The influence of drilling on the performance of a yielding self-drilling rockbolt

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Abstract

In recent years self-drilling anchors (SDA) have received increased attention from the ground support industry. This includes studies and field trials at Oyu Tolgoi mine in Mongolia and Malmberget mine in Sweden which have highlighted the installation success rate of SDAs in fractured rock masses. Typical challenges associated with rockbolt installation in such conditions include hole closures and blown out holes, resulting in a reduction of bolt installation success rates and achieved support capacity.

To improve the efficacy of installation in fractured rock masses, an SDA replaces the conventional drill steel required to bore the support hole, combining both the drill steel and rockbolt into a single component. This negates the need for equipment to alternate between a drilling operation and bolt insertion as an SDA combines these traditionally separate processes into one. For squeezing and seismically active ground conditions, yielding SDAs offer an additional performance benefit derived from the ductile mechanical properties of the bolt from which these anchors are produced. However, a consequence of this bolt design is that the SDA is subjected to the percussive loading normally applied to the drill steel during the drilling operation, which can affect the performance of the bolt.

This investigation quantifies the influence of this percussive drilling on the performance of a yielding SDA when subjected to dynamic loading. An experimental group of bolts were drilled into quartzite and thereafter subjected to impact testing in a laboratory. The performance of these samples is compared to a control group of samples, not previously subjected to drilling forces. This investigation provides insight into the in situ performance of a yielding self-drilling anchor.

Keywords: *yielding self-drilling anchor, bulk resin systems, impact testing, mechanised mining, rock reinforcement*

1 Introduction

During a typical installation of a rockbolt the support hole is drilled using a conventional drill steel. The support hole is then filled with resin capsules or cementitious grout and then the rockbolt is installed. In a fractured rock mass, hole closures are typical as observed by Watt et al. (2018) preventing the installation of the rockbolt. This forces operators to then re-drill the hole, resulting in an increase in the diameter of the borehole commonly referred to as a 'blown out hole'. This challenge results in a reduction in installation quality and rates (Watt et al. 2018). Self-drilling anchors (SDA) provide a solution to the challenges as the drill steel, which is retracted from the support hole, is replaced with a self-drilling rockbolt, which is not retracted from the support hole, preventing the closure from affecting the installation by negating the need for the hole stand up time. The installation success rate was demonstrated by Bray et al. (2019) when installing SDAs into a Biotite Schist at LKAB's Malmberget mine. SDAs are not new to the mining industry, however, in recent years the mechanisation of the installation processes of SDAs and bulk resin systems has renewed interest in the application of SDAs as part of the ground support system. The combination of SDAs and rapid curing bulk resin systems ensure high rates of successful installation. As a result, several yielding SDAs have been presented to the mining industry in recent years (Watt et al. 2018; Bray et al. 2019; Epiroc 2022, Normet 2022).

A successful ground control management plan matches the response of the ground support system to the anticipated failure mode of the rock mass. In conditions where seismically induced deformation or large deformation is anticipated as the result of squeezing, the installation of yielding rockbolts is considered best practice (Potvin & Hadjigeorgiou 2020). The designs of yielding rockbolts vary, however, the paddled energy absorbing rockbolt has received industry acceptance and is widely used. A paddled energy absorbing rockbolt absorbs energy through the plastic deformation of steel between two anchor points (Li 2010). The presented yielding SDAs are functionally similar to typical paddled energy absorbing rockbolts and absorb energy through the plastic deformation of the steel tendon between two anchored points. The steel from which the yielding SDA are produced is ductile. In contrast, drill steel is a high-strength, brittle material designed to efficiently transfer the excitation force generated by the rockdrill into the rock mass.

Prior to a field trial, rockbolts are typically tested in a controlled laboratory environment. Yielding rockbolts offer high energy dissipation capacities when compared to conventional rockbolts. An industry accepted index test method for determining the energy capacity of a rockbolt is an impact test (Li 2017; Potvin & Hadjigeorgiou 2020). These tests are typically conducted on 'prime' samples selected for testing from the production line. Efforts are made to replicate the installation procedure during sample preparation; however, samples are typically installed into steel host tubes during testing and consequently the drilling cycle of a yielding SDA is bypassed. This preliminary investigate aims to quantify the effect of the drilling cycle on a yielding SDA when subjected to an impact load.

