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The environmentally induced corrosion failure of cable bolts in underground coal mines

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THE ENVIRONMENTALLY INDUCED CORROSION FAILURE OF CABLE BOLTS IN UNDERGROUND COAL MINES

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ABSTRACT: The failure of cable bolts, made from high carbon cold-drawn steel wires, is frequently observed in underground coal mines. Hydrogen-induced stress corrosion cracking (HISCC) is known to be the main mechanism of such a failure. The groundwater and geomaterials (mixture of coal and clay) collected from the affected mines have not been found to be corrosive. In this study, we examine the effect of sulfate-reducing bacteria (SRB), which exist in affected mines, on the failure of cable bolts. We make stressed coupons from cable bolt wires and test the coupons in different solutions containing SRB. We find that the hydrogen sulfide produced by SRB promote hydrogen diffusion into the steel and causes HISCC while the steel is under constant load. The fractures in failed coupons show similar features to those failed in underground coal mines. This study provides insights into the role of microorganisms in the failure of underground structures. We recommend future studies to develop prevention measures to stop hydrogen diffusion into steel or microbial activities around the bolts.

INTRODUCTION

Cable bolts are made from high-carbon cold drawn wires and, thus, have higher strength and flexibility than conventional rockbolts. Due to the excellent flexibility of cable bolts, they can have lengths larger than the height of roadway. They are generally manufactured in 8-10 meters length and anchor to deep stable rocks. In Australia, the cable bolts are usually installed as secondary support, and their integrity is critical to the safety of the mine site.

Although cable bolting technology has been continuously advanced since its first application, failures of cable bolts are still observed. The failure can occur within the grout, cable-grout interface, grout-rock interface, and the cable bolts themselves. Several underground mines have reported the corrosion failure of both rockbolts and cable bolts due to stress corrosion cracking (SCC) (Wu et al., 2018c, Wu et al., 2018a, Crosky et al., 2012, Vandermaat et al., 2016, Chen et al., 2018, Kang et al., 2013, Wu et al., 2018b, Smith et al., Hebblewhite et al., 2003, Gamboa and Atrens, 2003). It was found that the failure has occurred through environmentally assisted hydrogen cracking, i.e., HISCC (Windsor and Thompson, 1994, Chen et al., 2016).

Microbiologically influenced corrosion (MIC) is corrosion due to microbial activities (Hadley, 1948). According to AlAbbas et al. (2013), one in every five corrosion failures worldwide is related to MIC. Generally, the environment for such corrosion activity is complex. The biomass in the surrounding rock strata, fluid and other deposits make the determination and observation of MIC very difficult. (Parkins, 1982). Sulphate-reducing bacteria (SRB) is one of the most well-known bacteria causing MIC. It was first noticed in 1934 (Li et al., 2001). Since then, a substantial amount of research has been conducted on SRB related corrosion failures (Stipaničev et al., 2013, King and Miller, 1971, Rajala et al., 2019, Jia et al., 2018). However, further research is still required to fully understand the role of SRB on other microorganisms in the failure of bolts.

In this study, we use materials from an underground coal mine to mimic the service environment of the cable bolt. The stressed cable bolt specimen (specially designed consistent with the loading within the mine tunnels) is tested in solutions containing the mine geomaterials and microorganisms. The pH and sulphate concentrations are monitored to understand the microbial reactions. The microscopic analysis is also conducted on the fractured specimen to confirm the mode of failure.

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EXPERIMENTAL PROCEDURES

The cable bolt coupons are made from the king-wire of the cable bolts. The wire diameter is 6 mm, and its surface is smooth. It has ~ 0.85% carbon, and its yield strength is 1650 MPa. The wire is cut into ~ 150 mm sections to make stressed coupons. The chemical composition and mechanical properties as provided by the supplier are reported in Chen et al. (2021).

