Laboratory and field testing of bolting systems subjected to highly corrosive environments

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Abstract

The capacity of ground support components which have been affected by corrosion is reduced and may ultimately lead to dynamic failure of the component and the strata. In order to maintain an effective, long-term ground support system, significant campaigns of rehabilitation are often required in corrosion affected areas which also expose the workers to hazardous conditions. The most common corrosion protection for steel ground support utilises sacrificial systems such as galvanising. Galvanising has previously been proven to be susceptible to some corrosion processes. Stainless steel is the most effective in resistance to corrosion, but can be cost prohibitive, and its mechanical properties often make it unsuited to use in ground support components. Providing an outer protective plastic coating to bolts has proven to be an effective means of protecting the inner steel bar from corrosion. However, these support systems tend to be susceptible to coating damage, and require post cement grouting to provide full encapsulation. In comparison to a standard bolt/resin system, they can be slow to install and expensive. These systems have also been shown to reduce overall load transfer performance of the bolting system. In order to provide a higher level of corrosion protection whilst maintaining current installation practices and bolting cycle times, Minova has developed the Enduro™ steel ground support range. The Enduro™ range consists of standard Minova steel ground support components which have been treated with a unique coating process. The Enduro™ coating has been tested in the harshest of conditions, in laboratory controlled conditions and in underground trials. It has been proven to effectively resist or completely eliminate the formation of corrosion, even in the most aggressive environments. This paper explains the process and provides the details of the laboratory and underground corrosion performance testing carried out on Enduro™ ground support products.

1. Introduction

Traditionally, the most common form of corrosion protection in steel ground support consists of a sacrificial protective coating such as galvanising [1]. Such coatings have proven to be ineffective in extreme high and low pH conditions with corrosion of the support system commonly encountered [2–4]. There is also evidence that common forms of galvanising may actually increase the rate of corrosion in certain pH environments. Fig. 1 shows typical corrosion and failure of a standard re-bar roof bolt.

In order to provide additional protection, double corrosion protected (DCP) systems were introduced. These systems, although effective in providing additional corrosion protection, have proven to be expensive, complex to manufacture, bulky and difficult to handle. They are normally slow to install which leads to a reduction in development rates. The outer layer can also be damaged during careless installations, permitting the coalescence of corrosive solutions on selected areas. Additionally flexible polymer coatings have been attempted in highly acid ground in two underground gold mines in Nevada, USA [5]. In addition to the challenges described above, Clarke and Sieders identified that the plastic “smooth” layer between the steel bolts may impact the axial load stiffness or friction of the installed ground support systems [6].

Due to these limitations in the double corrosion protection systems, Minova developed the Enduro™ range of steel ground support products. The Enduro™ bolt, whether it be a solid bolt or friction bolt, is installed like any other common bolting system.
It is no heavier than a standard bolt and requires no additional training or special equipment to be installed.

2. Endure coating

There are two components to the Enduro™ coating:

1. The Enduro™ or base coat which covers entire surface area of the bolt. The Enduro™ coating is a unique and protected Minova application to ground support components.
2. An optional top coat applied to either the entire surface area or selected sections (i.e. exposed tail of bolt).

The Enduro™ Coat is applied using the cathodic dip coating (CDC) process. In this process the system applies a direct current (DC) charge to the component, which is immersed in a bath of oppositely charged coating particles. The particles are drawn to the component surface and are deposited forming an even, continuous film over the surface (including every crevice) until the coating reaches the desired thickness, typically 20 μm.

An optional top coat is applied using a thermoplastic powder coating process and is suitable for most metals that can withstand 180 °C oven temperatures that are required for curing the powder. The thickness of thermoplastic powder coating is typically 150–250 μm. The top coat can be used to provide extra confidence in the protection of the steel, particularly where physical damage through extreme handling may be encountered. It is also effective in UV protection to the Enduro™ coat should the tail be exposed after installation.

The thickness of either the Enduro™ or top coat can be increased, or the coating process repeated to provide even greater confidence in the corrosion protection for extremely difficult environments.

3. Laboratory testing and results

In order to validate the performance of the Enduro™ product, a series of controlled laboratory tests have been completed.

