Review of quality assurance methods for hydro-powered resin bolting

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Abstract

Resin bolting in South Africa has been developed and refined in underground coal mines (i.e., soft rock) since the late 1940s. The extension of resin bolting to hard rock mines started in 2003 and has required significant adaptations, challenging the status quo from both a supplier and applicator perspective. As far as resin bolting is concerned, the most affected aspect in coal mining and hard rock mining environments, is the rock drills or machinery used for installation. Hard rock mines mostly use hand-held airlegs with limited thrust, low torque, and rotation speed, relative to coal mine mechanised bolters. Resin bolt development for hard rock mines was, and still is today, predominantly focussed on compensating for the 'shortfalls' of using hand-held airlegs.

At face value, hydro-powered rock drills, which are more powerful than traditional hand-held equipment, provided hard rock mines with a means to attain more consistent and reliable resin bolt installations. This paper assesses the quality and performance of hydro-powered resin bolting at an intermediate to deep level platinum mine in South Africa and its potential contribution to rock-related instabilities when applied erroneously. The findings of this paper necessitate a revision of current quality control and quality assurance measures related to resin bolting for underground support.

Keywords

hydro power, underground support, resin bolting, pull test, encapsulation, load transfer

Introduction

Since its earliest application in the late 1940s (Ferreira, Franklin, 2008), South Africa has developed a rich history of resin bolting in underground coal mines. From 2003, the application of resin bolting extended to other underground commodities, including the platinum mining industry. The transition to underground hard rock mines, using airleg installations in larger diameter support holes, was particularly challenging as the performance and reliability of resin bolts were tested beyond their typical benchmarks and limits. More than 20 years later, resin bolting remains one of the most researched topics in underground mine support, focused on delivering consistent and dependable support solutions.

This paper presents a practical assessment of the quality and performance of hydro powered resin bolting at an intermediate to deep-level hard rock platinum mine in South Africa.

Background

The study site is located on the northern end of the western limb of the Bushveld Igneous Complex in South Africa, operating at depths up to 2400 m below surface. Conventional drill-and-blasting techniques are used to access and extract platinum group metals from both UG2 and Merensky reef deposits. Multi-reef mining strategies are deployed with de-stressing taking place on the Merensky Reef horizon, situated approximately 20 m to 40 m above the UG2 Reef horizon. Given the relatively low middling between the UG2 and Merensky Reefs, both ore bodies are extracted using the same primary tunnel development. Both orebodies dip at approximately 20° towards the south-east.

Haulages, orientated along the strike of the ore body, are typically off reef and situated in the footwall of the UG2 Reef horizon. Crosscuts, orientated along the dip of the ore body, are broken away from haulages and are for the most part off-reef. These crosscuts are developed up to Merensky and/or UG2 reef intersections, followed by the development of on-reef raises to the level above. A layered sequence of these access ways (~63 m vertical middling) is repeated to expose the entirety of the ore body.

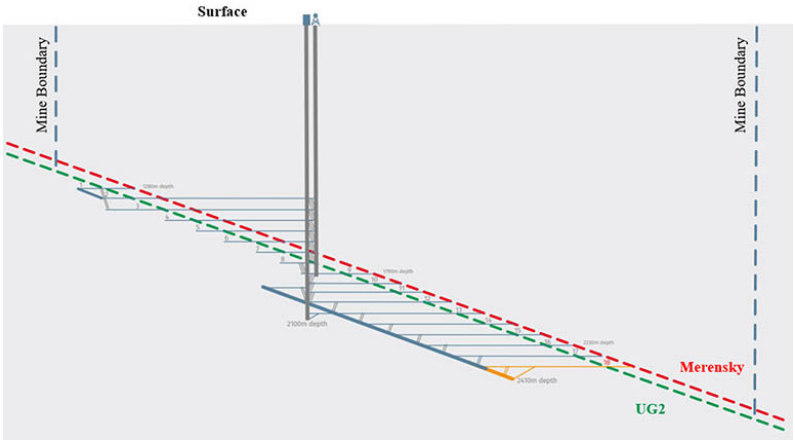


Figure 1—Dip cross-section of the case study mine

Considering the inter-level distance between haulages or crosscuts and the dip of the ore body, raise lengths up to 180 m can be effectively established, allowing for six stoping panels on each side of the raise at an average face length of 30 m.

Resin bolts are installed as primary and secondary support at the case study mine. Primary support implies that it is installed to secure the immediate stability of an excavation as it is being developed or mined, whereas secondary support is installed to secure the long-term stability of an excavation. Resin bolts, as primary support, are installed along the hangingwall of stoping centre gullies, stoping strike gullies, as well as the hangingwall and sidewalls of tunnels during development. Resin bolts, as secondary support, are installed in crosscuts and haulages where initially installed support has corroded (i.e., rehabilitation).

The case study mine experienced several rockfalls where resin bolts were installed, especially near the skin of the excavation. Once fallout has taken place and the fractured zone around the excavation has unravelled, the section of the resin bolt towards the collar of the support hole was exposed (refer to Figure 2). Of concern was that the bottom section of the resin bolts was not encapsulated in resin. In addition, most resin bolt installations were not tensioned (i.e., shear pins still intact), resin capsules were gloving inside support holes, and resin bolt installations were not centred inside support holes.

Rock mass behaviour

To better understand the role and performance of resin bolting at the mine, it was necessary to study the geotechnical environment in which the resin bolts are installed. The principle of resin bolting at the mine is a combination between suspension and rock reinforcement. Resin bolts are long enough to penetrate the natural pressure arch and densely spaced to establish an artificial pressure arch within the fractured zone around the skin of the excavation (refer to Figure 3).

