JAKTEN PÅ EN BÄTTRE LÖSNING FÖR MEKANISERAD BULTNING I SVÅRA BERGFÖRHÅLLANDEN

THE SEARCH TO FIND A BETTER SOLUTION FOR MECHANISED BOLTING IN DIFFICULT ROCK CONDITIONS

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Abstract

När underjordisk bergbrytning går allt djupare i jakten på malmkroppar är det sällsynt att bergförhållandena blir bättre. Det typiska scenariot är högre permanenta påfrestningar i berget ju djupare ner bergbrytningen sker. Detta kan leda till problem som sprickbildning, kollaps eller pressande bulthål, seismiska aktiviteter och tomrum. Dagens befintliga lösningar och utrustning för mekaniserad bultning tillhandahåller ingen enkel och pålitlig bultinstallation. Resultatet blir ofta att det skapas en flaskhals i bergbrytningsprocessen. Minskningen i produktivitet har såklart även en ekonomisk påverkan. Utöver det innebär ofta oförmågan att installera bultar säkert och med hög framgångsandel att ytterligare bergförstärkning måste installeras. Det behövs en drastisk förändring inom bultning i gruvindustrin.

Denna artikel dokumenterar projektåtagandet av LKAB och Epiroc Rocks Drills AB som en del av Sustainable and Intelligent Mining Systems (SIMS) initiativ att utveckla och fälttesta en potentiell lösning för att öka produktiviteten inom mekaniserad bergförstärkning. Resultatet från dessa fälttester och jämförbar information från befintliga bultningsmetoder presenteras för egen utvärdering.

1. Introduction

Significant advances have been made in recent years with regards to automation for underground face drilling and long-hole drilling equipment. Face drills are able to drill on full automatic, with up to 70% or more of the number of blast holes being achieved. Long-hole production drills are able to be almost fully autonomous whilst drilling a blast ring – with cases such as LKAB Malmberget and LKAB Kiruna taking the step to have several of their long-hole drills operating autonomously with monitoring of operations for all machines being from a central control room.

Rock bolt drilling equipment however has lagged behind with regards to automation. Not because of any mechanical or software control system deficiencies, indeed the basic design of face drilling, long hole drilling and rock bolt drilling rigs is very similar. The fault behind lack of progress in automation for rock bolt installation can be found with the design of the rock bolt and its ease for mechanized installation. Common long term rock bolts such as the resin cartridge rebar family and cementitious grouted rebar family of bolts have several design limitations that increase the chance of there being a stoppage or requiring human intervention during installation. As mines go deeper in the pursuit of ore bodies, inherent ground stresses will increase resulting in even greater issues with rock bolt installation. In order to address this gathering bottle neck in mine development and drive the possibilities for future automation, a different approach to the complete rock bolting system was needed. Machine, bolt and bonding agent all needed to be evolved together in order to create an optimum solution.

2. Cementitious grouted rebar rock bolt family

Cement grouted rebar bolts are widely used in civil tunnelling rock reinforcement, and are still an important bolt variant for many underground mining operations. There are several variants of bolt designs used with cement grout, more common types being known as plain rebar, kiruna bolts, CT bolts and D-bolts. They all share in common the use of a cementitious grout to act as the bonding agent between the rock mass and the steel bolt body. The cementitious grout is most typically a mixture of cement (e.g. Portland cement) and water. The mixture ratio being according to the cement manufacturers recommendations. Mixing of the cementitious grout is either done using a manual mixing machine, or via auto-mixing machines such as that used on the Epiroc Boltec EC fully mechanized rock bolting machine, see Figure 1.

Figure 1. Boltec EC with Auto-mix cement grout system

Installation of cement grouted rebar bolts with a fully mechanized rock bolting drill rig utilizes a cement injection tube in order to pump the cement grout into the pre-drilled bolt hole prior to the insertion of the bolt. Figure 2. shows a typical installation sequence for a cement grouted rebar (D-bolt example shown).