2 Yielding self-drilling anchors

Typically, a resin–rockbolt is installed in a multi-step process consisting of drilling the support hole, inserting resin capsules, and then inserting the rockbolt. This could be done in a single pass where the equipment is positioned once and manoeuvred after the installation is complete or, alternatively, with multiple passes. An SDA replaces the drill steel and is used to drill the support hole as illustrated in Figure 1. The SDA is not retracted from the support hole, negating the need for a hole stand up time to allow for the installation of resin capsule.

Historically the grouting of the SDA was a second step, often conducted once the drill rig has moved to the next ring. This can be replaced by the integration of a resin injection system onto the bolting equipment which facilitates 'one-step' bolting. Once the support hole has been drilled, the rockbolt is injected with a two-component resin system. The injection is complete when resin is observed at the perimeter of the plate. Consequently, variation in the diameter and profile of the support hole are accommodated by ensuring a full encapsulation of the bolt. The resin cures rapidly resulting in an installation that can be completed within a single step without repositing the boom or the bolting equipment. The 'one-step' process of installing an SDA is illustrated in Figure 1, which is identical for both conventional and yielding SDAs.

A conventional SDA is a fully threaded bar where the thread along the length of the bar interlocks with resin, resulting in a stiff load response. In rock masses where self-drilling is a requirement for a successful installation, and large deformations are anticipated, yielding SDAs are required. Several yielding SDAs have been presented to the market, functionally similar and relying on a similar yielding mechanism as the paddled energy absorbing rockbolt (Epiroc 2022). For this investigation, the R28 by 2.4 m BoraBolt, illustrated in Figure 2, was selected. The BoraBolt is produced from a Ø28 mm hollow steel. Two threaded 600 mm sections are formed onto both ends of the rockbolt forming the resin–rockbolt anchor. Under loading, the section of smooth bar between the two threaded anchors decouples from the resin, uniformly distributing the strain between the two threaded anchors. The response of the debonded section of the rockbolt is thus governed by the mechanical properties of the steel.
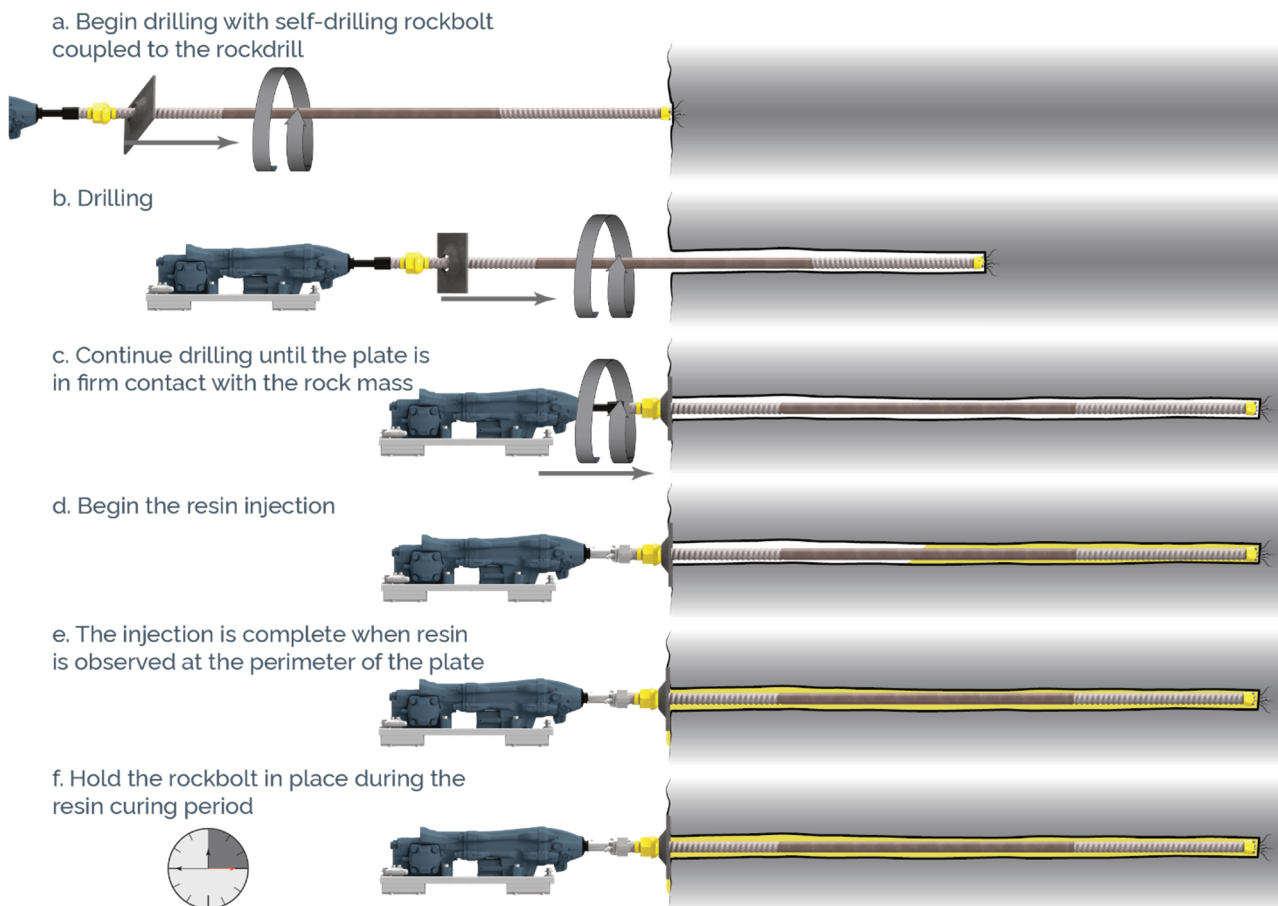
Figure 1   Installation of a self-drilling anchor
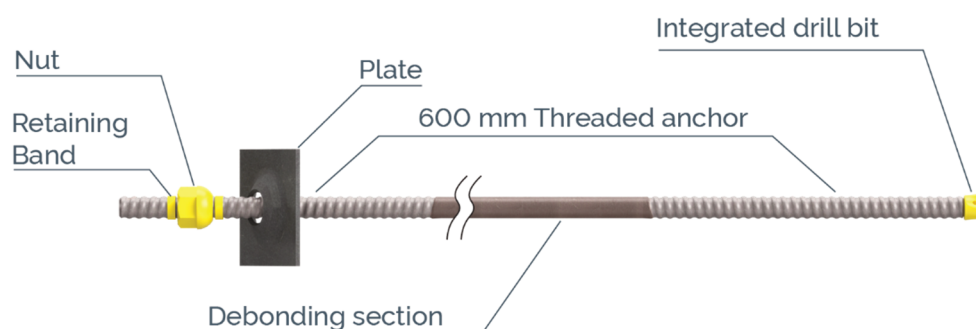

