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Investigations into the corrosive environments contributing to premature failure of Australian coal mine rock bolts

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ABSTRACT

University of New South Wales (UNSW Australia) had been involved in the study of premature failure of rock bolts in Australia coal mines from the initial identification of the problem in 1999. 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.
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1. 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 J, 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 [1,2].

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 approximately 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.

2. 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 21.7 mm core diameter, "X" grade steel which is typically >600 MPa yield and >840 MPa UTS. Three main failure modes are visually evident as

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(a) Rebar SCC (b) Localised pitting corrosion (c) Thread SCC

Fig. 1. Three types of rockbolt corrosion fracture surfaces.

shown in Fig. 1. 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.

3. Broken bolt in-situ surveys

3.1. 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 Fig. 2 with respect to some major features. The support pattern included 2.1 m rock bolts and a mixture of 4 and 8 m 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.

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 3 m length of roadway and then added together. The flow rate and frequency of broken bolts is plotted in Fig. 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 Fig. 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. Resin capsule length used with the roof bolts

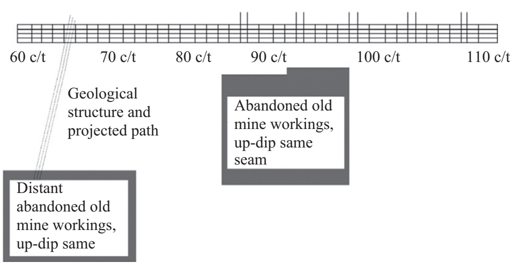

Fig. 2. Schematic Mine 1 main roadways and associated features.

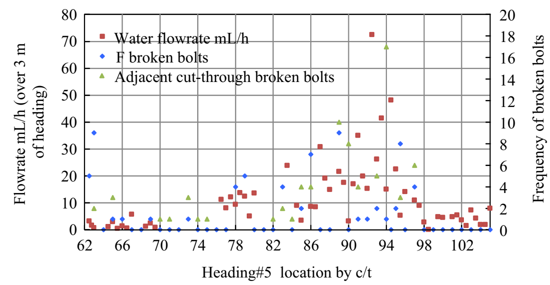

Fig. 3. Mine 1 survey of broken bolts and dripper flow rates.

was increased from 1400 to 1700 mm at 89 c/t. The distance into the roof at which the bolts broke were found to average 290 mm before increasing resin encapsulation and 166 mm after increasing encapsulation. The number of broken bolts in heading #5 before 89 c/t accounted for 40% of broken bolts, whilst after increasing resin capsule length accounted for 60% of broken bolts.

Mine 1 longwall gate road 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: (1) higher levels of horizontal stress caused a higher incidence of premature bolt failure; (2) an increased presence of groundwater drippers can lead to increased incidence of broken bolts; and (3) 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.

3.2. 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 ton. 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

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