The coupons are made using the 3-point bending method (**Figure 1**) to recreate the service condition loading (Wu et al., 2019). Coupons are fabricated by tightly joining two parallel wires and securing the ends with a retention ring. The loading pin made from the same cable bolt material is pushed in by a hydraulic press to create the load on the outer surface of the coupon. The load on the coupons is ~ 90% of the material yield strength.

An underground mine in NSW is investigated to determine the failure environment for bolts. Water samples are collected from the dripping roof water where the failure occurred. The groundwater analysis of the mine water show that the concentration of corrosive ions is low, and the pH is near neutral (Chen et al., 2021). The water sample is used in the SRB immersion tests.

DNA extraction and sequencing are conducted on 25 mL of the groundwater sample according to Bürgmann and Lee's method (Luk et al., 2018). The samples are analysed at the Ramaciotti Centre for Genomics, UNSW Sydney, Australia. The community analysis finds a number of bacteria known to cause MIC, including *Thiobacillus*, *Desulfovibrio*, *Desulfotomaculum* and *Sulfurospirillum* (Chen et al., 2021). *Desulfovibrio* and *Desulfotomaculum* are SRBs known to produce MIC in steel (Ilhan-Sungur et al., 2007, Cetin and Aksu, 2009). Therefore, a *Desulfovibrio* species, *D. vulgaris,* is used to create sulphate reduction activity.

Five different test solutions representing different environments were prepared in triplicate. Solution 1 and solution 2 are non-bacterial control with distilled water and groundwater. Solution 3 has 5%, v/v *D.vulgaris*; solution 4 has 15 %, v/v *D.vulgaris* as the accelerated environment; Solution 5 has 5%, v/v *D.vulgaris* with geomaterials (mixture of coal and clay). The detail of the preparation process can be found in the study by Chen. et al. (Chen et al., 2021).

The imaging of bacteria on the coupon surface is done using a DeltaVision Elite inverted fluorescence microscope. The fractographic and detached biomass analyses are conducted using a Hitachi S3400 scanning electron microscope (SEM) unit.

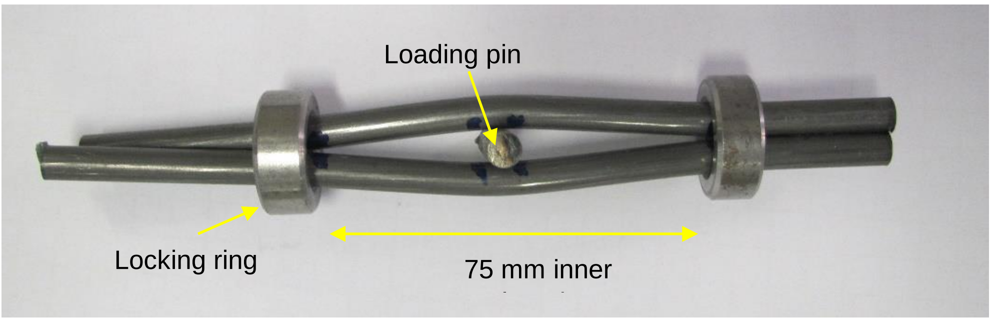

Figure 1: Design of coupon.

RESULTS AND DISCUSSION

All coupons in solution 4, which has the highest concentration of SRB (the accelerated condition), fail in the three months duration of the experiment. Other than solution 4, none of the coupons is fractured by the end of the experiment. The SEM analyses of the fractured surfaces of all three failed coupons indicate that they all have similar features. **Figure 2** exemplifies one of the fracture surfaces. The fracture origin, highlighted in blue, is approximately 300 µm (**Figure 2a**). The high magnification images on the fracture origin (**Figure 2b**) shows a tearing topography surface (TTS) feature, which is known as a characteristic of HISCC (Toribio et al., 1992, Wu et al., 2018c, Ramandi et al., 2018). The fast fracture region (**Figure 2c**) shows a stepwise appearance that follows the material's microstructure (Toribio and Vasseur, 1997).