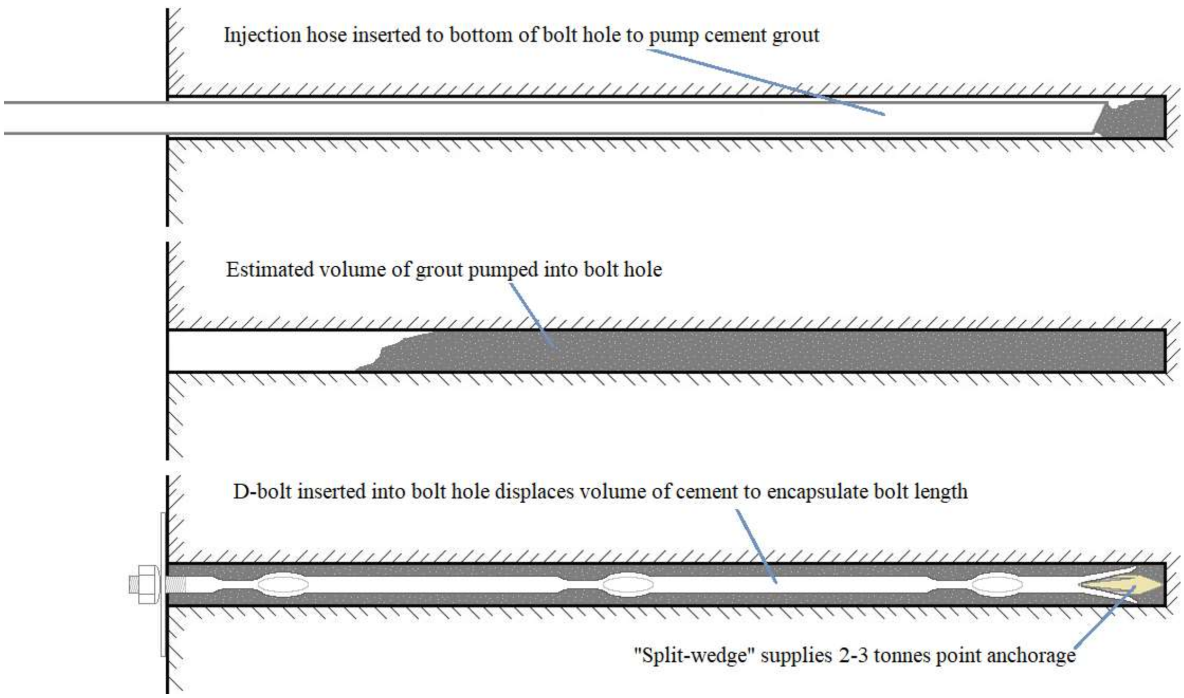

Figure 2. Installation sequence of a cement grouted D-bolt

A brief investigation of the advantages and limitations of the cementitious grouted rebar bolt finds the following key points:

Advantages:

- Inexpensive unit price = In good ground, relatively inexpensive to install.
- Cementitious grout has long service life = 100+ years service life of cement grout is desirable for mines and civil tunnels where many years life for openings is needed.

Limitations:

- Slow setting speed of cementitious grout = Up to 24 h setting time unless using accelerants before achieving close to maximum load bearing capacity means delays in heading utilization. Additionally, in squeezing or high stress ground conditions this may mean that the rock mass can move, potentially compromising the excavation integrity.

- Sensitive to hole volume increase = Cracks, voids, over drilling, eroded bolt hole diameter and incorrect drill bit diameter can mean an increase in bolt hole volume. As injection of the cement grout is done prior to bolt insertion, there is a fixed volume of grout in the hole with no means to compensate for change in volumes. This means that the bolt body might not be fully encapsulated, leading to higher risk of corrosion over time and/or poor load transfer from rock to bolt.
- Inserting the grout hose into blocked bolt holes difficult = Poor ground often has blocked or partially blocked holes, preventing the grout hose from being fed to the bottom of the bolt hole. It is not possible therefor to inject the desired volume of cement grout from the bottom of the hole. The hole must be cleaned and a second attempt made to insert the injection hose. If still not possible, then the hole may have to be abandoned. This leads to increased time for installation. Figure 3.Illustrates the problems associated with bolt hole blockages.
- Inserting the grout hose when installing mesh is difficult = The grout hose can be often caught on the steel mesh wire, making it difficult to insert the grout hose into the bolt hole. This can slow down the bolting process. See Figure 4. for illustration of the issue.
- Cementitious grout is difficult to work with = Bolting rigs equipped with cement grout systems require regular cleaning of the grout mixing and pumping system during operation. Failure to do so can lead to blockages, equipment failure and reduced life of components. Cement based grout tends to stick to surfaces, especially on the feed and boom – again demanding regular cleaning with water and form oil application.

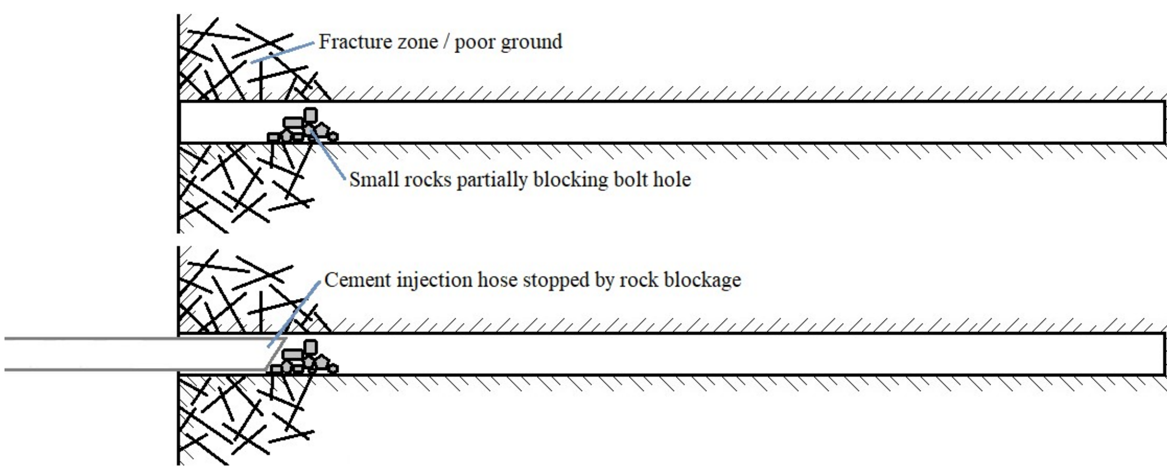

Figure 3. Illustration of the difficulties with injection hose against bolt hole blockages

