts to have a minimum impact toughness of 23 Joules as determined by the Charpy 'V notch' test. The chemistry of such steel requires special attention to achieve high impact toughness with an attendant higher cost of manufacture.

Australian Research Council (ARC) linkage, University of Queensland

In response to recommendations made in the report by Crosky *et al* (2002) to benchmark rock bolt steel performance for toughness, a follow up study was commissioned.

Here the focus was primarily on metallurgical influences and it assumed hydrogen embrittlement was the main mechanism of crack growth that led to premature failure by SCC (Villalba and Atrens, 2007).

The study encompassed laboratory tests using machined blocks of different steels rather than actual cold-drawn rock bolts. The steel samples were subjected to a linearly increasing stress test (LIST). A corrosive environment was created involving a low pH solution and an electrochemical potential applied to promote hydrogen embrittlement.

The study showed that low carbon micro alloyed steels, which have high impact toughness, were susceptible to SCC. However high carbon steels and cold worked steels were less likely to succumb to SCC. It was stated that the conflicting findings between the laboratory results and the field evidence suggest that the testing technique may not be the best approach.

UNIVERSITY OF NEW SOUTH WALES/ARC LINKAGE PROJECT

Significance of project

The project now underway at UNSW is innovative as it aims to investigate the effect of bacterial factors contributing to SCC as indicated in the earlier ACARP study; traces of bacteria were identified in samples of ground water from mine sites. Ground water from mine sites will also be used in the test work to investigate its effects on the extent of SCC. The research not only aims at determining the chemistry or biology behind corrosion in coal mines, but aims at developing an accelerated corrosion testing method to simulate the underground coal mine environment. It is anticipated that once the factors have been determined then the project will target the testing of various corrosion protection techniques that could be used in Australian coal mining roof control practices. The main significance of the study is to reduce incidents of roof falls as well as savings on cost on rehabilitation of long term roadways and improved productivity in underground coal mines.

Approach

The project will have both laboratory and field test components. Four mine sites have been selected for investigation, which has a history and/or concerns about SCC, these being:

1. Springvale Colliery (Centennial Coal) in the Lithgow seam – Western Coalfields;
2. Blakefield Colliery (Xstrata Coal) in the Bulga Complex – Hunter Valley;
3. Narrabri Colliery (Whitehaven Coal) in Gunnedah Basin; and
4. Moranbah North Mine (Anglo Coal Australia) in Bowen Basin.

Mines involved in the project suffer from corrosion of rock bolts and provide ideal sites from which physical specimens of groundwater and rock along with geotechnical information can be collected and analysed. The following individual studies, which address the project objectives, would be performed at varying sites, which suffer varying degrees of corrosion of rock bolts.

Partner organisations

The proposed project has support of a number of key coal mine operators including Centennial Springvale, Xstrata Blakefield South, Whitehaven Narrabri and Anglo Coal as well as a Jennmar, major rock bolt manufacturer, as industry partners.

Centennial's Springvale Colliery is a well-established modern longwall mine producing over 3 Mtpa into local power stations near Lithgow, NSW along with export markets. The mine has completed metallurgical tests on failed rock bolts verifying the presence of stress corrosion cracking. The technical service department has established mapping such failure locations throughout the mine plan and considers the issue to be significant.

Xstrata's Blakefield South Colliery is a longwall operation recently completing development of the first longwall block and has commenced longwall operations. The mine has replaced the Beltana longwall by mining the lower coal seam. Beltana was a consistent highest producing longwall operation in Australia for many years with over 7 Mtpa. Blakefield South is a 405 m wide longwall face, which has made it the largest extraction width in Australia. The geology and hydrology of the Blakefield seam has lead to major design considerations to corrosion of rock bolts being implemented in 2008. The mine has installed galvanised rock bolts throughout the entire main access roadways but plan to revert to standard steel rock bolts in development roadways.

Narrabri Coal Operations Pty Ltd is developing a new underground coal mine with intentions of the being the first longwall operation in the Gunnedah Coal Basin. Narrabri Coal reached the coal seam and started roadway formations within the coal seam in July 2010. The operation is giving much consideration to the corrosion of rock bolts due to the groundwater expectations for the mining area.

Moranbah North Mine is an underground longwall mining operation located in the Bowen Basin, which produces approximately 4.5 Mt per annum of coking coal. The mine has a history of difficult geological conditions and has identified failed rock bolts due to Stress Corrosion Cracking.