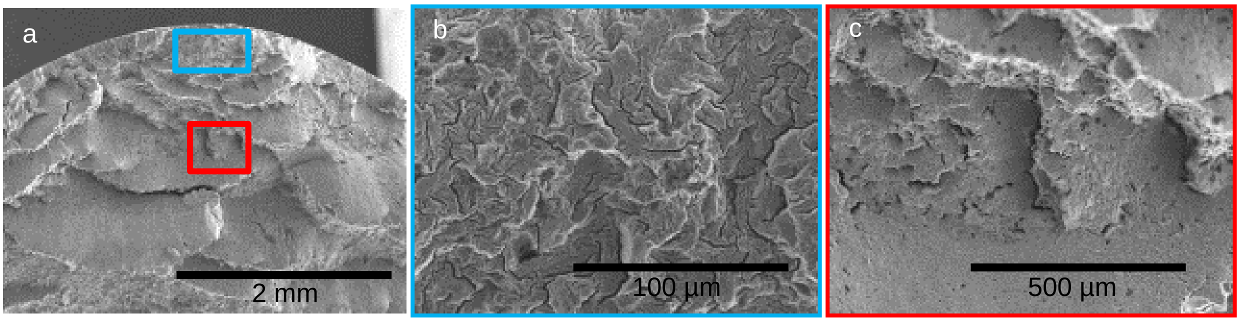

Figure 2: Fracture surface of failed coupon; a) fracture surface overview; b) high magnification imge on fracture origin (blue box in a); c) high magnification image on fast

The sulphate concentration of all solutions containing bacteria is examined during the experiment (**Figure 3**). The initial sulphate concentration in solution 5 (with geomaterials) is the highest among all solutions. This suggests that the geomaterials in the cable bolt location can potentially have some roles in sourcing sulphate in underground mines. Solution 3 and 5 have an insignificant sulphate reduction over the first two weeks. In contrast, there is a much higher sulphate reduction in solution 4, which contain a high amount of bacteria and extra organic materials (lactate). The high sulphate reduction is due to the *D. vulgaris* activities: oxidising the organic material (lactate) and reducing sulphate (SO_4^{2-}) to sulphide (S^{2-}) (Enning and Garrelfs, 2014, Coetser and Cloete, 2005, Straub and Schink, 2004, Biezma, 2001, Beech and Sunner, 2007). Therefore, the overall metabolism of the SRB generates H_2S by producing (S^{2-}) and then reacting with (H^+) in the environment. Such a reaction increases the pH of the environment (Chen et al., 2021), which is also observed in solutions 3, 4 and 5.

The main reason for the occurrence of failure only in solution 4 is concluded to be the high concentration of SRB. The extra organic compound (lactate) potentially accelerates the biofilm growth rate on steel surfaces resulting in severe MIC (Enning and Garrelfs, 2014). This also results in high H_2S concentration, leading to HISCC. The other solutions, despite no fractures, also show sulphate consumption and pH increases, indicating that a lower concentration of *D. vulgaris* and the native microbes can also produce H_2S.