Figure 2—Instabilities recorded close to the skin of the excavation, exposing the proximal end of the resin bolt

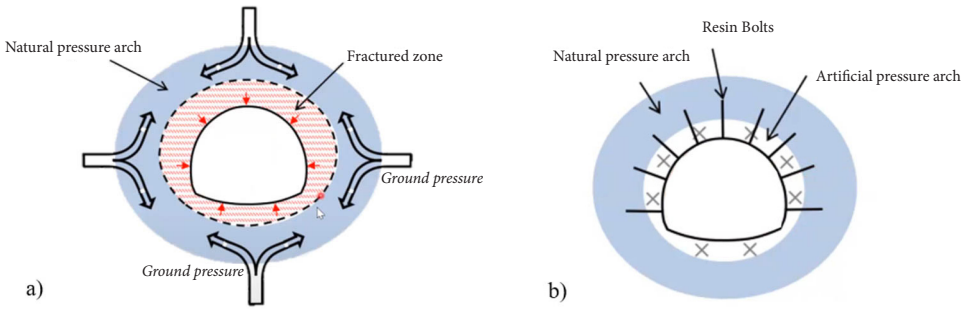


Figure 3—The principle of creating an artificial pressure arch using rock bolting (after Li, 2017)

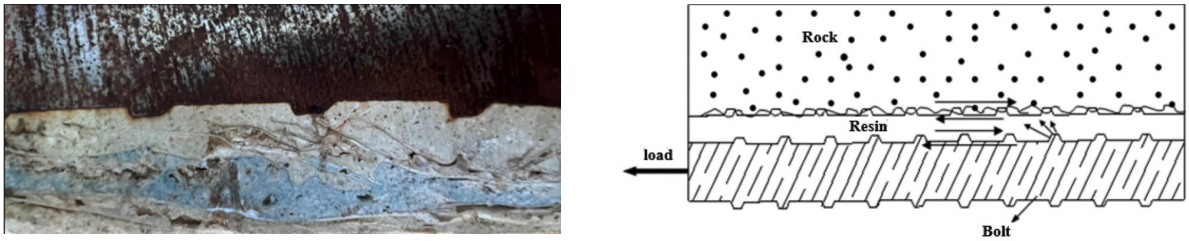


Figure 4—Partially over-cored resin bolt indicating the principle of load transfer through mechanical interlocking of surface irregularities

Figure 5—Transversal ribs are visibly still intact following unravelling of the surrounding rock mass

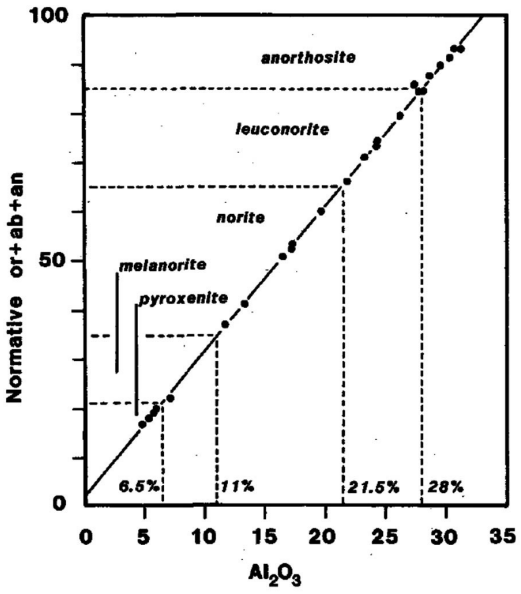


Figure 6—Terminology adopted for orthopyroxene-plagioclase rocks (after Eales et al., 1988)

During rock movement, predominantly from the fractured zone, resin bolts are dependent on the mechanical interlocking of surface irregularities between the resin, the bar, and the rock to successfully transfer load (refer to Figure 4). Load is transferred from the unstable or fractured rock mass to the resin bolt and then into the stable ground.

Load transfer capabilities are particularly inhibited when rock movement is not laterally constrained, e.g., when unravelling ensues following an initial rockfall, with little to no interlocking taking place between the surface irregularities of the resin, bar, and rock (see Figure 5).

Haulages are predominantly situated in norite, which is a type of igneous rock (layered intrusion), composed of plagioclase feldspar and pyroxene. This rock type has a uniaxial compressive strength ranging between 124 MPa and 173 MPa (Vogler, 1990). Uncontrolled rock falls in these areas are rare, despite challenges related to the installation quality of resin bolts.

Crosscut breakaways are also situated in norite, however, the tunnel transitions through different classes of norite as it develops up to the UG1 reef marker. The mine has different distinctions or field terms for norite depending on its content ratio and distribution of pyroxene to plagioclase feldspar (refer to Figure 6). The transition from norite to leuconorite is distinguished by feldspar distributed in a network of lighter colour veins, commonly referred to as 'Streepies' norite (shown in Figure 7). The transition from leuconorite to anorthosite is abrupt with distinct contacts.

Norite, supported by a strong network of plagioclase feldspar, is known to be prone to rock bursting due to its higher stiffness (Malki et al., 2024). To this end, rock drill operators have reported localised strain bursting at tunnel faces when 'Streepies' norite, leuconorite and anorthosite are exposed. The strain bursts are not severe, and no instances of typical rockburst damage have been recorded, however, strain bursting is followed by a notable regression in the condition of the excavation rock walls (comparing Figure 8 and Figure 9). Densely spaced fractures develop in the tunnel hangingwall, and when it is inadequately supported, especially close to the skin of the excavation, it can lead to fallout. Initially, potentially high