3.1. Corrosion resistance acetic acid salt spray (AASS)

The corrosion resistance performance of the Enduro™ product in acetic acid salt spray (AASS) has been observed over 1000 h and compared to a traditional galvanised bolt. A total of three bolts were tested that included a ‘standard’ galvanised bolt, a bolt with an Enduro™ base coat and a bolt developed from raw steel.

A straight forward test procedure has been used whereby each of the products were placed in an acidic solution (dilute sulphuric acid with a pH of 1.69) for a period of 50 days. The visual appearance was observed and recorded at 30 min, 5, 21 and 50 day increments for each of the bolt types. The acid bath and pH measuring instrument is presented in Fig. 4.

Immediately upon immersion, the hot-dip galvanised bolt (grey colour Fig. 4, part A) commenced ‘fizzing’ (reacting). The raw steel bolt (charcoal colour Fig. 4, part B) commenced reacting after approximately 30 min. Over a period of testing, there was no apparent reaction with the black Enduro™ base coated bolt (Fig. 4, part C).

After 5 days of immersion, a pH of 2.25 was measured. Sheets of corroded material can be seen on the galvanised and raw steel bolt. There was no corrosion observed on the Enduro™ bolt (Fig. 5 left). After 21 days, additional corrosion was observed on the raw steel and galvanised bolts (Fig. 5 right).

After 50 days (Fig. 6) both the raw steel and galvanised bolts have corroded significantly with the nut on the galvanised bolt completely corroded. There were still no obvious signs of corrosion on the Enduro™ bolt.

From the observations, it is clear that the galvanised and the raw steel bolts are severely corroded after 50 days of immersion. The Enduro™ bolt still looks ‘intact’ with no apparent corrosion evident. The dissolution pattern of the raw and galvanised bolt appears different: (1) the raw bolt appears to be dissolving uniformly with the nut showing severe corrosion, and (2) the galvanised bolt shows severe pitting and complete dissolution of the nut.
In both cases, the threaded areas of the raw steel and galvanised bolt area have been significantly reduced in diameter. The Enduro™ nut and thread is observed to be unaffected showing no signs of corrosion (Fig. 6).

### Table 1
Testing results of Enduro™ bolt and traditionally galvanised bolts.

<table>
<thead>
<tr>
<th>AASS testing hour</th>
<th>257</th>
<th>518</th>
<th>722</th>
<th>1012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Corrosion observations after elapsed hours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required specifications</td>
<td>No visible corrosion observed for acceptable performance result</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanised bolt</td>
<td>Severe white rust, some red rust</td>
<td>Severe white rust, some red rust</td>
<td>Severe white &amp; red rust</td>
<td>Severe white &amp; red rust</td>
</tr>
<tr>
<td>Observed result</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>Enduro™ bolt (base coat only)</td>
<td>No visible corrosion</td>
<td>No visible corrosion</td>
<td>Minor red rust spots</td>
<td>Minor red rust spots</td>
</tr>
<tr>
<td>Observed result</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>Enduro™ bolt (base coat and topcoat)</td>
<td>No visible corrosion</td>
<td>No visible corrosion</td>
<td>No visible corrosion</td>
<td>No visible corrosion</td>
</tr>
<tr>
<td>Observed result</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

### Fig. 3.
Corrosion observations during AASS testing at 257, 518 and 722 h.

### Fig. 4.
Acid bath and pH monitoring instrument used during Enduro™ product testing.

### Fig. 5.
Acid bath test results after 5 and 21 days.

### Fig. 6.
Acid bath immersion testing results after 50 days.

#### 3.3. Accelerated corrosion tests

Monash University has conducted accelerated corrosion tests (ACT) to provide a rapid comparison of the corrosion resistance of the Enduro™ product to other products currently being used to determine corrosion expected from 2 to 100 years (specifically thickness loss data in mm/year).