Jennmar Australia Pty Ltd is the largest supplier of strata control consumables in the Australia underground coal sector with a bolt and resin capsule plant in Sydney, New South Wales along with a bolt plant in Mackay, Queensland.

Objectives

The project aims to establish the factors responsible for SCC of rock bolts in order to develop novel and innovative strategies for producing rock bolts resistant to this form of attack. Specifically the work will involve:

- identification of the environmental factors responsible for SCC of rock bolts,
- identification of the metallurgical factors responsible for SCC of rock bolts,
- development of strategies and materials for SCC resistant rock bolts, and
- defining reliable and practical non-destructive testing technique for assessing the integrity of installed rock bolts.

Identification of the environmental factors responsible for stress corrosion cracking of rock bolts

Ground water analysis

Initially data will be collected from the field that can be used to characterise the geological and geochemical environment including quality of ground water and quantity of water inflow in selected active mining areas. Ground water samples will be collected from the field test sites, as often ground water ingress about a roadway will reduce and change physical appearance over time. Previous studies into premature rock bolt failure involved collection of material from around rock bolts and microbiological analysis. The samples were limited to one mine suffering from premature rock bolts failures but the analysis did identify the presence of such bacteria. The testing regime would target the same iron and sulfur reducing bacteria but would be expanded to include at least the four mine sites involved in the project. The microbiological analysis is specialised and this would be outsourced to known laboratories with experience in these types of bacteria. The collected water samples will also be analysed to identify the inorganic species and also any relevant bacteria and to establish any changes that take place over time. The suitability of known groundwater corrosivity classification systems will be assessed across the range of collected data. Such existing systems include the groundwater corrosion classification DIN 50929 and the underground hardrock corrosion classification by Li and Linblad which was developed in 1999. It is envisaged that the study may form the basis of an underground 'coal mine' corrosion classification system when complete. In terms of general corrosion of rock bolts and lasting the design life of a roadway, such a classification of ground water would be highly beneficial for coal mining industry.

Geochemical analysis

The geochemical characteristics of surrounding rock will be analysed and logged at each site. The mineralogy of the immediate roof in which the rock bolts are in contact will be measured and the selected sites by taking rock core samples. Earlier work suggested that the presence of clay layers within the bolted rock has a higher incidence of SCC related failures (Crosky *et al*, 2002). Particular attention will be given to the clay mineralogy and the potential electrochemical environments they may create in the presence of groundwater. X-Ray Diffraction analysis will be conducted to obtain chemical composition of the coal and surrounded rock samples gathered from the mine sites.

Laboratory-materials testing

SCC tests will be conducted using the 1055, 1355, 5150, 840 grade steel to confirm that the water sampled does cause SCC as seen in service. This may require taking water samples from a variety of locations in each of the mines and repeating the testing. Once the service experience has been replicated, water samples will be prepared containing, individually, each of any species considered important. SCC testing of the four steels will be conducted in each of these solutions to identify the species responsible for SCC. It may be necessary to conduct testing in solutions containing combinations of species in order to replicate the service experience.

Geotechnical analysis

Understanding of rock mass characteristics is critical for this project. A series of geomechanical tests will be conducted to investigate the geomechanical parameters from the collected coal and rock samples (density, porosity, durability, permeability, water sorption and capillarity, unconfined compressive strength, direct/indirect tension tests, direct shear tests, tri-axial strength tests).

Identification of the metallurgical factors responsible for stress corrosion cracking of rock bolts

The metallurgical factors that contribute to SCC are alloy chemistry and microstructure.

Alloy chemistry

Crosky *et al* (2002) found that plain carbon steels containing 0.35 - 0.55 per cent C and low alloy steels of similar carbon content containing manganese, silicon and chromium, as well as vanadium micro-alloying, are all susceptible to stress corrosion cracking in the mine environment.

Microstructure

Microstructure also affects resistance to stress corrosion cracking. The steels known to fail have a range of microstructures including essentially fully pearlitic (eg 0.55 per cent C alloy steels), ferritic pearlitic (eg 0.4 per cent C steels) and martensitic (Tempcore treated steels). The crack paths in these steels will be examined in detail to determine how they are affected by microstructure. Using this information it may be possible to isolate microstructural features that could reduce susceptibility to stress corrosion cracking. It is noted that the rock bolts are made from hot rolled steels and are thus decarburised at the surface where the stress corrosion cracks initiate. The stress corrosion cracking behaviour of susceptible steels will be compared with and without removal of the decarburised layer to establish the relevance of this effect.