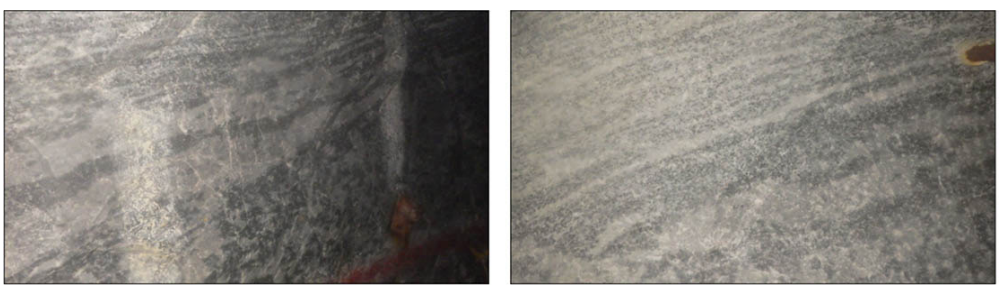


Figure 7—Plagioclase feldspar veins

Figure 8—Good and competent hangingwall – crosscut situated in mela norite

Figure 9—Densely fractured hangingwall – crosscut situated in 'Streepies' norite

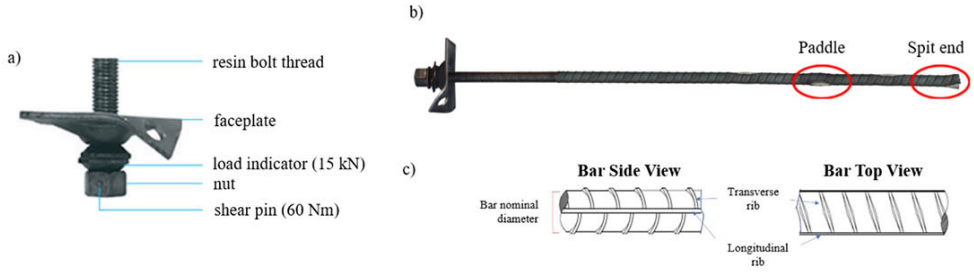


Figure 10—(a, b) Schematic of the proximal and distal ends of the resin bolt with (c) transverse and longitudinal ribs

horizontal stresses were considered as a contributing factor as fracturing was predominantly along the hangingwall of the tunnel, such as gothic arching described by Johnson et al. (2009), however, the effects were too localised and unaffected by regional mining abutments or major geological structures. It is rather suggested that the natural fracture initiation and propagation surrounding tunnels are adversely affected by the abundance of plagioclase feldspar. Rock masses dominated by plagioclase feldspar exhibit brittle behaviour, fracturing quasi-dynamically at depth and causing micro seismicity as fracturing propagates. At shallower depths, fracturing of these rocks occur over an extended period (quasi-statically), and its manifestation is curbed by the timeous installation of support (Nyungu et al., 2014).

Underground observations indicated that crosscuts broken away in a south-easterly direction experienced more ground control difficulties transitioning through 'Streepies' norite, leuconorite, and anorthosite than crosscuts broken away in a south-westerly direction. This phenomenon was attributed to stress-induced anisotropy considering that major and minor principal stresses (σ_1 and σ_3) act on crosscuts broken away in a south-easterly direction, whereas major and intermediate principal stresses (σ_1 and σ_2) act on crosscuts broken away in a south-westerly direction.

Actual underground observations provided valuable insights into the rock mass' behaviour and understanding the perceived underperformance of resin bolt installations.

Hydro powered resin bolting

There are several factors that can contribute to the under-performance of resin bolts. In 2005, Canbulat et al. tabled extensive quality control guidelines for underground resin bolting. This paper will focus on direct controllables impacting the performance of resin bolting at the case study mine.

Rock bolt parameters

Resin bolts or bars were originally produced according to SABS 920, now SANS 920:2011, which is still the national specification covering the physical and mechanical requirements for steel bars used in concrete reinforcement. As resin bolting became more prominent in underground mining support, mainstream manufacturing companies started developing improved resin bars in partnership with steel mills for more repeatable and consistent underground resin bolt installations. The latest version of SANS 920:2011 Edition 2.3 was released in 2022. SANS 1408 was also revised in 2019, stipulating the requirements and testing methods for resin bolt components.

The nominal diameter of a resin bolt used at the case study mine is 20 mm. It has a uniform and continuous rib that is parallel to the long axis of the bar (i.e., longitudinal rib) with several ribs across the long axis of the bar (i.e., transverse ribs), as indicated in Figure 10c. The ribs are geometrically controlled and designed to aid in the mixing of resin capsules, subsequently enhancing the load transfer capabilities of resin bolt installations.

The resin bolt has a modified section or paddle set, 40 cm long, situated at the distal end of the bar (refer to Figure 10b). The paddle set consists of three deformities, where the bar was pinched or compressed perpendicularly to the long axis of the bar, to effectively

Table 1

Resin capsule specifications

Property	Resin A	Resin B
Colour	Blue	Yellow
Capsule length	900 mm	900 mm
Capsule diameter	32 mm	32 mm
Resin mastic content	80,1%	80,5%
Pipeline viscosity	283 N	432 N
Set time	90 sec	280 sec
Punch shear strength	>23 MPa	>19 MPa

increase its diameter. Also situated at the distal end of the bar was an open split end. The bolt diameter at these modifications is 24 mm.

The resin bar has an ultimate tensile strength of 195 kN and a yield load in the range of 150 kN. The physical and mechanical properties of the bar are comparable to what is generally used in the rest of the South African mining industry.

Resin parameters

Resin cartridges or capsules are made up of two parts, that being resin and catalyst, separated by a thin plastic film. When a rock bolt is inserted and spun into a support hole, the plastic film is torn, and the two components mix, causing a chemical reaction and curing the resin mastic within a predetermined period. After curing has taken place, the resin is usually more rigid than the surrounding rock mass.

The case study mine utilises two different resin capsules for each support hole. Firstly, a blue resin capsule ('Resin A') is inserted into a support hole, followed by a yellow resin capsule ('Resin B').

Resin capsules are contained in water-resistant packaging and typically stored in humid conditions with temperatures up to 32 °C. Little consideration is given to the storage temperature and subsequent shelf life at the mine (refer to SANS 1534:2018), however, this does not imply that the resin capsules are not usable.

Rock drill parameters

Hydro-powered equipment was not commercially available when the mine started narrow tabular stoping in the late 1990s (Kendall et al., 2000). In partnership with the Chamber of Mines Research Organisation, the mine started to develop and adjust equipment

Sulzer Hydromining NG Rock Drill
- 160 - 260 Rotation Speed (Unloaded)
- 90 - 130 Rotation Speed (Loaded)
- 60 N.m Torque
- 180 N.m Stall Torque
- 1078 N to 1666 N Thrust Force

Novatek MK 5 Rock Drill
- 150 – 200 Rotation Speed (Unloaded)
- 90- 120 Rotation Speed (Loaded)
- 60 -100 N.m Torque
- 200 N.m Stall Torque
- 1000 N to 2000 N Thrust Force

Figure 11—Comparison between the Novatek and Sulzer hydro power rock drills

to cater for the water powered system (i.e., hydro power). The primary benefit of the cooled water system was its ability to reduce the heat in underground workings as the geothermal gradient of the Bushveld Complex was higher than other deep level mines in the Witwatersrand Basin (Fraser, 2010). However, hydro power also provided the operation with the means to improve drilling efficiencies and productivity, which has indirectly benefitted resin bolt installations. The principle of hydro power, as far as drilling is concerned, is delivering more power to a rock drill in a pipe or hose than what is possible with compressed air (higher pressure).