Figure 2   Configuration of the yielding SDA used during the investigation: the R28 BoraBolt

2.1   The percussive drilling process

Support holes in a hard rock environment are drilled using a percussive drilling process where the SDA or drill steel is coupled to the shank of the rockdrill. Figure 3 illustrates that the rockdrill generates a cyclic excitation force when the piston strikes the back of the shank, generating a longitudinal wave which is transferred through the drill steel into the rock mass. While much of the energy is dissipated into the rock mass, a portion of the energy is reflected into the drill steel or SDA. The reflected energy interacts with the subsequent excitation force generated by the rockdrill, potentially amplifying localised stresses within the drill steel or SDA.

For hard rock applications, the distal end of the SDA or drill steel is equipped with a carbide button drill bit. The pressure generated by the contact between the buttons of the drill bit and the rock results in fracturing of the rock as the wave energy from the rockdrill is dissipated. The drill steel is then rotated, and the cycle repeated. Water is flushed through the centre of the SDA or drill steel to flush the fractured rock out of the support hole and to cool the drill steel. Drill steel is typically produced from high-strength brittle steels, suited to efficiently transferring the percussive energy to the rock mass. A yielding rockbolt is produced from comparatively lower strength ductile steel to meet the deformation capacity requirements of the anchor. Consequently, SDA are typically less efficient during drilling and the steel is more susceptible to steel aging during the drilling process.
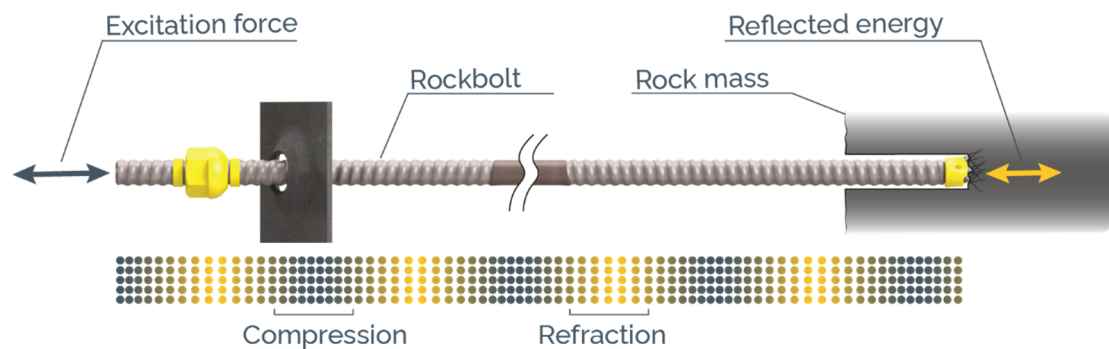