Identification of strategies and materials for developing stress corrosion cracking resistant rock bolts

While it is anticipated that the work described above will allow identification of steels that will resist SCC in the mine environment, it is possible that such steels may be prohibitively expensive and other approaches may be required.

Testing fully intact rock bolts

A test facility will be constructed containing a loading apparatus to test fully intact rock bolts with tensile and shear loads applied within a corrosive environment. The effect of deformation pattern and surface features on the rebar will be investigated. Allied with this will be computer modelling to assess the impact of stress concentration points such as the rib profile on rock bolt performance.

Evaluating the polyester resin performance

Polyester resin is used to bond the rock bolts to the rock. This resin has potential to prevent ground water contact with the steel greatly reducing the corrosive potential. Current resins are brittle and will crack easily with roof displacement. These factors will be considered in trialling new resin compounds. Partner Organisation – Jennmar has capabilities to manufacture the potential new resins.

Corrosion inhibitors

- Validating the laboratory test results: a temperature and humidity controlled laboratory environment room will be constructed at UNSW. Selected rock bolts will be overcored and recovered from individual field test sites for metallurgical and structural analysis. Data from the water and geomechanical rock testing will be used to simulate accelerated corrosion in a controlled and measured method in the laboratory facility.
- For stress corrosion cracking to occur all of the following factors must exist simultaneously:
  - a susceptible material,
  - a corrosive environment, and
  - an applied and/or residual stress.

  Removal of any one of these factors is likely to eliminate the problem. One solution would be to find a chemistry that is not susceptible. There are a number of other different ways in which the problem may be overcome, or at least alleviated, some of which include:
  - reducing the strength of the bolts,
  - increasing the toughness of the bolts,
  - reducing the prestress on the bolts,
  - galvanising the bolts,
  - cathodically protecting the bolts,
  - use of a corrosion inhibitor in the polyester resin, and
  - decarburising the surface to lower the surface strength.
- Inhibitors in polyester resin.

Identification and validation of reliable and practical non-destructive test technique for assessing the integrity of installed rock bolts

There are currently two main technologies available, these being vibration response and ultrasonic devices. There is a limited application within underground environments of these technologies. The project will include *in situ* trials to evaluate of using the technologies in underground coal mines. Non-destructive testing of rock bolts will allow mines to assess the integrity of ground support. It will also assist the project in identifying areas affected by SCC. Vibration response and ultrasonic devices will be calibrated to typical coal mine rock bolts in the laboratory followed by *in situ* calibration at Springvale mine. Once proven, these devices will be used to identify corroded rock bolts at each partner mine site from which environmental conditions will be monitored.

CONCLUSIONS

The research project will identify the environmental causes of SCC and ultimately provide a tool for the identification of SCC high risk environments within a coal mine. The subsequent knowledge and understanding gained about the SCC environment will be applied in building a laboratory facility for testing of various rock bolts. The laboratory facility will enable the development and testing of new coal mine rock bolts to withstand SCC.

The establishment of a rock bolt accelerated corrosion laboratory will provide new and existing mines with a means of assessing their rate of corrosion considering their local environmental conditions. Various rock bolt types can be tested to determine the most cost effective support system for roadways with different intended life span.

As part of the project ground water will be collected from a number of mine sites and tested for their geochemical and biological content.

The research project will identify the mine specific environmental causes of corrosion and ultimately provide a tool for the identification of high risk environments within a coal mine. The project intends to subject actual rock bolts in service to various non-destructive testing apparatus, which has been developed in recent years. In both field and laboratory experiments, the accuracy and reliability of the non-destructive testing devices will be assessed.

With a future prediction of a growing longwall industry in Australia, the national benefit will be to reduce deaths due to roof falls in coal mines. The economic benefit in preventing SCC related rock falls is an increase in overall productivity of the sector through reducing lost production.

With the expected increase in coal production rate in Australia, the benefits to the coal mining industry of this project will be a reduction in the incidence of catastrophic roof falls and the associated losses in production and revenue.

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