The loaded rotation speed of the rock drill was measured during the spinning process using a tachometer (refer to Figure 12). When a rock drill is loaded, frictional forces resist the free and synchronous rotation of the spinning adapter. In practise, rotation speeds decreased by up to 50% from the specified unloaded rotation speeds.

Installation process

The installation process outlined in the following is based on the mine's safe operating procedure and over inspection/verification of actual installation practices (work-as-prescribed versus work-as-imagined versus work-as-done):

- Entry examination and safe declaration (including the application of a Trigger Action Response Plan) is conducted before any work takes place.
- Once the area has been dressed and declared safe, temporary support (e.g., mechanical jacks) and areal support (e.g., safety netting or mesh sheets) are installed.

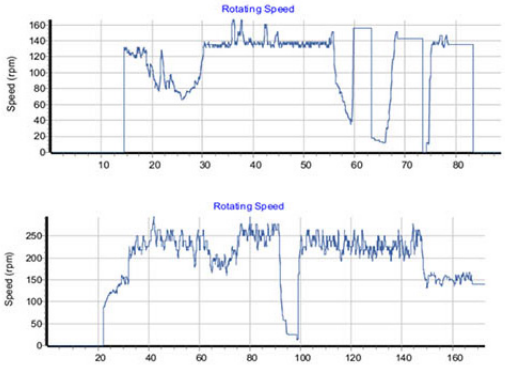


Figure 12—Unloaded and loaded rotation speeds

- From a safe and supported position, the responsible competent person demarcates the position where resin bolts need to be installed.
- Support holes are drilled to their required length, not less than 70º to excavation rock surfaces. All support holes are drilled under the cover of areal support.
- As soon as the support holes are flushed, resin capsules are inserted into the support holes. The quick set (i.e., blue cartridge) capsule is inserted, followed by the slow set (i.e., yellow cartridge) capsule.
- To retain resin capsules inside support holes, top hats are supplied with each container or box. Operators dislike using top hats and instead use cut-offs from resin containers as a wedge at the collar of support holes.
- Once the resin capsules are secured, the resin bolt is pushed into the support hole by hand, far enough so that the bar can be placed in the rock drill's bolt tensioning socket (spinning adaptor).
- Using the rock drill, the bar is pushed further into the support hole with aid from the thrust leg, as deep as practically possible.
- The rock drill valve is completely opened allowing for maximum potential thrust and torque, mixing for at least 15 seconds. During the spinning cycle, the inner barrier sheath and outer sheath are torn by the bar, allowing both the catalyst and resin mastic to mix. The spinning process also generates heat, which aids the chemical process taking place (polymerisation). Considering the rotation speed of the rock drills, the bar will rotate between 22 and 32 times inside the support hole.
- After the spinning cycle, a hold time of 120 seconds is observed. During the holding period, the mixed resin mastic is curing to build up strength. The operator keeps the resin bolt in place with the rock drill, followed by the tensioning process, however, most installations are left un-tensioned.

Support hole length and annulus

The bond strength of resin bolts is often constrained by the relationship between the resin bolt and support hole diameter, known as the annulus (Hagan, 2003). Effective mixing of the resin is typically achieved by ensuring the resin annulus does not exceed a specified maximum limit. The intention of modifications (e.g., paddles and split-end) to the resin bar is to increase the diameter of the resin bolt over the modified section, which decreases the annulus between the bolt and rock interface. This fundamentally increases the bond strength of the installation by providing improved mixing of the resin and catalyst up to the boundary of the support hole. However, this only applies to the section of the bolt that includes modifications.

In 2019, Bierman et al. conducted a large-scale evaluation on resin bolt installations. The paper indicated that Ø 38 mm support holes were possible using Ø 34 mm drill bits, which was initially confirmed by Tadolini (1998). Many factors can impact the hole diameter, such as the condition of the rock drill, available water pressure, age and wear on the drill bit, as well as adherence to drill bit discard criteria. Similar to the findings by Bierman (2019) and Tadolini (1998), Ø 42 mm support holes were measured at the mine where Ø 38 mm drill bits were used. Geotechnical designs rarely consider this phenomenon, resulting in hole annuluses exceeding design limits and a reduction in resin encapsulation (refer to Figure 14).

The diameter and length of resin capsules inside a support hole are important because of the resin requirements for full encapsulation. Equally important is the length of support holes when they are drilled. Maepa and Zvarivadza (2017) recorded 'under- and over-' drilling of support holes during a study that was conducted in the Bushveld Complex. In the study, support holes were within 0.1 m of the designed length. Similarly, support hole lengths at the case study mine ranged between 1.7 m and 1.9 m against the designed length of 1.8 m. The deviance may not be considered extreme; however, it directly impacts the extent of resin encapsulation inside the support hole. The correct resin bar diameter and support hole diameter are critical to ensure that sufficient resin is used to form a fully bonded or full encapsulated installation.

