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A new dynamic bolt design with improved resin mixing and high-capacity anchoring

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Abstract

Dynamic rockbolts continue as an important geotechnical requirement for deep and high-stress mining environments, with product development work progressively evolving within this technical arena. For rockbolts used as primary ground support, numerous approaches have been taken to design ground support elements that provide initial stiff anchoring and load-bearing response for static ground conditions, but further to this, are able to perform dynamically in a rockburst event where rapid load onset and associated rock mass displacements can occur within the order of milliseconds.

The fundamental requirements of a rockbolt design are to deliver secure anchoring within the rock mass, the transfer of load from the rock mass to the bolting element and to deliver the required mechanical response of the bolt element as it remains anchored within the displacing rock mass, ideally for both static and dynamic conditions. Geotechnical performance, simplicity in design and ease of installation remain primary considerations, these requirements being true of any ground support element.

Polyester resin cartridges that employ a two-component resin and catalyst format are commonly used to provide bonding and encapsulation for rockbolts installed within pre-drilled boreholes, typically providing excellent load transfer properties for the installed system. However, during rotational installation of the rockbolt, if the two components are not well mixed within the borehole, resin curing, strength and load transfer are ultimately compromised.

This paper outlines the development and validation of a new dynamic rockbolt design that addresses the fundamental requirement for well-mixed and cured cartridge resin, providing reliable anchoring and load transfer that exceeds the capacity of the bar element. Centric to this bolt design is a simplified and robust dynamic mechanism that provides repeatable performance and achieves the full mechanical energy available from the bar element during rock mass displacement. For industry reference, this new dynamic bolt design is the Sandvik 'Versamix' bolt.

Keywords: *dynamic, rockbolt, resin mixing effectiveness, load transfer, Versamix*

1 Introduction

Ground reinforcement requirements continue to evolve within the underground hard rock mining industry, given the ever-increasing geotechnical demands that arise in the pursuit of mining at greater depth. Many mines now operate at depths well in excess of 1,000 m and the associated stresses in the rock mass increase correspondingly (Bartlett 2010). As stresses are redistributed within the rock mass, rockburst events can occur to varying degrees of severity, in which ground support elements are subjected to rapid loading (Morissette et al. 2014). The ability for ground support elements to be able to absorb these loading scenarios is a continued area of research and development – and dynamic rockbolts form a significant aspect of this field (Thompson et al. 2004; Player 2012).

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Several dynamic mechanisms are used within rockbolt designs that are well known to the industry. These typically involve an elongating or a displacing mechanism of some form, while ideally holding a sustained, elevated load during displacement of the rock mass and providing a stiff response to the initial onset of load. The mechanism that carries the greatest load-bearing response and dynamic capability is utilisation of the energy of deformation of the bar element itself, achieving sustained loads ideally at displacements that are appropriate within the context of rock mass movements (Villaescusa et al. 2023).

Anchoring of the rockbolt into the ground is of fundamental importance. The rockbolt will only work to the load transfer capacity of the anchoring mechanism – if the anchoring mechanism fails, the rockbolt will slip under the onset of ground loads and the full dynamic capacity available from the bolt element will not be achieved. Therefore, it is of critical importance that the ground support element and the anchoring mechanism are considered as a cooperative working system (Gibbons & Lee 2019). Two-component polyester resin cartridges are commonly used for the encapsulation and anchoring of rockbolt installations and are known to provide very high levels of load transfer into the rock mass, if installed and mixed correctly (McTyer et al. 2014).

For resin-anchored dynamic rockbolts, to permit the bar element to elongate, the region of elongation must be decoupled from the rock mass and the corresponding encapsulation media (Villaescusa et al. 2023). For dynamic bolts that are based on the use of ribbed bar or thread bar profiles, the surface geometry of the bar must be decoupled from the encapsulation media and this is typically achieved by using a tubular debonding sleeve to cover the elongating portion of the bar element. However, debonding sleeves are subsequently an additional component in the bolt design that can also be at risk of damage during underground installation.

An alternative arrangement for a resin-anchored dynamic bolt design is to use smooth round bar that has an inherent decoupling effect from the encapsulation media. However, to ensure effective resin mixing and anchoring of the bolt, additional geometric features need to be added back into the smooth round bolt element. This requirement is often addressed with the use of 'anchor' deformations that are cold-worked into the smooth bar (Li & Charette 2010). These anchor deformations are also commonly referred to as 'paddles' (Knox & Hadjigeorgiou 2022; Venter & Knox 2023). However, concerns exist regarding the resin mixing effectiveness of such anchor deformations, particularly within the context of comparatively large annulus bore hole diameters and variability in bolt installation parameters – specifically rotational speed and feed rate. Various anchor sequences have been provided that seek to ameliorate this resin mixing and anchoring problem; however, a more repeatable and reliable solution is required.