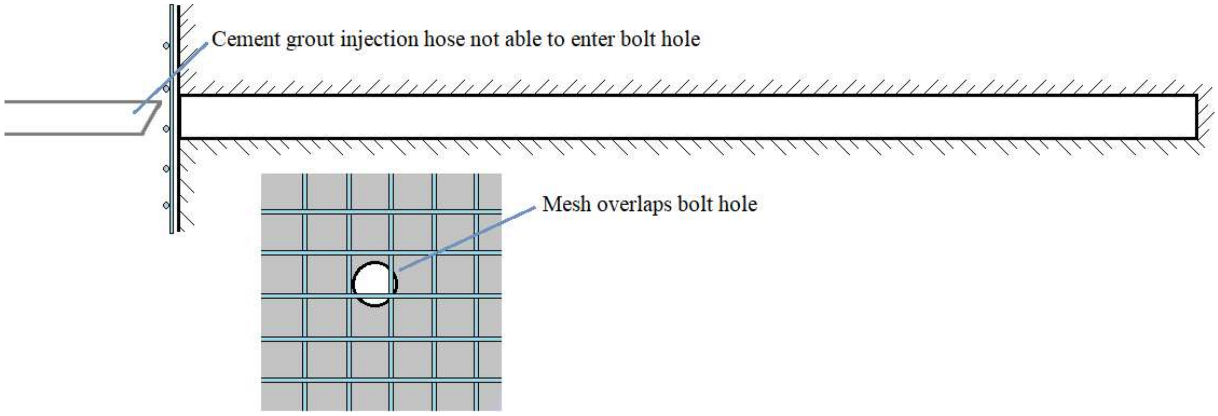

Figure 4. Difficulty of inserting cement grout injection hose through steel mesh

Like their resin cartridge rebar cousins, cementitious grouted rebar bolts suffer from limitations in poor ground conditions. Which for many underground mining operations is becoming a more and more prevalent problem.

3. Self-drilling anchors and pumpable resin

From late 2011, Epiroc had been looking at various technologies that could have the potential for improving bolt installation productivity. Self-Drilling Hollow bars or Self-Drilling Anchor (SDA) bolts were identified as having the ability to give significant positive aspects to bolting cycle times, especially in poor rock conditions as they would negate issues related to collapsing bolt holes and would be indifferent to mesh installation. SDA bolts are characterized by the bolt body acting as a drilling steel during drilling and installation with percussive rotation rock drills. The bolt body is hollow allowing its use as a flushing channel during drilling, and as an injection channel for the introduction of a bonding media during final installation. In order to drill into rock and other broken materials, the bolt has a sacrificial drill bit that remains in the hole after installation. Figure 5. illustrates the main components of a typical SDA bolt installation.

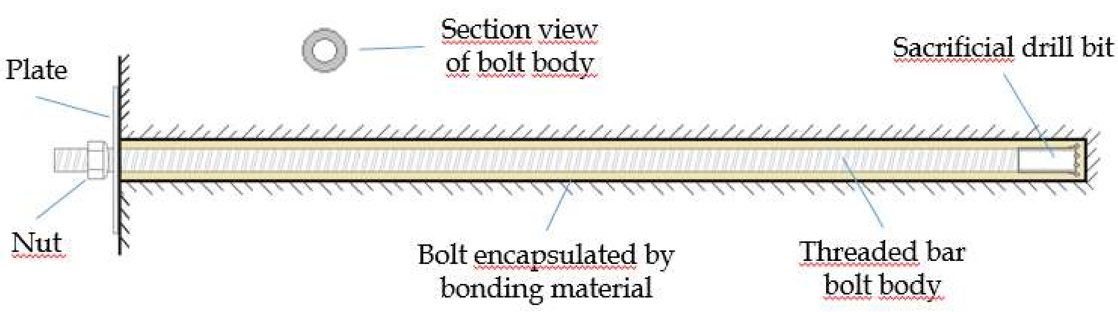

Figure 5. Typical Self-Drilling Anchor installation

SDA bolts are not a new product, and have been used extensively with pumped cementitious grout as the bonding agent in civil applications such as soil nailing, micro piling, slope stabilisation and spiling activities for many years (Irvin et al. 2014). Use in hard-rock underground mining applications had been somewhat limited to situations where ground conditions did not allow installation of other commonly used bolt types such as resin cartridge rebars or cement grouted rebars. The perceived unit cost of the SDA bolt being one of the reasons why the SDA bolt system had not been widely adapted. In order for a SDA bolting system to become viable, the unit cost of the bolt would need to be offset by superior productivity and quality of installation. To that end, Epiroc identified that a fast-setting bonding agent would be required in place of the slow-setting cementitious grout traditionally used. What was needed was a pumpable product with similar setting times as the commonly used resin cartridges. The problem however, with the material used in resin cartridges is its relatively high viscosity – which made its use in a pumpable system not feasible. A new chemistry was needed.

Epiroc approached leading chemical suppliers in the mining industry to see if there were any chemical products readily available that could fulfil the desired pumpability and fast setting time requirements. What was discovered was that there were polyurea silicate based products available that had been used previously as ground consolidation products in both civil tunnelling and underground coal mining. The product was of a two component sort, where once the two components were mixed together a chemical reaction is started which results in a solid product that would be suitable for transferring loads from the rock mass to the steel bolt. Even though the results from the initial tests with the pumpable resins were encouraging, the resin characteristics needed adjustments regarding setting time and thickening of the mixed resin to prevent resin from running out of the bolt hole. Figure 6. shows the results of a pumping tests against a cardboard backing to investigate the pumpability and thixotropy of that particular resin formulation. The results from this particular test were very positive.