Gloving

Resin mastic and catalyst need to be properly mixed for it to be

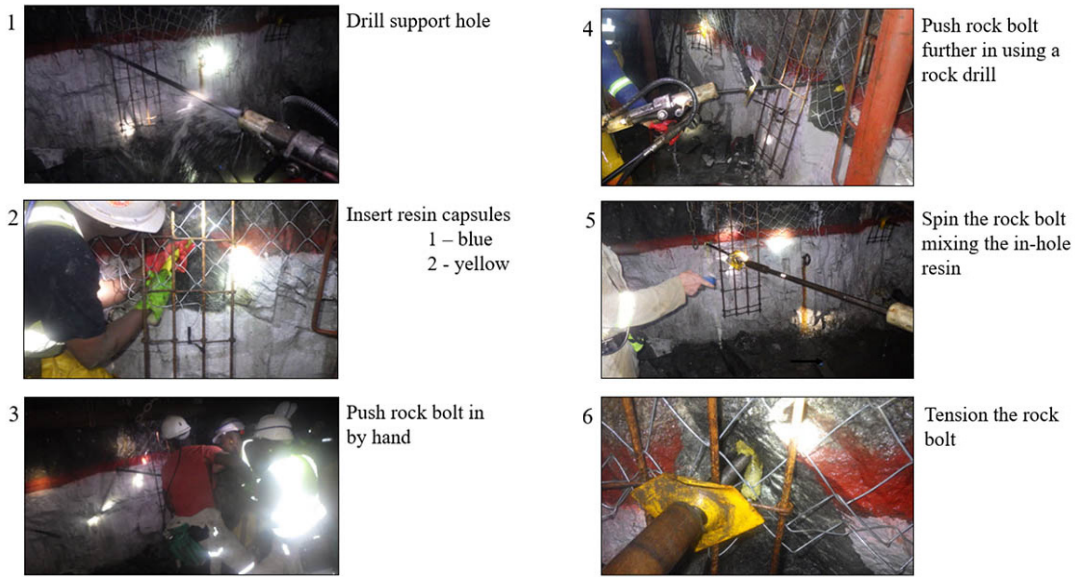
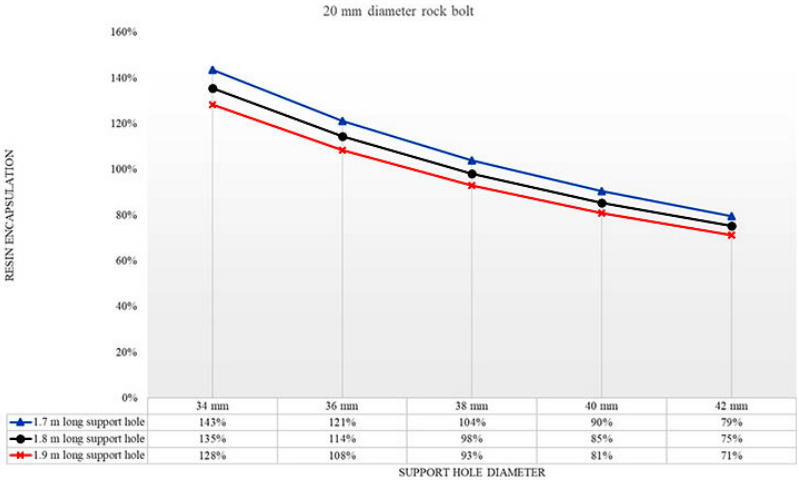


Figure 13—Simplified resin bolt installation process. A holding period of 120 seconds is observed between the mixing and tensioning processes



	34 mm	36 mm	38 mm	40 mm	42 mm
1.7 m long support hole	143%	121%	104%	90%	79%
1.8 m long support hole	135%	114%	98%	85%	75%
1.9 m long support hole	128%	108%	93%	81%	71%

Figure 14—Percentage resin encapsulation as a function of the support hole diameter and length

effective. Installations with large annuli are more prone to be compromised resulting in gloving. Gloving occurs when the resin mastic and/or catalyst film was not pierced during the spinning process, preventing the components from mixing and ultimately the resin from curing (Pastars et al, 2005).

The installation procedure of the mine dictates that resin bolts should be driven halfway into support holes before spinning takes place. In practise, another variation was found where operators drive resin bolts to the back of support holes before spinning. As a result, the mixing of the slow set capsule was questionable, considering that the modified resin bolts used at the mine only had one set of paddles at the distal end of the bar (last 40 cm). In principle, the 'unmodified' portion of the 20 mm diameter bar was solely responsible for mixing the slow set resin for annuli up to 11 mm. Overspinning of resin capsules was not prevalent at the mine, however, the under-spinning of capsules did indicate a trend resulting in gloving and inadequate mixing.

During the investigation process into gloving, it was also discovered that the condition of the installation tool played an important role in the mixing of the resin capsules. When the installation tool was worn, on either side, the rock drill was unable to grip the resin bar. In these cases, the resin bolt was merely hammered into the support hole and no mixing took place, as shown in Figure 16. Visually, these defects are difficult to identify. Historical pull test data gathered from development tunnels indicated that significant gloving led to a reduction in bond strength, with pullout loads as low as 57% of their designed strength.

Annulus is typically not a concern at underground coal mines as these operations are accustomed to using small diameter drill bits (Campbell et al., 2004). However, for many underground hard rock mines using conventional equipment, an additional set of drill bits is required. This inadvertently introduces a safety risk as human behaviour (i.e., discipline) directly impacts the reliability and performance of the support system.

Centralisation

Crompton and Sheppard (2019) reported that the centralisation of a resin bolt inside a support hole encouraged the consistent mixing of resin, maximised the corrosion protection provided by resin, and