2 Design overview

2.1 Design objectives

The design objective was to create a resin-anchored dynamic bolt that is robust for underground application, can be readily installed using standard practices and achieves excellent resin mixing and anchoring capabilities within routine run of mine use. Rigid anchoring into the rock mass was viewed as a critical requirement, to ensure full load transfer between the rock mass and the bolt element for both static and dynamic applications. The bolt design was specified to provide a static load-bearing capacity that exceeds 200 kN and a dynamic energy capacity of the order of 50 kJ at 200 mm of elongation. A further objective was to design a robust 'steel-only' bolt, eliminating the use of non-steel materials.

2.2 Bolt features and layout

A dynamic elongation mechanism is required within the central portion of the bolt design – and to simplify the solution, the entire bolt design is based on the use of a smooth round bar profile, removing the need for a debonding sleeve and avoiding the use of more complex dynamic mechanisms. Given the smooth round bar profile, further geometric features, such as paddles, need to be added into the bolt design for resin mixing and anchoring. However, such paddles on their own do not provide high levels of resin mixing effectiveness. Helical spring wire elements are known to enhance resin mixing capabilities. By combining paddling deformations and resin mixing springwires in the correct sequence, a design solution is determined that provides strong nodes of load transfer into well-mixed and cured resin. Note that there are two anchoring regions in the bolt design – an upper distal and a lower proximal region. The design of the bolt is shown in Figure 1.

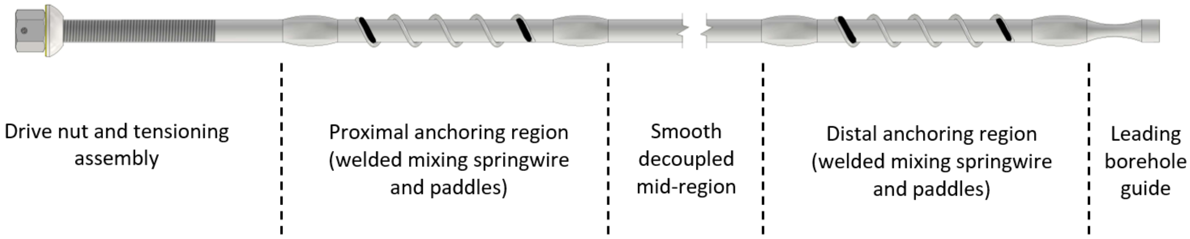


Figure 1 Key features of the Versamix bolt design

2.3 Materials selection: bar element

A steel grade was specifically developed for the bar element to address a number of design and performance requirements. A 21.7 mm bar diameter was selected to match the provision of a standard M24x3 male threadform. Further to this, the combination of the material grade and cross-sectional area achieves typical tensile strengths of 254 kN and standard elongation values of 22%. The steel grade also permits paddling deformations to be formed without fracture, as well as having suitable steel chemistry properties for welding of the mixing springwires.

2.4 Paddle design

The combination and location of paddle deformations are specifically designed to work in cooperation with the springwire elements. The paddles provide nodes of load transfer within the resin encapsulation media but also cooperate with the springwires to create a highly rigid, localised anchoring mechanism. The paddles and springwires are also sized to operate within a 35–38 mm drilled borehole, providing improved centralisation of the bolt within the resin annulus at the anchoring regions. During insertion of the bolt, the paddles further act as a progressive guide into the borehole, avoiding any catching of the springwires with the borehole collar or surrounding mesh. An additional paddle is also used at the leading end of the bolt to provide space for the upwards accumulation of plastic film from the resin cartridge.

2.5 Mixing element design

Using a combination of left-handed bolt rotation and thrust during installation, the springwire resin mixing elements are sized to thoroughly mix a 30 mm diameter, two-component resin cartridge, through the full column of the borehole. This ensures that the catalyst is well mixed with the mastic portion of the resin, increasing the volumetric completeness and speed of the chemical reaction – and the final cured strength of the resin. The springwires are wound in a right-handed orientation so that under left-handed rotation of the bolt, the resin is pumped forward into the borehole, creating backpressure that further enhances mixing turbulence. This forward pumping action also assists in gathering the plastic film from the resin cartridge towards the top of the borehole, reducing the risk of gloving around the anchoring regions of the bolt design.