Figure 3   Illustration of the longitudinal wave formation during drilling

To estimate the stress generated within the rockbolt during the drilling process, a finite element analysis (FEA) was conducted to estimate the compressive stresses that may be generated by the interaction of the above-described energy waves. The simulation estimates a maximum compressive stress of 421 MPa may be generated within the rockbolt (Rao 2022). The yield strength of the material from which the BoraBolt is produced is 350 MPa, consequently low levels of plastic strain (>1%) are anticipated during the drilling process. The specific simulation was conducted assuming the rockbolt was being drilled into a granite with a COP RR14 rockdrill. The excitation velocity and mass of the piston striking shank we determined based on the specifications of the rockdrill.

The simulation provides valuable insight into the potential compressive loads generated in the rockbolt. The results are, however, to this configuration. Varying the rock type and quality will alter the compressive load generated in the rockbolt. Alternatively, the drilling parameters such as feed, percussion and rotation pressure and percussion frequency may result in variations in the resultant compressive load generated.

The drilling processes adds additional loading requirements to the rockbolt during the anticipated service life. When reinforcing the rock mass, a rockbolt is typically loaded in a combination of shear and tension (Thompson et al. 2012); while during drilling, the rockbolt is loaded in compression. Therefore, the materials resistance to both cyclic loading beyond yield and strain reversal should be a consideration in the design and characterisation of yielding SDAs. The Bauschinger effect "is the manifestation of non-isotropic hardening during plastic deformation in an isotropic material" (Richards et al. 2011); in summary, when plastically loaded in compression, the material is aged during the strain hardening process. This reduces the strength of the material when a reversed strain is applied, as illustrated in Figure 4. The typical loading regime of an SDA subjects the anchor to the loading cycle described by the Bauschinger effect.
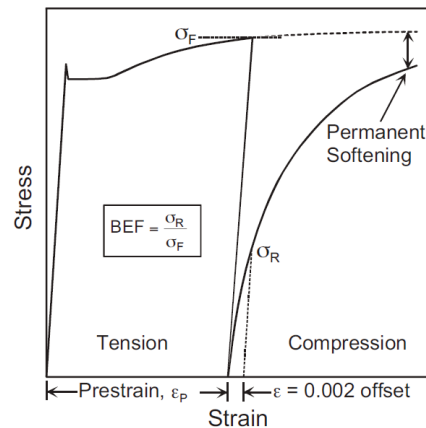
Figure 4   Schematic of the Bauschinger effect phenomenon (Richards et al. 2011)

3   Investigation plan

The aim of the investigation was to quantify the effect of the drilling process on a yielding SDA and to determine if the Bauschinger effect can be identified in tensile performance of an installed anchor. Should this prove true, the performance of the rockbolt after drilling should be considered as the installed performance of the anchor. From a common batch of steel, six R28 by 2.4 m BoraBolts were prepared and split into two batches of three samples as defined by Table 1. The initial three control samples were produced and prepared for a direct impact split-tube test (ref BB-2824-S0X) using the Epiroc Impact Tester. The remaining three samples were the experimental samples (ref D-BB-2824-S0X). The experimental group was transported to a mine site and used to drill a single support hole into quartzite with a Epiroc COP RR14 rockdrill. During drilling the rockbolts were directly coupled to the rockdrill with a female R28 shank. The rockbolts were then retracted from the rock mass, decoupled from the rockdrill, and returned to the Epiroc Application Centre for preparation, instrumentation, and impact testing. At the time of installation, the rockdrill was configured for drilling with a conventional drill steel, the rockdrill control parameters we unaltered.