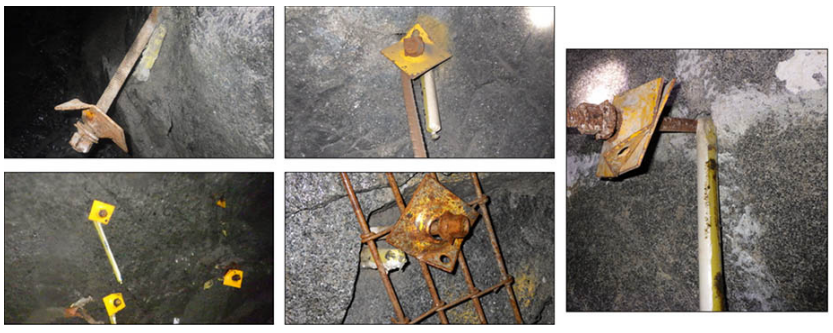


Figure 15—Gloving resin bolt installations

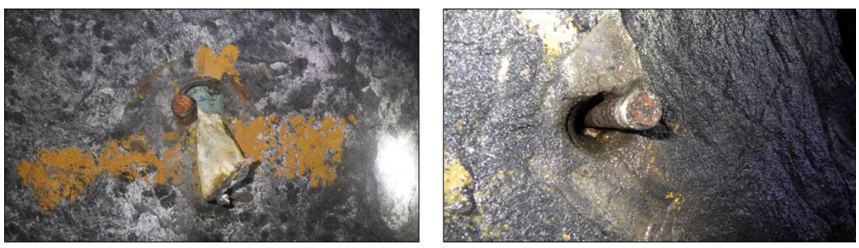


Figure 16—Wear and tear on both ends of the installation tool

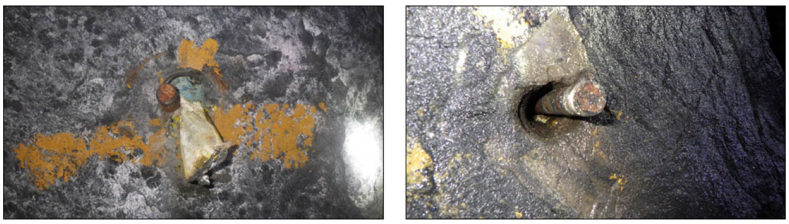


Figure 17—Off-centre resin bolt installations

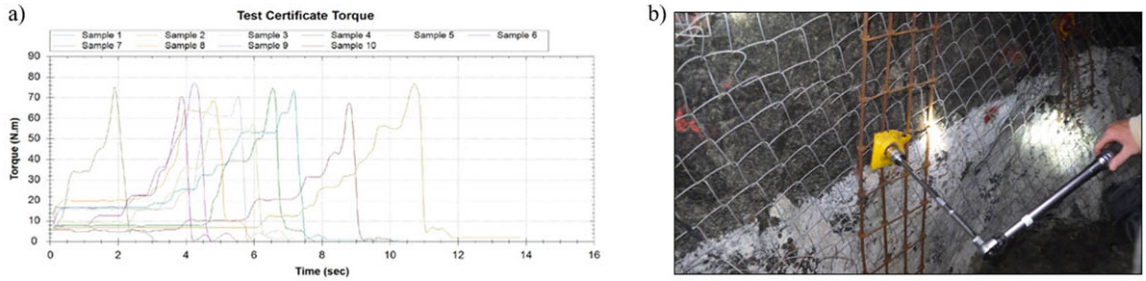


Figure 18—(a) Torque – time performance of shear pins, and (b) a torque wrench used to determine the load at which the shear pins break

ensured the even distribution of stresses during tensile loading. Resin bolt installations that were off-centre had an increased likelihood of gloving, unmixed resin, and voids. Numerous resin bolt installations at the case study mine were off-centre to the critical determinant of support capacity (see Figure 17).

Shear pin

Shear pins connect the rotating nut and bar at their threaded end. These pins are mechanically designed to break when a predetermined force/load is exceeded. The case study mine utilises a 4.5 mm shear pin that fails between 60 kN and 90 kN, illustrating that the resin inside the support hole has cured and that the tensioning process has been initiated.

Spanner tests were conducted on underground installations to verify that the shear pins in the nuts failed at their designed torque (refer to Figure 18b). A total of 40 tests were conducted, 20 tests on 30-day old installations and an additional 20 tests on the same day of installation. Shear pins on 30-day old installations failed at an average torque of 118 N.m (standard deviation of 15 N.m), whereas shear pins tested on the same day of installation failed at an average torque of 73 N.m (standard deviation of 5 N.m). It is believed that corrosion may have contributed to the increase in failure load of shear pins on the 30-day old installations.

Load indicator

Load indicator washers have been around since the early 1960s. These washers are situated between the nut and faceplate to visually represent the clamping force or preload during the tensioning process. Tensioning of resin bolts provide clamping forces into the surrounding rock mass, critical to rock reinforcement and effective skin control. The case study mine utilises a 40 mm x 2 mm load indicator that collapses at 15 kN, illustrating the tension applied between the rock bolt faceplate and nut.

Corrosiveness

The prevalence of gloving not only impacts the bond strength of resin bolt installations, but it also detrimentally affects the corrosion protection of the resin bar. Fully encapsulated resin bolts offer excellent protection from corrosion, however, poor mixing during resin bolt installations and resultant voids expose the bar to corrosive elements.

Resin bolting applications in hard rock mines tend to undervalue the importance of faceplates. Faceplates typically have smaller dimensions compared to other rock bolting applications, and based on industry practices or norms, do not require replacement or re-tensioning after the resin mastic has cured. The need to re-tension or replace faceplates is one of the most discussed topics in resin bolting. It is thought that if the resin inside a support hole is properly mixed, cured and the bar is fully encapsulated in resin, the resin bolt installation can transfer load along its entire length. Unfortunately, these underlying assumptions cannot be verified unless the resin bolt installation was personally inspected, which is not practically feasible. Observations at the case study mine strongly suggest that faceplates are a vital component for effective

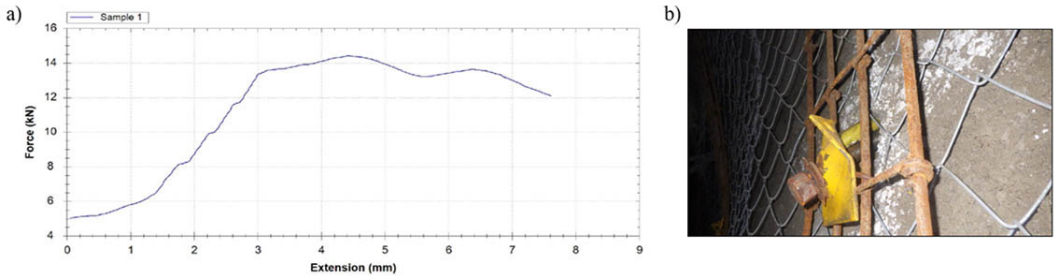


Figure 19—(a) Load – deformation graph of load indicators, and (b) a collapsed load indicator against a mesh strap

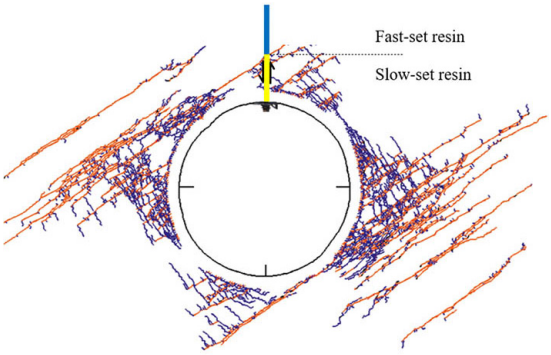


Figure 20—Simplified cross-section showing the slow set resin capsule (i.e., yellow capsule) in the fractured zone around an underground tunnel

skin control, especially in highly discontinuous rock masses. In addition, the faceplate should not be analysed in isolation, as in most cases, it forms part of a greater support system. For example, resin bolt faceplates are integral to the overall performance of the greater support system where interaction with areal support elements is prevalent, such as mesh and/or shotcrete (Gouvea, Du Plessis, 2022).