The upper distal springwire progressively mixes the resin cartridge as the bolt rotates and advances through the borehole. The lower proximal springwire, upon entering the borehole, also captures the pre-mixed resin and pumps it forward to reduce the loss of mixed resin from the borehole and improve encapsulation of the lower region of the bolt. The upper and lower springwires both cooperate with their respective paddles to form localised, highly rigid anchoring regions within the well-reacted and cured resin.

2.6 Drive nut

The bolt design includes a standard drive nut and shear pin combination, enabling the transmission of torque for left-handed rotation of the bolt through the resin column. Upon reaching the back of the borehole, bolt rotation is ceased, permitting final curing of the mixed resin. Following the completion of a curing hold time, rotation is again engaged to over-torque and shear the pin, subsequently advancing the nut along the thread to pre-tension and secure the surface plates. The design also includes a standard ball washer and anti-friction washer to facilitate the seating and enhanced tensioning of the surface plates.

3 Laboratory validation

3.1 Bar element: mechanical testing

Baseline mechanical properties tests were conducted by the steel manufacturer on the specialty grade, returning typical mechanical properties of 207 kN yield strength, 254 kN tensile strength and 22% elongation. These mechanical properties fell within the targeted design range for the performance of the bolt. Further to this, a quasi-static tensile test was conducted across a 1.4 m free length of the bar element, this free length being the same as the decoupled length in the mid-portion of a 2.4 m bolt. This test returned a peak tensile value of 246 kN and elongation of 206 mm prior to rupture (refer to Figure 2, quasi-static result). Note that this particular series of mechanical test results were all conducted in laboratory conditions at slow quasi-static loading rates.

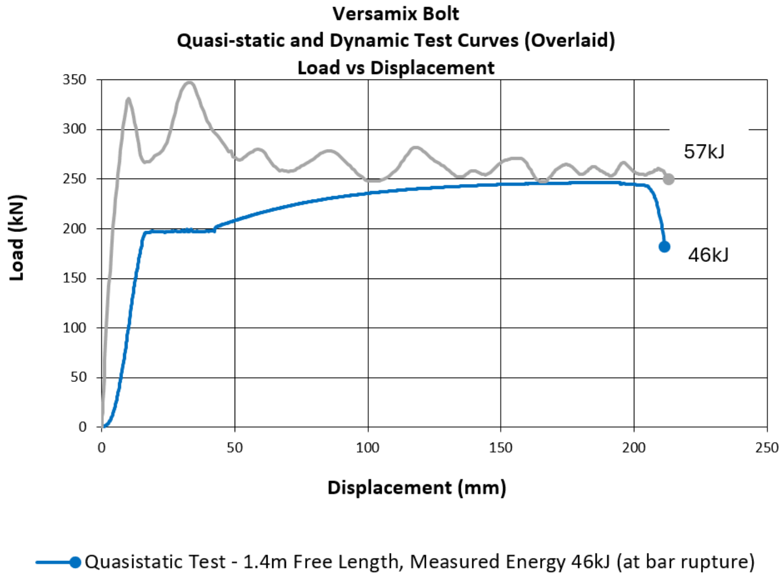


Figure 2 Example quasi-static and dynamic test curves for the Versamix 1.4 m decoupled region

3.2 Weldability: mechanical testing

The steel chemistry of the bar element is selected for excellent weldability properties. Each end of the upper and lower springwires is welded to the bar element adjacent to the corresponding paddles – that is, four welds in total. The specification of this weld is tightly controlled to ensure correct weld penetration and strength. A total of 18 axial tensile tests were conducted with all test pieces passing successfully, confirming that the weld does not affect the tensile properties of the bar element in this region. Ultimate fracture of the bar element occurred away from the welded zone, as exhibited by the post-test samples shown in Figure 3.