Table 1   Sample descriptions

Sample ref.	Quantity	Description
BB-2824-S0X	3	Control samples
D-BB-2824-S0X	3	Experimental samples

3.1   Epiroc Impact Tester

Laboratory-based impact testing is conducted using one of two methodologies: the impact test method where the mass impacts with the test sample, and the momentum transfer method where the mass and sample are coupled and impacted with a stopper. Both methods rely on the concept of momentum (Li et al. 2021), transferring a calculated kinetic energy of the mass at impact into the rockbolt. The Epiroc Impact Test rig, shown in Figure 5a, employs the impact test method. A simplification of the system is illustrated in Figure 5b. The instrumented samples are installed into a steel host tube, which in turn is installed through the bore of the load trolley and electromagnet and attached to the support beam. An impact load cell, plate load, distal flag and proximal flag are attached to the prepared sample. The input energy is adjusted by either adjusting the mass in the load trolley or the height from which the trolley is released. During the impact test line scan cameras are used to track the flags and calculate the displacements of the sample at both. As described by Knox & Berghorst (2018a), the load and displacements are recorded at a rate of 10 kHz.

The test is initiated by raising the load trolley to the predefined height using the electromagnet and then releasing it. The kinetic energy of the trolley is dissipated by the sample during the impact and the recorded loads and displacements are automatically processed to calculate the energy, impact load and displacement metrics. These are used to evaluate the performance of the rockbolt.

(a)   (b)
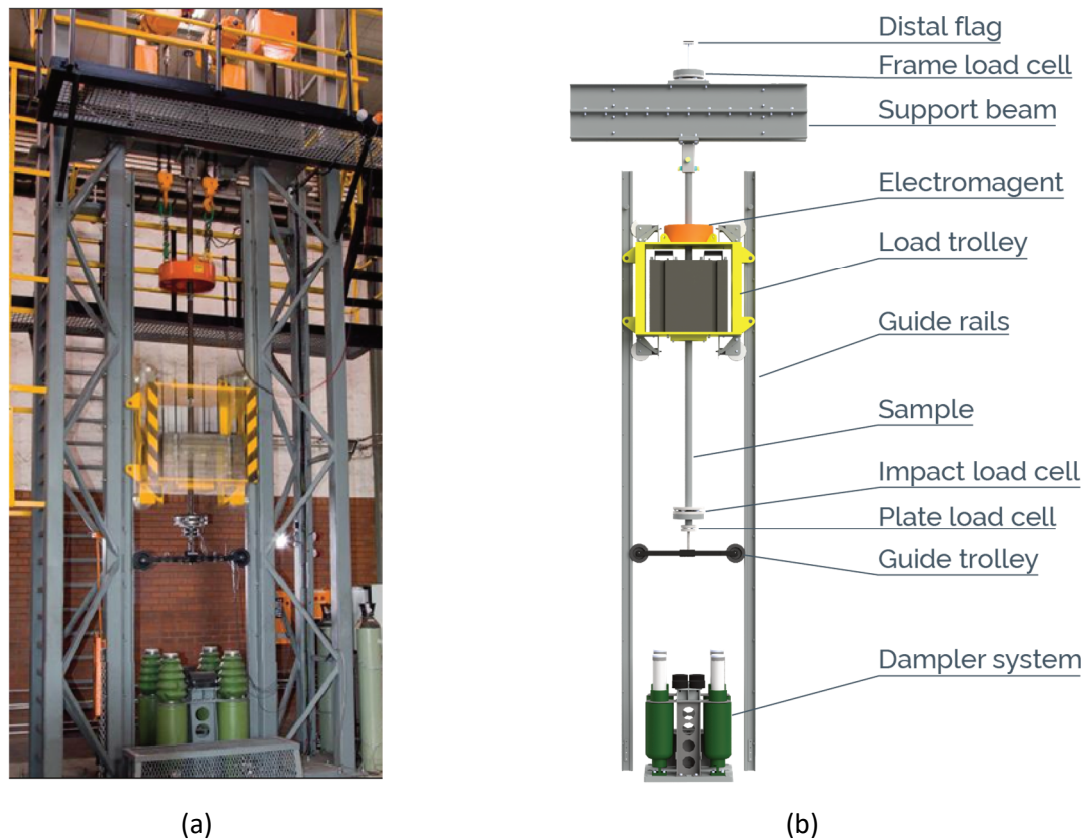
Figure 5   The Epiroc Impact Tester: (a) Image during a test (Knox & Berghorst 2018b); (b) Illustration of the primary components

3.2   Sample preparation

The performance of a BoraBolt was assessed through an indirect split-tube impact test. The rockbolts were installed into host tubes with an internal diameter of Ø38 mm and an external diameter of Ø56 mm. The internal diameter of the host tube was determined by the fact that R28 BoraBolt has a Ø35 mm drill bit affixed to the distal end as illustrated in Figure 2. The two batches of samples, the control batch and experimental rockbolts, were prepared using an identical process.