Underground testing

Rock falls recorded at the mine were predominantly close to the excavation surface. As a result, full-scale underground testing was conducted to determine the ability of resin bolts to transfer load close to the skin of the excavation.

Methodology

Based on the depth of fracturing and historical fallouts recorded at the mine, it was evident that the yellow cartridge or slow set resin capsule was situated in the 'unstable' fractured zone surrounding excavations (refer to Figure 20). It is therefore crucial that the proximal end of the resin bolt is encapsulated in resin and tensioned for effective skin control and load transfer. Underground pull testing was conducted to quantify the load transfer capabilities of resin bolts for the section of the bar encapsulated in slow set resin.

Considering that fallout heights were limited and close to the skin of the excavation, in addition to the configuration of the resin bolt favouring mixing at the distal end of the bar, there was no evidence to question the encapsulation or performance of the fast-setting resin.

Test setup and parameters

The Novatek MK5 rock drill was used to drill support holes and install resin bolts at the underground test site. The performance and specifications of the Novatek rock drill were comparable to those of the Sulzer, hence only one rock drill was used during testing. Support holes were 1.8 m long, drilled using both Ø 34 mm and Ø 38 mm drill bits.

A 900 mm x 32 mm inert resin capsule was inserted into the support hole, followed by a 900 mm x 32 mm slow set resin capsule (refer to Figure 21). Inert resin capsules are chemically inactive as their catalyst component has been removed. As a result, the bonding strength of the resin bolt installations relied entirely on the section of the bar encapsulated by slow set resin. Inert resin capsules were specially manufactured for these tests, as removing the catalyst from existing cartridges reduced their rigidity, causing them to bend or flop.

Two different installation practices were observed at the mine where resin bolts were driven halfway into support holes before spinning took place, and where resin bolts were driven to the back of support holes before spinning. In addition to these practices, a third variation was tested where resin bolts were mixed starting from the collar of the support hole (see Figure 22). The spinning cycle of 15 seconds was measured from the point at which the resin bolt came into contact with the inert resin capsule (during spinning).

Five resin bolts were installed and tested per variation. Pull testing was conducted on the installed resin bolts 24 hours after they were installed, amounting to a total of 30 tests. Pull tests were

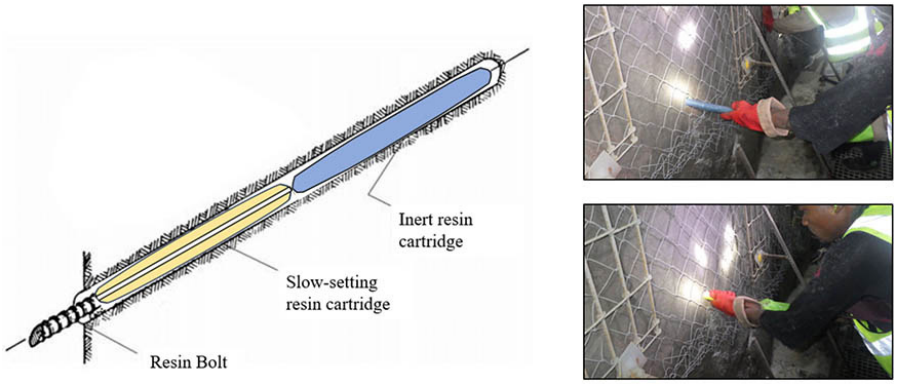


Figure 21—Resin sequence and setup during testing

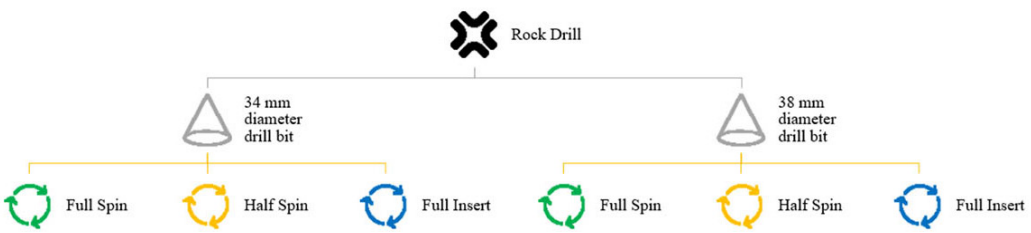


Figure 22—Testing process map

Figure 23—Underground pull testing

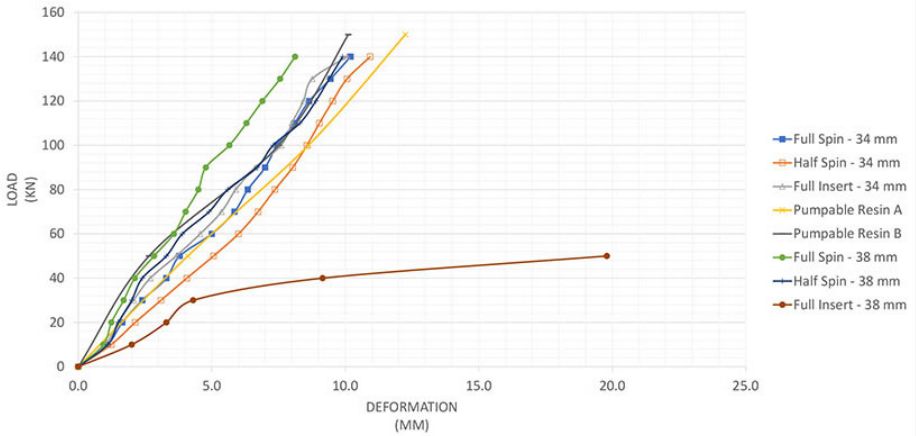


Figure 24—Load vs. displacement graph (mean of five tests per combination)