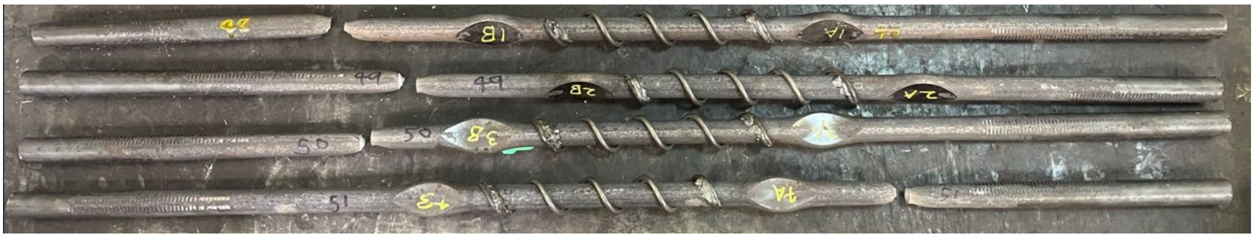


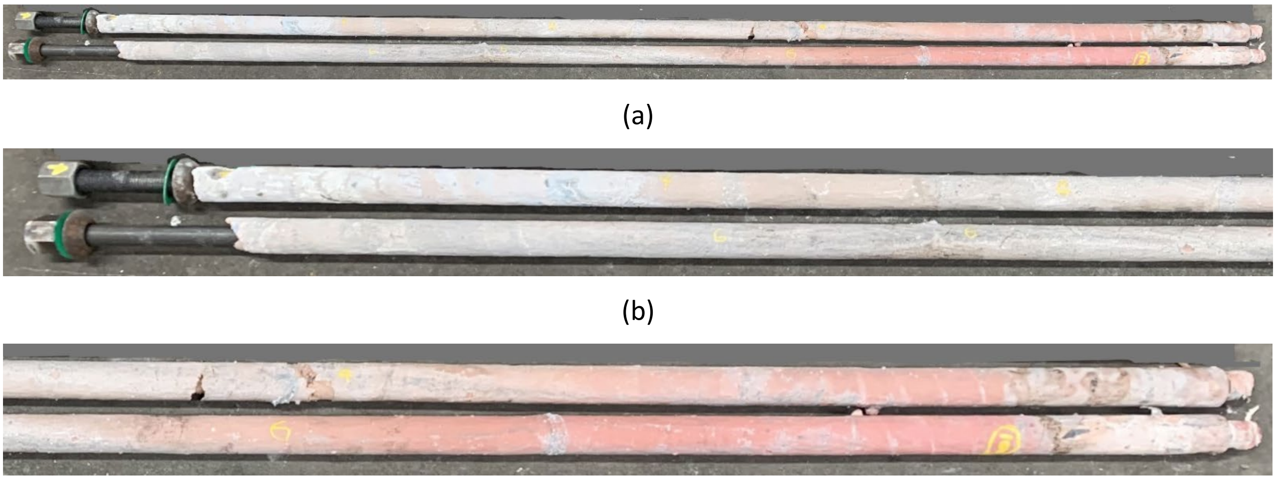
Figure 3 Post-test specimens from axial tensile tests loaded across the welded springwire and paddle regions

3.3 Paddle element: mechanical testing

Tooling was established to ensure repeatable dimensional forming of the paddle elements. The geometry of the paddle element is critical for load transfer within the cured resin, but also for the transmission of axial stresses across the paddle element without compromising the ultimate strength of the bar. Numerous tensile tests were performed across the paddle element, with rupture of the bar occurring away from the paddled region. It is to be noted that cold-forming of the paddle will metallurgically work-harden this region of the bar – hence rupture of the bar under axial load occurs away from the paddled region. Figure 3 shows test samples of the welded spring wire and adjacent paddles following axial loading through to rupture of the bar, with all 18 test pieces passing successfully (i.e. no fracture in the paddled elements).

3.4 Resin mixing validation

A vertical drill-rig test facility was used to install bolts of 2.4 m in length into grouted test pipes having a pre-drilled bore hole of 37 mm. The selected resin for these tests was a 30 mm diameter, 2.4m long two-speed cartridge resin. Installation was conducted under left-handed rotational speeds of 200 rpm. Installation time to the full depth of the bore hole was typically 20 seconds, with a further 4 seconds of rotation at the back of the hole. The test pipes were subsequently sectioned along the full axial length to reveal the annulus of mixed resin around each bolt. Resin was observed to be well mixed and fully cured through the full column of the borehole. Plastic film from the resin cartridge was gathered by the pumping action of the springwire towards the top of the bolt. The bolts were also observed to be well centralised within the borehole by the springwires. Figures 4a–c show the axial section and encapsulated bolt extraction from two installations.