The BoraBolt is designed for installation with a bulk resin system; the bolts were installed with Potentia Thixo F60. The two components of the resin (resin and catalyst) were mixed and injected with the system configuration defined in Table 2. The pumping system used within the testing laboratory is a replica of the Epiroc Boltec resin injection system developed for the high performance Boltec. A simplified schematic of the resin pump system is illustrated in Figure 6. The pumping system has a closed loop feedback system to control the flow rate and ratio between the resin and catalyst, this maintains the ratio throughout the injection cycle, improving the consistency of the resin strength. Prior to injecting the samples, 40 mm resin cubes were prepared and tested to confirm the mechanical properties of the resin.

Table 2   Potentia Thixo F60 pumping parameters

Parameter	Value
Mixing ratio (A/B)	1:1
Flow rate	8.5 L/min
Number of mixer elements	14
Temperature	23°C
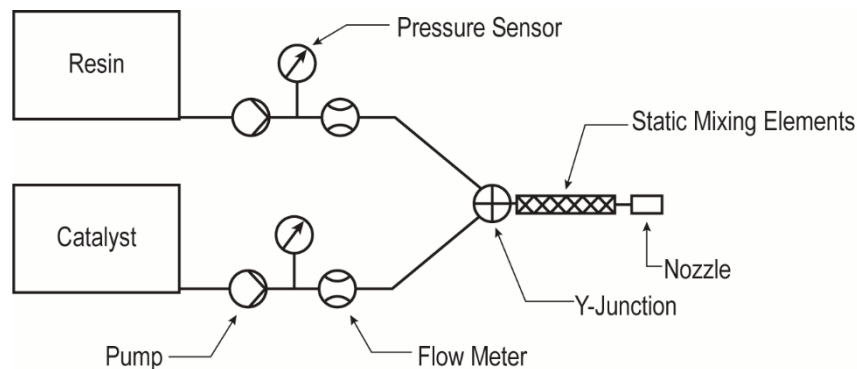
Figure 6   Simplified schematic of the Epiroc resin pump

4   Results of the investigation

4.1   Verification of materials

The core advantage of a laboratory-based investigation is the controlled environment in which they are conducted. Considerable effort was directed towards quantifying the properties and controlling each variable during the investigation. The six BoraBolt samples were produced from the same batch of hollow steel. Consequently, the mechanical properties of both sample batches are considered as identical prior to drilling. The mechanical properties (ultimate tensile load and elongation) of the steel were verified in accordance with the procedure defined by the International Organization for Standardization (2019) method for tensile testing. Five steel samples were tested with an average ultimate load of 242 kN and a strain at rupture of 25%. The consistent response of the steel to the loading is illustrated in Figure 7.
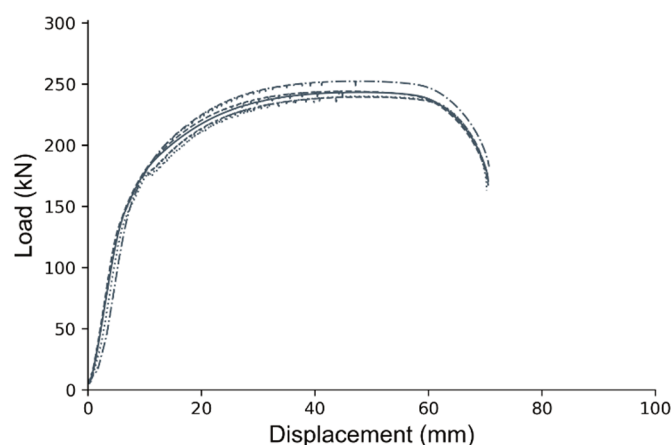
Figure 7   Load–displacement response of the steel used to produce the R28 BoraBolts

The BoraBolt was anchored with Potentia Thixo F60 resin, the mechanical properties were verified through compression testing of the 40 mm cubes. The unconfined compressive strength of the samples was

determined to be on average 40 MPa, demonstrating the proficiency of the injection system and the consistency of the resin (Table 3).

Table 3   Summary of the resin cube compressive strength tests

Sample ref.	Yield strength (MPa)	Unconfined compressive strength (MPa)
Control samples	21	40 [-2, +3]
Experimental samples	21	40 [-2, +2]

4.2   Pre-installed samples

The samples that were shipped to the mine site for drilling were inspected upon return and no significant mechanical damage was observed on the samples. As anticipated with a post drilled rockbolt some minor damage was observed to the carbide button drill bits and the profiled portion of the BoraBolt as shown in Figures 8a and 8b, however, no damage was observed on the thread which was coupled to the rockdrill.