To complete the tests, a test solution of 3.5% (by weight) NaCl, was prepared by dissolving 35 g of NaCl in 1 L of distilled water. This solution has a normal pH of approximately 7.8. For the development of other pH solutions, 0.1 N solutions of HCl or NaOH were added to achieve pH environments of 2, 7 and 9 for testing. The accelerated corrosion testing procedure used included taking potentiodynamic polarization measurements using a typical three-electrode electrochemical cell that was connected with a Bio-Logic potentiostat. Prior to each corrosion test the open circuit potential (OCP) was measured to confirm stability over a period of time of 1000 s.

A total of five bolt materials were tested that included; Enduro™ with basecoat, black (e.g. ungalvanised), hot dip galvanisation, thermally diffused galvanisation (TDG) and stainless steel. Results for each of the products at a pH 2 are presented in Fig. 7.

The Enduro™ product specimens provided the best observed corrosion resistance in acidic conditions (3.5% NaCl at pH 2) fol-
lowed by stainless steel and then the other products tested. It can be observed that HDG and TDG coatings have extremely low resistance to corrosion from low pH solutions.

The corrosion performance of the Enduro™ product (base coat only) over a range of pH conditions are provided in Fig. 8 for the purposes of estimating service life.

4. Field testing and results

A series of underground tests on the Enduro™ product were carried out to determine the durability of the bolt when exposed to highly acidic mine water. A summary of the in situ trials are provided below.

4.1. Mine A

Six sections of Enduro™ bolts (Type A) and six sections of hot dip galvanised bolts (Type B) were selected for using in this trial. Each section was 600 mm in length. The bolts were placed Fig. 9. After 330 days, a section of each bolt type was extracted from the acidic water, the excess build-up was removed, and the level of corrosion observed (Fig. 11). It can be seen, that under the highly acidic mine water conditions at Mine A, the Enduro™ bolt outperforms the hot dip galvanised bolt in resisting the effects of the corrosive mine water.

Fig. 12 presents a solid Enduro™ bolt that has been installed for six weeks at Mine A. At this point discoloration is observed but no corrosion is evident on the bolt. The galvanised mesh surrounding the Enduro™ bolt is eight weeks old.

4.2. Mine B

At Mine B, in situ trial sites for the Enduro™ product were selected based on a significant observed degradation in the existing galvanised friction bolt support which had been installed approximately 3 years previously. Fig. 13a shows a heavily corroded friction bolt and plate that has been installed for approximately two weeks. Visual observations regarding the corrosion of the bolts have been made in addition to corrosion assessments of the inside of the bolts using a hand-held wand camera (Fig. 13b).

The performance of the Enduro™ product was measured along with red bolt over a two-month period whereby exposure of the bolts was maximised by placing them on the floor under dripping mine water (Fig. 14).

In order to replicate mining conditions the bolts were extensively scratched and scoured on the inside and outside. The extent of corrosion on the bolts was recorded every month. The red bolt and the black Enduro™ bolt showed minimal evidence of corrosion over a two-month period.

4.3. Underground installation at Mine C

Minova was approached regarding the support system currently being installed in Mine C’s surface to underground declines. Mine C were having issues complying with the geotechnical design criteria to fully encapsulate the bolt prior to the application of shotcrete. At the time Minova got involved, this issue was severely hindering development rates and had led to a substantial amount of re-support having to be carried out.

Minova proposed using the Enduro™ solid bolt along with our standard resin anchor to overcome this issue. Having proved the durability of the Enduro™ bolt, the system was adopted. With the Enduro™ bolt Mine C was able to accept a less than 100% encapsulation with traditional resin anchors due to its effective resistance to corrosion. Implementing this system also eliminated manual handling issues and exposure to cement dust encountered while using the previous post grouting system. As a result of the application of the Enduro™ product, advance rates increased significantly and no further re-support was required.
5. Conclusions

Corrosive ground control conditions can be difficult to control and be extremely hazardous to workers. Previous developments have been partially successful in extending the service life of support bolts and fixtures. Both field and laboratory testing of Enduro™ rockbolts and ground support components have shown significant reductions in rates of corrosion compared to other traditional corrosion resistant steel ground support systems. Additionally, Enduro™ bolt installation offers significant efficiency benefits over other 100 year design life rockbolts. The authors believe that project designers and geotechnical engineers now have a viable option for ground support systems to consider where long service life is required and/or extreme corrosion potential exists.

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References