Figure 6. Shows an early test of pumpable resin to explore it's properties (Minova)

Once a suitable resin was found that would satisfy the parameters needed with regards to setting time and thixotropy, the next step was to develop a delivery system that could be integrated into a dedicated rock bolting rig.

However, before moving forward it was important for the development team to gather input data and design targets in order to set project goals. To this end, LKAB was brought into the project as a key mining industry partner. LKAB is a Swedish Iron Ore producer owned by the Swedish Government with two underground operations in northern Sweden. LKAB is known globally as a company that is at the forefront of mining technology, and is particularly adept at pushing suppliers and technology in order to improve the efficiency and safety of their operations. LKAB chose to work with Epiroc to develop a solution to improve the productivity of mechanised rock reinforcement equipment. LKAB had recognised that their existing cement grouted rebar bolting equipment was displaying slower and slower performance numbers, especially as their underground operations at Kiruna and Malmberget were going deeper and encountering more difficult rock conditions as a result.

From 2012 to mid-2015 LKAB and Epiroc conducted many workshops and testing demonstrations. Work was progressing well, and received an additional boost in mid-2015 when the project was incorporated into the Sustainable Intelligent Mining Systems (SIMS) (https://www.simsmining.eu/) initiative. SIMS is a Horizon 2020 project sponsored by the European Union. The goals of the SIMS initiative was to provide funding and a framework for mining companies, equipment and systems suppliers and top-class universities to collaborate on various work packages that address various aspects of the mining industry. The aim being to realize the vision of a sustainable intelligent mine with safe working conditions, high efficiency and low environmental impact. To achieve these goals several new, innovative and disruptive technologies, processes and methods must be implemented in todays and tomorrow's mining industry.

The area of the SIMS project that the pumpable resin research and development fell under was: Improvements in rock bolt and mesh installation efficiency, a part of the Ground Control Work Package. The culmination of the SIMS work was the manufacture and field test of a Proof Of Concept (POC) bolting drill rig.

4. Field test

4.1 Site description

The field test was conducted in the Malmberget underground iron ore mine, operated by Luossavaara-Kiirunavaara AB (LKAB), in turn owned by the Swedish government. The Malmberget mine is the second largest underground iron ore mine in the world and is located in northern Sweden, 100 km north of the Arctic Circle, close to the municipality of Gällivare. Large scale mining activities in the Malmberget area have been in operation since 1888, with all mining operations shifting underground during the 1920's. The mining method in use at Malmberget is Sub-Level Caving (SLC) which is considered one of the larger scale underground mining methods. Production from underground during 2017 was 13 million tonnes of ore. This translated to 9 million tonnes of saleable products.

The rock conditions in Malmberget vary between different areas, but increasing seismic activity with depth has put additional demand on the required rock support. Increasing amounts of ore are also being mined from within areas known to be susceptible to seismicity, and from within areas affected by highly-challenging geologic conditions. Over 170 geophones are located throughout the underground workings to monitor seismicity and identify hazardous areas, and a great deal of emphasis is placed on installing proper support underground. Figure 7. illustrates one of the areas within the mine where ground conditions were particularly difficult, with heavy rock reinforcement in evidence.

Figure 7. LKAB Malmberget, example area of difficult ground conditions

Rock support installation in Malmberget mine is fully mechanized with multiple bolting rigs in operation both owned by LKAB as well as several contractor machines. For rock support the mine uses cement grouted rebar (static) and D-bolts (yielding), cement-grouted cable bolts, mesh/screen support and shotcrete/steel-fibre reinforced shotcrete. The mine has a detailed plan (standard operating procedure) for all rock support. Figure 8. is the standard 1m x 1m bolting pattern for Dynamic (yielding) 3 m D-bolt installation, including 100 mm steel fibre reinforced shotcrete and welded steel mesh.

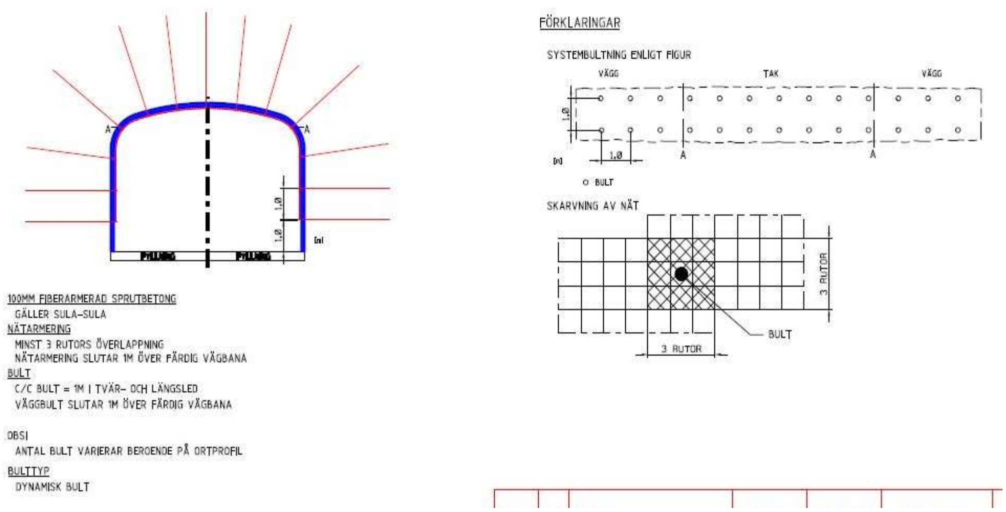

Figure 8. Systematic dynamic bolt installation design (LKAB)