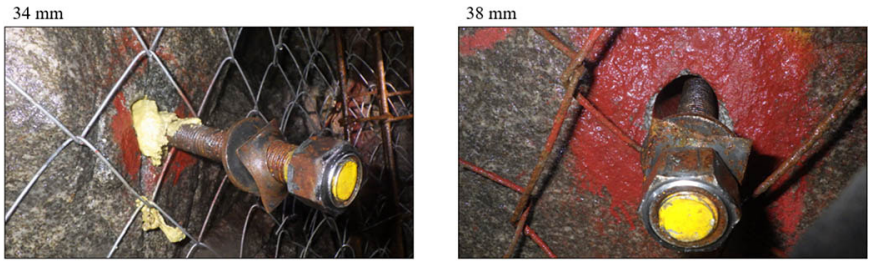


Figure 25—Resin outflow comparison between a Ø 34 mm and Ø 38 mm support hole

conducted up to 140 kN, as the resin bolt yield load was 150 kN, measuring deformation at 10 kN intervals. Measuring deformation with a vernier in this application was challenging due to the confined space between the pull test frame and the hydraulic ram.

Test results

Figure 24 shows the results of the pull tests that were conducted. 'Pumpable Resin A' and 'Pumpable Resin B' were added to the graph for comparative purposes. These two variations were tested at a deep-level gold mine using pumpable resin with similar hole annuli.

Test results indicated that the bond strength of resin bolt installations was mostly unaffected for hole annuli up to 11 mm. The only records of premature pullout were recorded where a Ø 38 mm drill bit was used, and the bar was inserted up to the back of the support hole before spinning. The stiffness of the resin bond was strikingly high for all stable results, indicating the resin's ability to prevent the opening of discontinuities.

Visually, resin was flowing from the support hole collar where a Ø 34 mm drill bit was used (see Figure 25). On average, the bottom 35 cm of the support hole towards the excavation skin was not encapsulated in resin when a Ø 38 mm drill bit was used (81% of the bar encapsulated in resin). While the effects of gloved but mixed resin inside most Ø 38 mm support holes may be minimal on bond strength, the debonded section of the resin bar close to the excavation surface offers no reinforcement or support and exposes the resin bar to possible corrosion.

Test results showed that resin bolt installations using Ø 38 mm drill bits were not fully encapsulated in resin and were therefore entirely reliant on the face plate for load transfer near the skin of the excavation. Considering that most resin bolt installations at the mine used Ø 38 mm drill bits, a comprehensive strategy is required to address the loss of load transfer capabilities and clamping in the fractured zone surrounding excavations.

Traditional pull testing, which is the primary underground quality control method for South African mines, failed to identify that resin bolt installations using Ø 38 mm drill bits were defective (i.e., not fully encapsulated in resin). This is an inherent flaw in current quality assurance systems across the country that poses a significant fall of ground risk, as evidenced by actual uncontrolled rockfalls between resin bolts at the case study mine. In its current state, defects related to encapsulation and load transfer capabilities are unfortunately only detected after a fall of ground has taken

place. Additional quality control or quality assurance measures are needed to determine the extent of resin encapsulation in a support hole to effectively identify defective resin bolt installations.

Non-destructive testing

There has been an increase in research efforts in the field of non-destructive testing to assess the encapsulation of underground resin bolts. Bačić et al. (2019) provided a useful overview of non-destructive testing methods available in the industry, indicating that rock bolt testing has taken a direction towards instrumentation with sensors. Many acoustics-based or vibration-based methods take advantage of modern sensor types such as piezoelectric sensors, optic fibres, etc. Additionally, modern signal processing tools, as well as other advanced computing systems such as neural networks, further open doors to the continuous development of non-destructive methods.

Hassell et al. (2019) conducted a series of non-destructive tests using a hammer blow to create a seismic source and a transducer to detect the resultant vibrations. These recordings were then interpreted to provide an estimate of bolt length and a qualitative assessment of encapsulation quality.

A total of 56 cable bolts and 58 solid bar bolts were tested at an underground site in Australia to validate the testing technique. The diagnosis of void spaces (regions of lack of bonding) was seen as crucial and was successfully trialled. A similar non-destructive testing method was presented by Godfrey et al. (1977). The historical testing method measured the vibration response of a rock bolt to broadband axial and/or transverse vibrations induced by striking the collar end of a rock bolt. The resonant frequencies of a partially encapsulated rock bolt were different from those of a fully encapsulated rock bolt and were interpreted to give the degree of bonding between the resin and rock bolt and the axial extent of a void.

In 2023, Staniek also reported on an experimental non-destructive method to test for the full encapsulation of rock bolt installations. The method, which uses modal analysis procedures, is based on impact excitation (i.e., impact hammer) where the natural frequency of rock bolts is compared to rock bolts installed underground. The method was successfully applied over two years, having tested 70 rock bolts with a length up to 2.5 m.

Destructive testing techniques, such as overcoring, are predominantly used in the mining industry to assess the encapsulation of resin bolts (Craig, 2012), however, these methods are relatively expensive and laborious. Notwithstanding the challenges associated with non-destructive testing techniques, it provides vital insights into the encapsulation of resin bolts.

Conclusions

The data presented in this paper illustrate the limitations that pull testing has, as the primary quality control or quality assurance testing method, to identify defective resin bolt installations. Traditional pull testing is a measure of bond strength; however, it fails to quantify or qualify resin encapsulation along the entire length of the resin bolt. Load transfer capabilities of resin bolts are primarily dictated by encapsulation and are critical to the success of a resin bolting support system. Non-destructive test methods need to supplement traditional pull testing to determine the extent of resin encapsulation and effectively identify defective resin bolt installations.

Despite the use of hydro-powered equipment, the installation quality of resin bolts was overdependent on the practices and actions of underground operators. The fundamental reliance on human behaviour to install resin bolts that are free from defects or significant variations is unfitting. Elimination, substitutive, and engineering controls (i.e., hierarchy of controls) should be considered to reduce the probability or impact of potential rock falls. The expected quality of resin bolt installations must be considered in their design to ensure robust support. The paper further signifies the importance of purposeful monitoring and over inspection of actual underground support installations (e.g., planned task observations and visible field leadership), ensuring that support products used at the mine are designed and operated in a manner that enhances health and safety (Mine Health and Safety Act, 1996).

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