During the transport, storage, and installation underground a deposit of surface rust developed over the length of the samples developed. The surface rust is superficial and assumed to have negligible effect on the mechanical properties of the rockbolt.

(a)   (b)
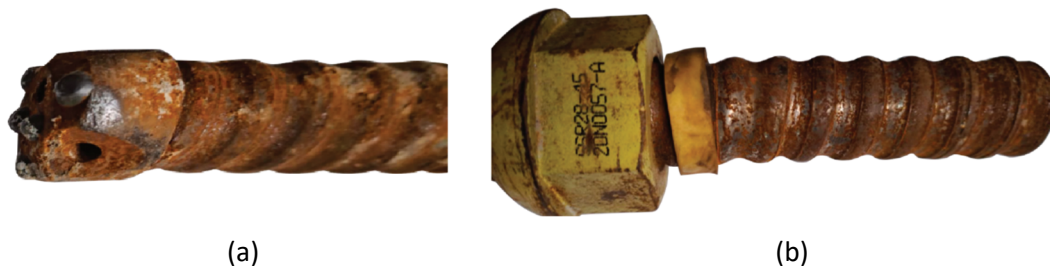
Figure 8   Pre-drilled sample observations. (a) Distal end of the SDA showing a worn drill bit; (b) Proximal end of the SDA showing the SDA nut, retaining band and shank thread

4.3   Impact testing results

The impact tests on both sample batches were conducted at an input energy of 47 kJ with an impact velocity of 5.4 m·s^{-1}. A summary of the results is presented in Table 4. The impact load–displacement response of the BoraBolts as shown in Figure 9, shows that the energy capacity of the BoraBolt was such that two impulses were required to rupture the sample.

Table 4   Summary of the individual results

State	Sample ref.	δ_{plate} (mm)	δ_{distal} (mm)	Avg. Impact F (kN)	E$_{total}$ (kJ)
Control samples	BB-2824-S01	297	3	292	89
	BB-2824-S02	306	4	279	87
	BB-2824-S03	282	4	285	82
Experimental samples	D-BB-2824-S01	231	10	264	62
	D-BB-2824-S02	240	3	254	60
	D-BB-2824-S03	226	5	240	53
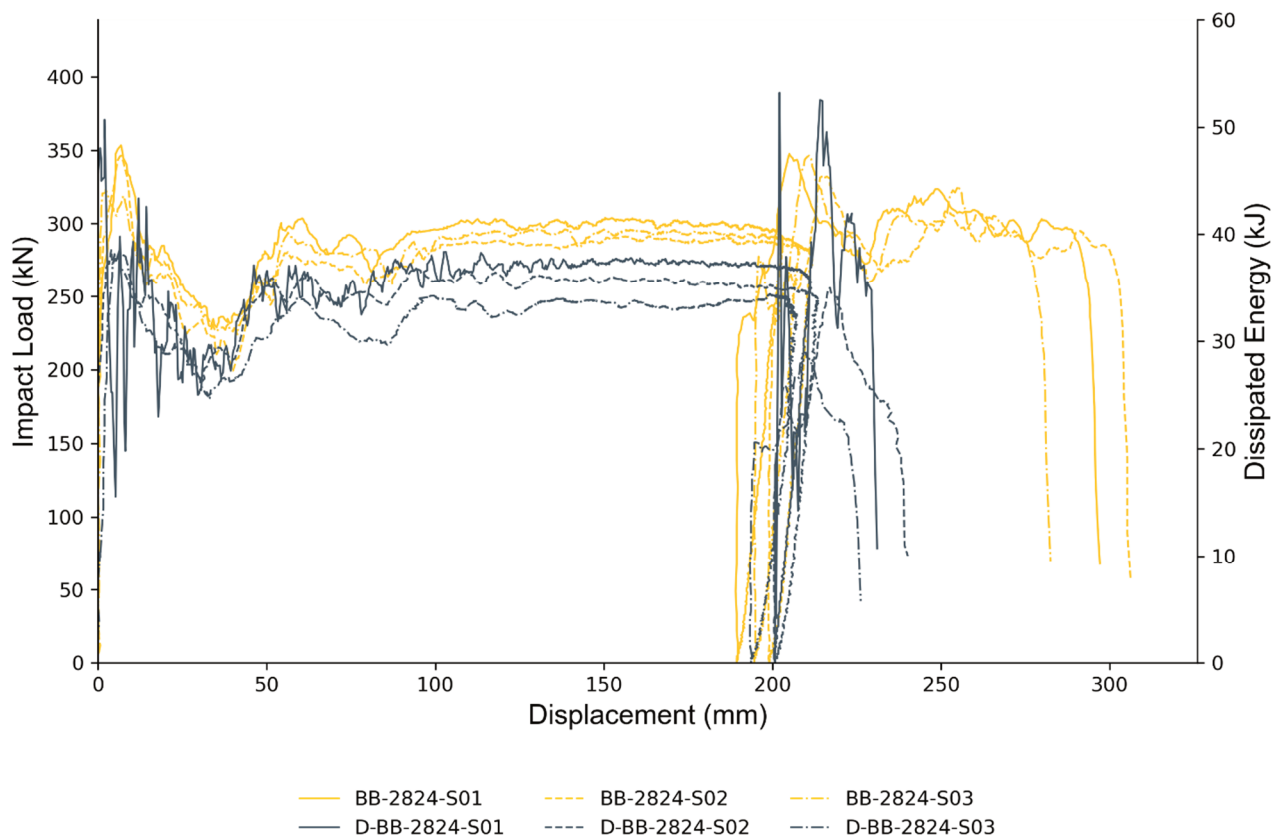
Figure 9 Comparison between the impact load and displacement response for the control and experimental batches