4.2 Rig description

The bolting rig used for the field test at LKAB's Malmberget mine was a Boltec EC manufactured by Epiroc Rock Drills AB, Sweden. The Boltec EC can be described as a fully mechanised rock bolting drilling machine designed for rock bolt installation in underground mining and tunnelling applications. The machine utilises a diesel engine for transportation from work site to work site, however makes use of a high voltage (1000 V / 50 Hz) electrical system driving hydraulic pumps which in turn provide hydraulic power for running a rock drill, boom and feed positioning systems and other hydraulic functions. Epiroc has been a manufacturer of underground mining and tunnelling equipment for many years, and is amongst the market leaders in the development of such equipment.

Figure 9. illustrates the Boltec EC and the locations of the key components of the machine used at the LKAB Malmberget field trial.

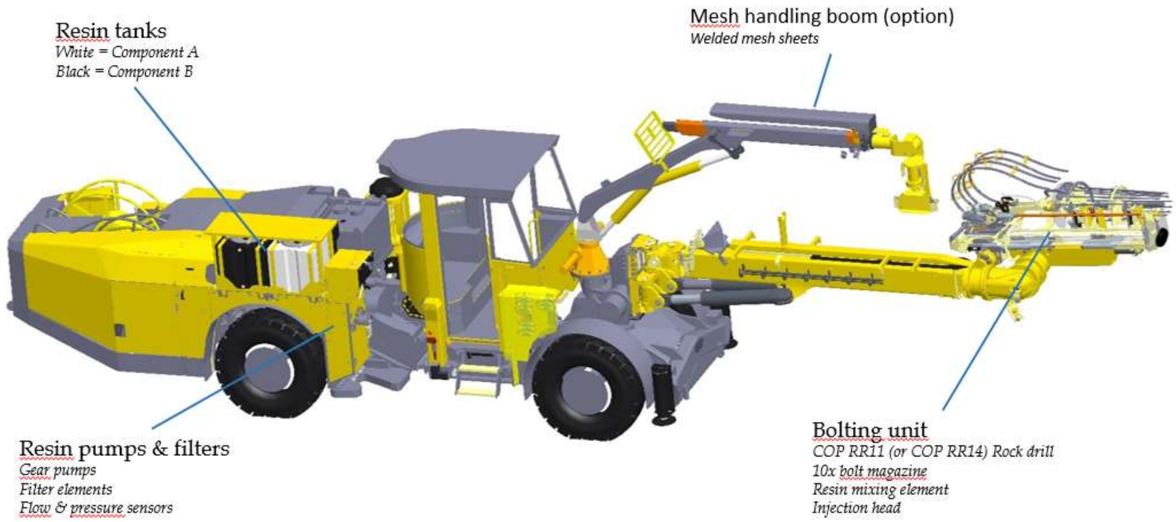

Figure 9. Field test Boltec EC with key components indicated

The new items that were developed specifically for the field test machine are

- On-board resin tanks (200 L each of component A and component B – 170 L each useable)
- Pumping system with minimal pressure & flow fluctuations
- Pumping monitoring system to ensure mix ratios are maintained
- Refilling system for on-board tanks that allowed filling whilst still installing bolts
- Integrated software control of the pumping and injection system with safety cut-outs if pumping pressure or pumping flows exceeds defined parameters
- New shank developed to work with SDA bolt type
- New drill steel support with three positions (full open, guide and grip)
- Resin mixing system that allowed multiple injections without need for replacement
- Mixing system flushing design that creates a closed system with minimum maintenance requirements

4.3 Self-drilling bolts

The bolts used in the field test were optimised self-drilling anchors with a welded bit and a central hole, through which resin is pumped, see Figure 10. Optimisation of these specific bolts was achieved by dispensing with the traditional screw on sacrificial drill bit and instead utilising a welded on design. By doing so, the bolt hole diameter was reduced from 38-39 mm to 35 mm. This bolt hole diameter reduction contributed to an increase in penetration rate and a reduction of the volume of resin needed per hole. Both features being of benefit in the search for increased productivity at a controlled cost.

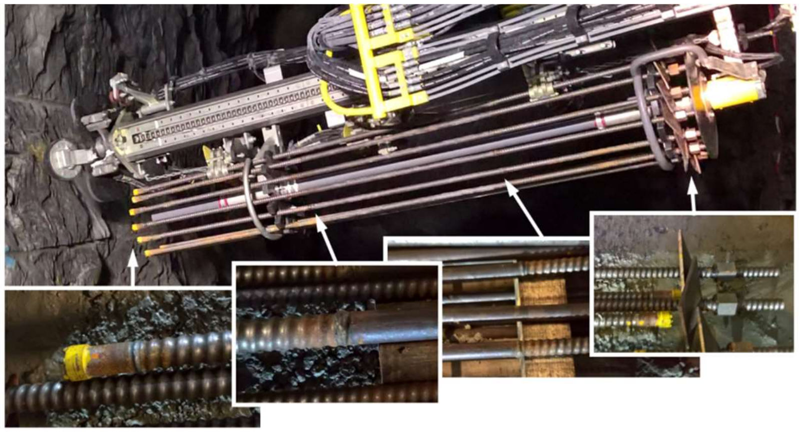

Figure 10. The self-drilling bolts used (LKAB).