(a)

(b)

(c)

Figure 4 Two resin-encapsulated Versamix bolts. (a) View of full bolt lengths; (b) Corresponding view of lower bolt regions; (c) Corresponding view of upper bolt regions

3.5 Point anchor tests

Given that the bolt design is for dynamic applications, anchoring is a critical requirement for the regions of load transfer. A series of point anchor tests were conducted to evaluate the load transfer performance of the upper region of the bolt. Bolts were installed under the parameters described in Section 3.4, but with the use of a half-length resin cartridge, 1.2 m in length. This installation method encapsulated the upper region of the bolt, but left a free length at the tail to enable laboratory pull testing to be conducted within a universal test machine. Subsequent tests loaded the bolt to rupture of the bar element. The test pipes were then axially sectioned for inspection, with no measurable slippage of the upper anchoring region. Figure 5 shows the sectioned test pipes and ruptured free lengths at the tail of the bolt.

Figure 5 Point anchored bolts, following axial loading and subsequent sectioning

3.6 Dynamic testing

A series of dynamic tests was conducted across a total of 9 bolts, using the split-pipe momentum transfer methodology (Evans 2024). The bolts were 2.4 m in total length and were of the format described above in Section 2 and Figure 1, having a 1.4 m decoupled region in the mid-portion of the bar. Energy input levels were progressively increased across the dynamic test series, with a peak stable result being achieved at 54.18 kJ and 202 mm of displacement at the mid-point discontinuity (the test pipe split). Figure 6 shows an example of a high-speed image from dynamic testing, at the point of bar rupture. Referring again to Figure 2, an example test curve from the dynamic test program is included. Figure 7 provides a summary chart of the 9 dynamic test results, each individual test shown as a data point on the chart, with stable tests shown in solid green and bar rupture tests shown in orange. Following the dynamic tests, test pipes were axially sectioned as shown in Figure 8, visibly revealing well-mixed and cured resin, with no measurable slippage of the anchoring region of the bolt. Overall, the dynamic test program returned highly successful and repeatable performance results, bringing the overall laboratory validation program to completion.

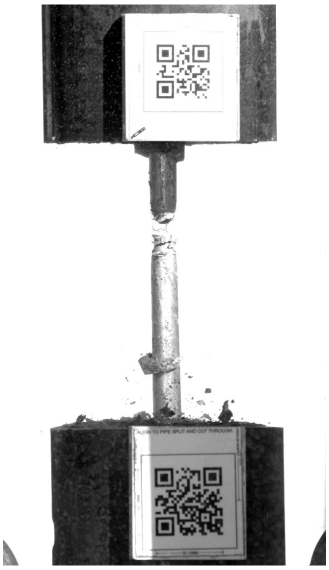


Figure 6 A high-speed image example from dynamic testing, taken at the point of bar rupture