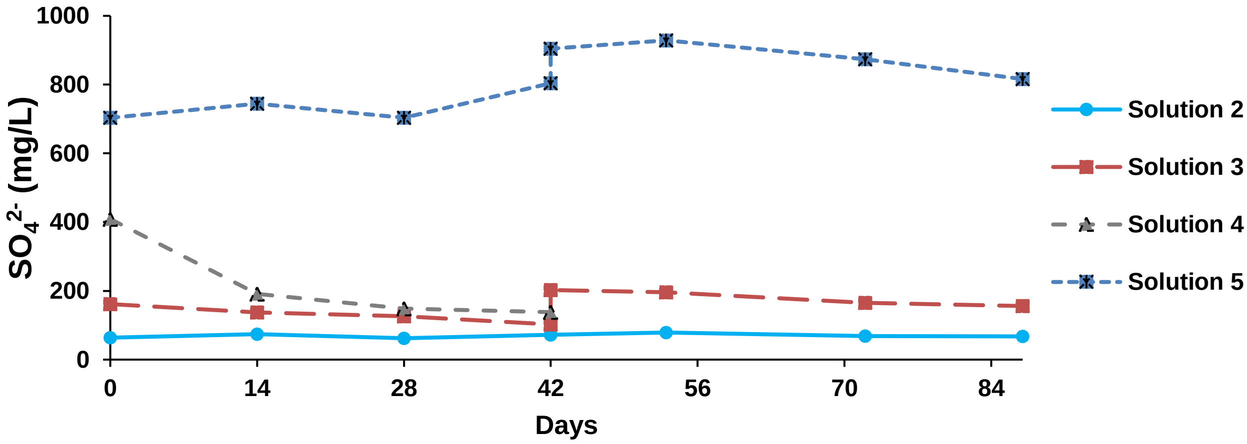

Figure 3: Sulphate quantification of all solutions during the experiment.

Figure 4a shows the biomass attachment on the coupon—the blue colour indicates the microbial colonies formed by microorganisms present in the groundwater, including *D. vulgaris*. **Figure 4b** demonstrates the high magnification image of bacteria from the biomass. Overall, the findings suggest that SRB can be one of the main causes of the HISCC failure of the cable bolt through H_2S production in the underground environment.

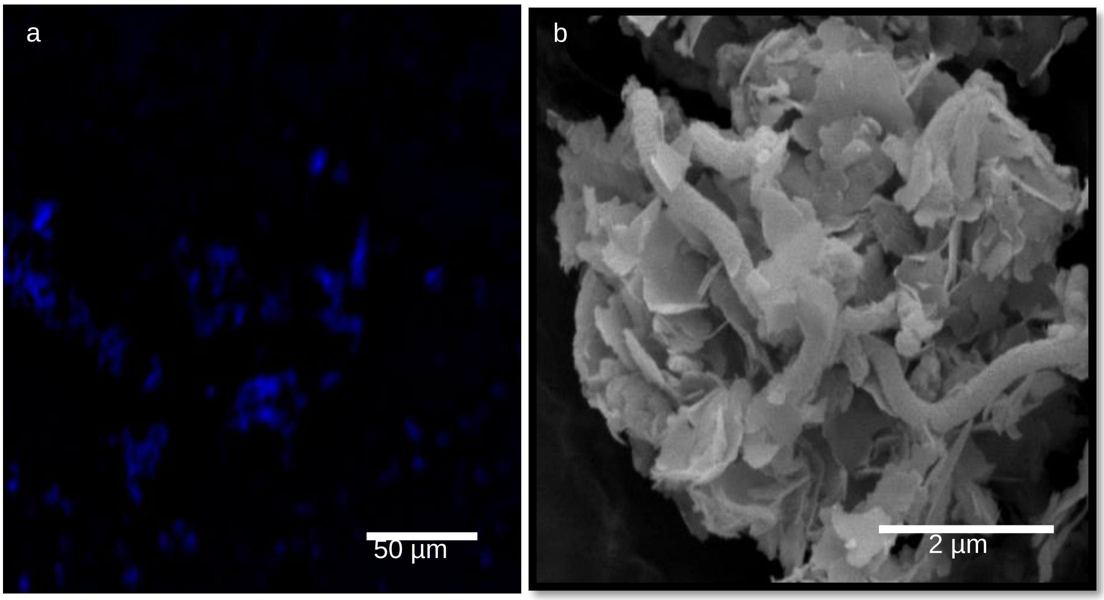

Figure 4: a) Biomass on the coupon surface; b) SEM image of detached biomass.

CONCLUSIONS

- SRB in the groundwater environment can cause the HISCC of cable bolt wires.
- Failure requires a critical concentration of hydrogen sulphide produced by the microorganisms.
- Groundwater and geomaterials in underground coal mines support the metabolism of microorganisms.
- HISCC may occur in anaerobic underground mining locations where sulphate and organic matter are present.

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