The specific bolts used are 3.05 m long Minova CB R28/200 bolts. The drilled length is approximately 2.8 to 3.0m. The bolts have an ultimate load of 210 kN, a yielding load of 145 kN and an elongation yielding section of 200 mm. Figure 11. Illustrates the installation procedure of the SDA bolts with pumpable resin.

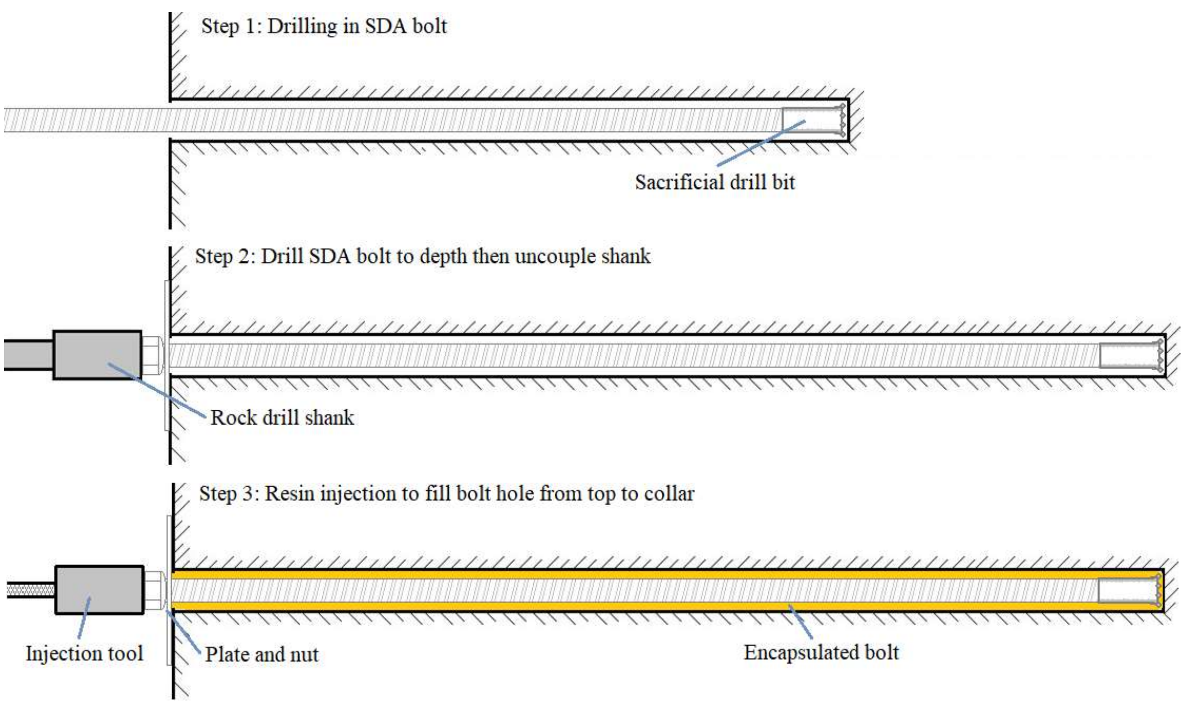

Figure 11. Installation sequence for SDA bolts and pumpable resin.

The bolt consists of a bit, a threaded section, a yielding section and another threaded section containing the plate and the nut. The bolts are welded in three different locations. The first between the bit and bolt body, and the second and third between the threaded and smooth dynamic section of the bolt body, see Figure 12.

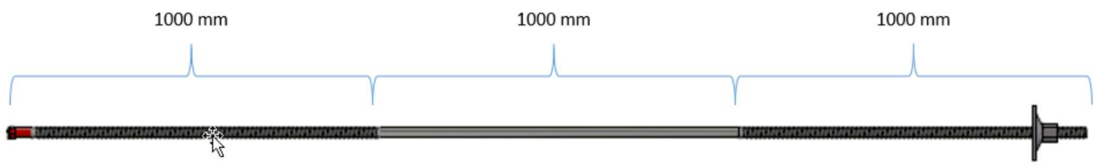

Figure 12. Diagram of yielding SDA bolt used during Malmberget field test

4.4 Resin

The resin used during the field trial was supplied by Minova, part of the Orica group. The resin used had the product name Carbothix, which is a polyurea silicate resin that consists of two components (component A and component B). Figure 13. shows the intermediate bulk containers (IBC) that were used to refill the on-board tanks located on the machine.

Figure 13. IBC containers (1 m^3 each) for components A and B that are used to refill the on-board tanks. (LKAB)

The properties to of the resin used during the field trial delivered a setting time of 15-30 sec in an operational temperature range of 10-15 C. During the field test the average underground temperature at Malmberget was closer to 17 C, which meant that the setting time was closer to 10-12 sec. This shorter setting time was still OK and worked well for the field test.