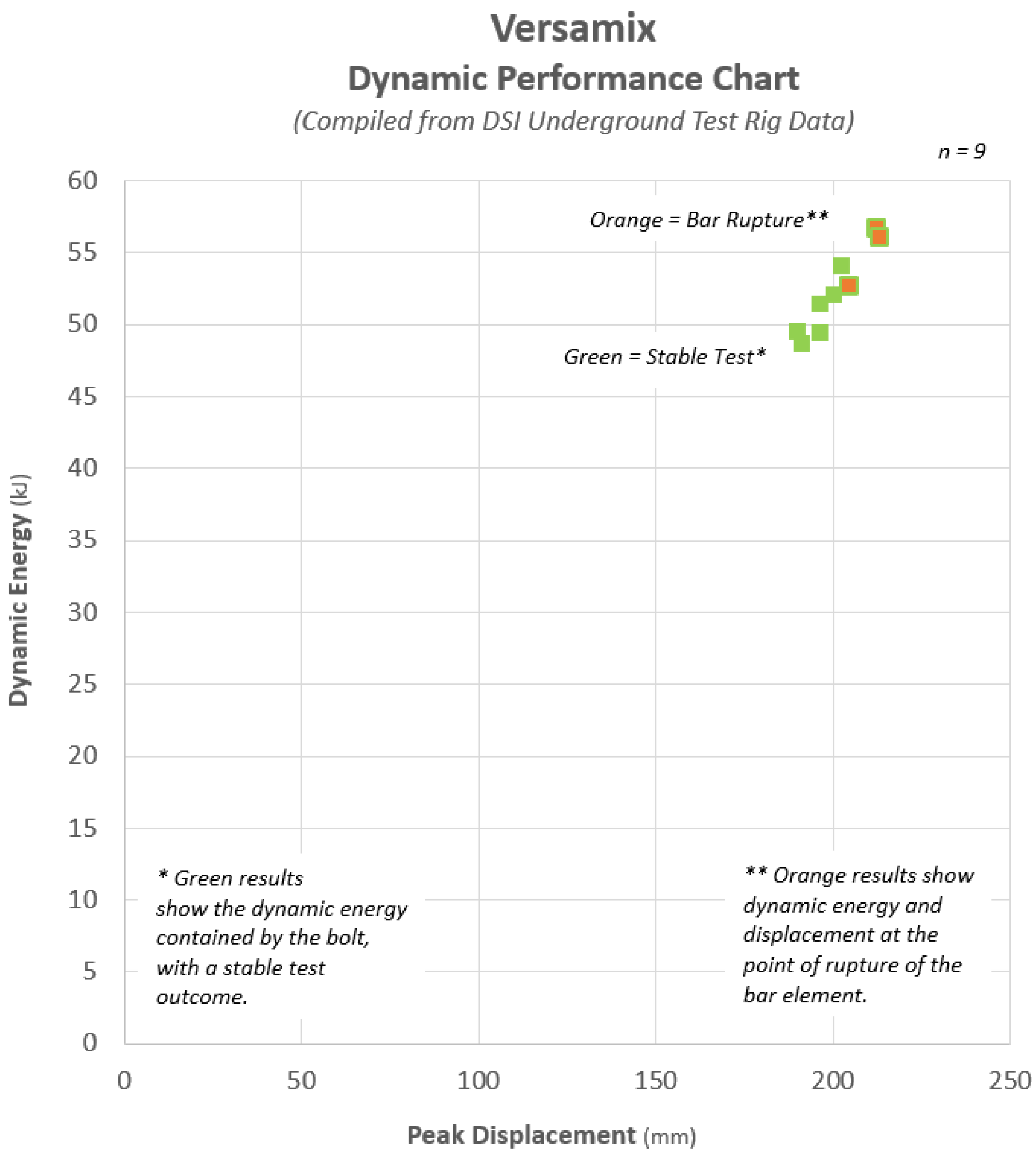


Figure 7 Dynamic performance summary chart for 2.4 m Versamix bolts, 9 tests in total

Figure 8 Example of sectioned dynamic test pipe

4 Underground trials

Installation trials were conducted at two Australian underground hard rock mines (sites undisclosed). A total of 35 bolts (thirty 2.4 m bolts and five 2.7 m bolts) were installed across the two sites, using a nominal 36 mm borehole. Of these, 10 bolts were installed for the purpose of short-encapsulation pull testing, using a single 30 mm × 1.2 m resin cartridge at the back of the borehole to point anchor the distal end of the bolt only. The remaining 25 bolts were installed with a typical twin resin cartridge system, 30 mm in diameter and of sufficient length to fully encapsulate the bolt. The borehole depth was drilled 0.1 m shorter than the respective bolt length. Typical bolt installations from these trials are shown in Figures 9 and 10.

Bolt installations were conducted under combined left-handed rotation and thrust at an estimated 200 rpm and timed at 20 seconds to reach the back of the borehole, with a further 4 seconds of rotational mixing while at the back of the borehole. A typical hold time of 20 seconds was further employed, prior to breaking out the drive nut and tensioning the plate. The installations all exhibited positive back pressure during advancement of the bolt, indicating effective mixing of the resin cartridge by the combined springwire and paddle elements in the bolt design. It should be noted that the employed hold time may be conservative, given the positive impact of thorough mixing on the resin reaction.

Eight short-encapsulated bolts were subsequently pull tested to site-specified targets of 20 and 22.4 tonnes of force. The target loads were achieved with a rigid response, successfully validating the distal anchor at the back of the borehole. A total of 12 of the fully encapsulated bolts were also pull tested, 10 to the site-specified target loads of 20 and 22.4 tonnes of force and a further 2 bolts to bar rupture, both occurring at 25.7 tonnes of force. The fully encapsulated pull tests also returned a rigid response, validating the proximal anchor region at the entrance to the borehole.

Figure 9 Versamix bolt installation

Figure 10 Panel of installed Versamix bolts

5 Conclusion

The development of the Sandvik Versamix bolt has achieved the desired design and performance goals – and specifically, has delivered very high anchoring capacity within the context of an 'all-steel', robust dynamic resin bolt design. The bolt design has been subjected to a highly intentional, multifaceted and rigorous validation test program, as conveyed throughout the content of this paper. Resin mixing effectiveness was a fundamental design objective and the exceptional capability that the bolt achieves in this aspect forms the foundation for the dynamic performance that the bolt reliably delivers. It is of critical importance, for any bolting design, that the ground support element and the method of anchoring are considered as a cooperative working system. The new Versamix dynamic resin bolt design and associated validation program delivers on this requirement.

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