In Table 5, the average results per batch are summarised. A 33% reduction in the energy capacity was noted in the BoraBolt after the drilling portion of the installation cycle was performed.

Table 5 Summary of the batch results

State	Avg. δ_{plate} (mm)	Avg. δ_{distal} (mm)	Avg. impact F (kN)	Avg. E_{total} (kJ)
Control samples	295	4	285	86
Experimental samples	232	6	253	58

5   Interpretation of results

Considerable effort was directed at ensuring the controlling variables; both steel strength and strength of the anchoring medium were quantified and controlled. The samples were all produced from the same cast of steel and the rockbolts were post-grouted with a two-component pumpable resin. Maintaining the ratio between the resin and the catalyst is vital to the strength of the two-component resin. This was ensured using a bespoke system replicating the injection system on the Boltec. The repeatability of the mixing is illustrated in the consistency of the compression strength results attained.

The consistency of the resin strength within the samples tests is illustrated in the distal displacement. The distal displacement represents the movement of the rockbolt within the anchoring medium relative to the host tube. A maximum of 10 mm was recorded on samples D-BB2824-S01, while less than 5 mm of displacement was recorded for the remaining samples. Based on the consistency of the resin strength and mechanical properties of the steel it can be assumed that prior to drilling the six samples were identical.

An average reduction of 63 mm was recorded in the plate displacement of the experimental samples when compared with the control samples. The reduction in the average impact load from 285 kN to 253 kN suggests that the reduction in displacement may not be a consequence of strain hardening. Rather, strain hardening would result in an increase in the mechanical strength of the material. During the drilling cycle the rockbolt is subjected to a compressive force. During an impact load a uniaxial tensile load is applied to the rockbolt. Consequently, the reduction in load observed is consistent with the Bauschinger effect. A steel plastically deformed in a direction (compression) result in aging reducing the strength in the opposite direction (tension). This effect could account for the reduction in load recorded during impact test. Consequently, a 33% reduction in energy capacity was calculated due to the reduction in both parameters from which the energy is calculated.

The relationship noted between the control and experimental group is related to the mechanical properties of the steel from which the rockbolt is produced and the induced stress. The effect of drilling on the performance of the rockbolt will vary for a rockbolt produced from a higher strength material, such as a conventional SDA.

6 Conclusion

The aim of the investigation was to provide preliminary insight into the effect of the drilling cycle on the performance of a yielding self-drilling anchor. Impact testing was conducted to quantify the variance in the performance of the yielding self-drilling anchor. Considerable effort was directed at quantifying the input materials and ensuring consistency between the control and experimental batches, therefor variations in the result can be attributed to the effect of the drilling cycle.

A reduction in the impact load and displacement was recorded resulting in a 33% reduction in the energy dissipated when comparing the experimental sample batch to the control sample batch. Consequently, it can be concluded that the drilling process does influence the performance of the yielding self-drilling anchor. This preliminary investigation has quantified the influence for a single rockbolt. Considerable future work is required to determine if the effects are either an unavoidable consequence of the installation method or can be mitigated by controlling the drilling parameters. In additional the effect of varying the profile and material of the hollow bar should be considered.

Acknowledgement

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