The design of the pumping system on the Boltec EC was such that the option existed for the machine to pump directly from off-board IBC containers or from on-board tanks. See Figure 14. showing the on-board tank installation on the machine. In a practical sense this would mean that a slower setting speed resin can be utilised when needed for areas where extension drilling operations are required. Due to the increased volumes typically used for extension drilling holes, a slower setting time is needed.

Figure 14. The containers for components A and component B on-board the rig.

The estimated consumption of resin is 1.4 litres for a 3 m bolt (0.7 litres of component A and 0.7 litres of component B). The average resin consumption during the field trial was 1.8 – 2.0 litres per hole. This indicates that the rock conditions encountered during the field test did contain some cracks and voids.

5. Results

5.1 Standard bolting with mesh installation

The field test started in April 2018 with a two day pre-training course for specific LKAB personnel with the correct handling procedures for the resin used in the trial. Delivery and commissioning of the machine was done between 2nd May and 6th June 2018. During this period there were some issues associated with the resin mixer flushing system hence only 129 bolts were installed during this period. Once the issues were resolved the main field test period lasted from 7th June to 29th August with some 1155 bolts installed. Note that a vacation period existed between 18th July and 14th August with the machine standing still during this time.

The measurement of productivity during the field test was calculated as the number of bolts installed as per the total work time spent on the machine at the face. This method therefore included all other activities surrounding the bolting application (tramming between rows of bolts, set-up and pack-up, bolting, mesh handling, reloading the magazine etc). In Figure 15. the face time and the total installed bolts are presented together with the calculated work capacity in bolts per hour. During the field test, the machine was only in operation during the 8 hour day shift. The test period was too short to accurately define logistic delay times, longer term maintenance requirements and total utilisation that traditionally reduce the long term capacity of a bolting rig. However, the high maintenance time and cleaning time that is associated with cement grouting can be assumed to be significantly reduced with this new rig. Operators of the machine did comment on how much easier it was to operate the pumpable resin system in comparison with their usual cement grouting machines.

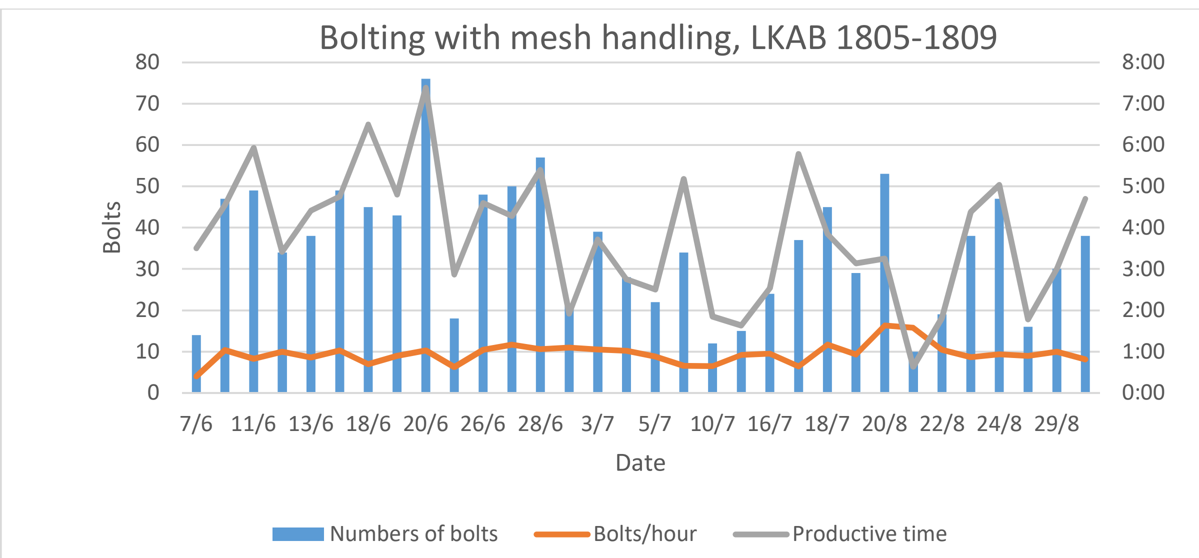

Figure 15. Productivity results achieved during the Malmberget field test

Despite the short field test period, the average bolts per hour worked achieved by the SDA and pumpable resin with mesh installation was 11 bolts per hour. This represented a 64 % improvement in productivity when compared to the existing cement grouted D-bolt installation with mesh. This result was considered very satisfactory by LKAB and the project. Especially considering that the machine was a prototype with small improvements being implemented during the test. Additionally, operators were still learning the machine during the test period. When asked, the operators of the machine both agreed that they could achieve even better results given additional time on the machine.

To check on the quality of the SDA bolt installation, an external company performed pull tests on 55 bolts in various locations. The bolts were pulled to 20 tonnes (not to failure) with all tested bolts exceeding the 20 tonne threshold requirement.

5.2 Long hole bolting

One of the standard support design used in Malmberget for bad rock conditions, is presented in Figure 16. The support is a combination of normal bolts, mesh/screens and cable bolts. Today the installation work requires two different rigs, one for bolts and mesh/screens installation and one for the installation of cable bolts. The installation of cables can be complicated, particularly in badly fractured or broken rock, and the installation of cables into the drilled hole, can be very time consuming. During the last few weeks of the field test the opportunity presented itself to try to drill longer holes with self-drilling bolts using extension rods.

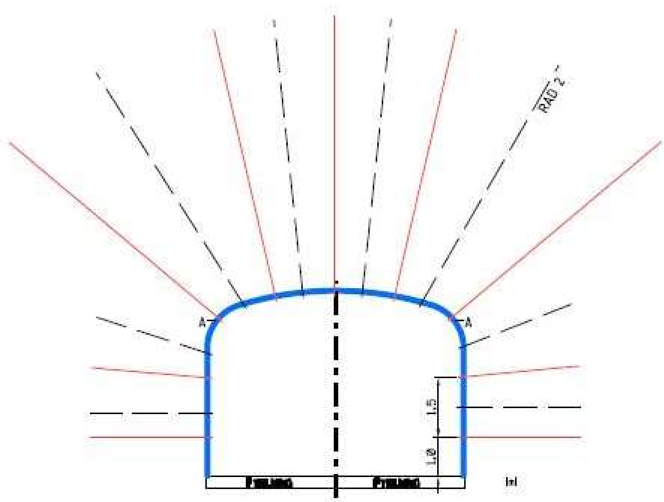

Figure 16. Combination cable bolt and rock bolt design (LKAB)

The tests were performed with 2x 6 m, 3x 9 m, 2x 12 m and 1x 15 m bolt holes – each with 3 m R28 rod sections. The hole diameters of 48 mm was found to work well, as was the practice of welding the drill bit and extension couplings to the rods to prevent accidental loosening when adding rods. A slower setting speed resin formula was used for the 9 m and 12 m bolts, with varying amounts of resin pumped into the holes. None of the holes had resin appear at the collar point, which would have indicated full encapsulation of the bolt length. Rather it was suspected that resin was being lost to cracks and/or voids in the rock mass. During drilling of the holes it was observed that the flushing water used to flush drill cuttings from the hole did disappear – a sure indication of such cracks and voids. The 9 m and 12 m bolts were subjected to a 20 tonne pull test and all passed. The 6 m bolts were successfully installed with fast setting resin as used with the standard 3 m bolt installations. For the 15 m bolt length it was decided to try with the fast setting resin as well due to the slow setting resin having run out on the previous tests. However only 2.7 L was able to be pumped into the 15 m bolt before the resin began to harden and the pumping back pressure cut-out stopped the pumping. When the 15 m bolt was pull tested it did not pass the 20 tonne limit. This was not surprising as the 2.7 L pumped into the hole was not sufficient to fill more than the internal flushing hole of the bolt – hence no anchoring bond was established at the end of the bolt hole.

Figure 17. illustrates the extension drilling configuration for the SDA bolts in the bolt magazine. Note that the extension couplings are located on the “top” side of the extension rods due to the use of the female shank adaptor on the rock drill.

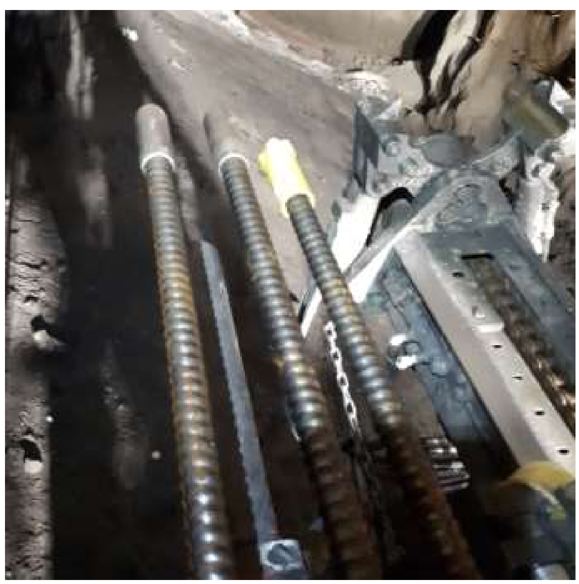

Figure 17. Extension drilling setup in the bolt magazine for a 9 m bolt (3x 3 m sections)

Fully mechanising the extension drilling and resin injection process greatly improves operator safety and productivity in poor ground conditions. The possibility to install all support with one rig is very interesting from a productivity point of view. The positive results of this test opens up new possibilities for improving both productivity and quality of rock bolt installation.

6. Conclusions

From the field test the following conclusions can be drawn:

- The bolt installation time for the SDA and pumpable resin system is comparable with installation times of resin cartridge rebar installations in good ground conditions without mesh installation. However was found to be significantly shorter than installation times of cement grouted rebar type bolt installations.
- Compared to both a resin cartridge rebar and cement grouted rebar the SDA with pumpable resin system displays reduced chances for stoppages or needs for human intervention, and as such could open the door to autonomous rock bolting applications in the future.
- In fractured and broken rock the benefits of the system increases since the SDA bolt remains in the hole, eliminating issues with bolt-hole blockages.
- The successful test with installation of long-hole self-drilling bolts opens a new important feature where long bolts (replacing cables) and mesh/screens can be installed with one rig from one setup.

Literature

[1] Irvin, C. Self-Drilling Hollow Bars: Ground Anchor, Tension Pile or Soil Nail. Deep Foundations Insititute – International Society for Micropiles, 2014