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A practical design approach for an improved resin-anchored tendon

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The use of resin-grouted tendons is a common ground support practice within the mining industry and various tendon designs are available. The support strength of a resin-grouted tendon is often constrained by the resin annulus between the tendon and the borehole. Effective mixing of the resin is typically achieved by ensuring the resin annulus does not exceed a specified maximum limit. Therefore, in some cases, the diameter of the tendon is dictated by the maximum allowable resin annulus and minimum diameter borehole that can be drilled and not by the support design requirements. The installation of tendons with mastic resin capsules is prone to gloving of the installed tendon by the capsule packaging, thereby debonding the tendon from the borehole, and compromising the mixing of the resin surrounding the tendon.

This paper documents a practical investigation into the effectiveness of typical resin tendon designs in large annulus installations and the development of an improved tendon design for such cases.

INTRODUCTION

Various designs of tendons and resin compositions are available for ground support in mining operations. In order to optimise the support design for safety and value, it is important to assess the resins and tendons as a system and not as separate elements. This paper presents a practical investigation of the effectiveness of various resin rock bolt systems and the design of a tendon to optimise the mixing of resin during installation, and maximising the strength of the installed ground support system.

Although this research was focussed on resin bolt applications in hard rock mines with airleg rockdrills, where a combination of larger support hole diameter and inconsistent resin mixing negatively impacts on the installation quality of resin rock bolts, the occurrence of gloving in mechanised and soft rock applications has been well documented, Campbell et al (*2004)* and Craig (2012). The findings are therefore relevant to resin bolting in general.

RESIN ANNULUS

The thickness of the resin surrounding the installed tendon (See Figure 1), is a critical determinant of the support capacity of the rock bolt as the mixing and resultant strength of the installed resin bolt is dependent on adherence to the resin annulus limits as specified by resin manufacturers Ferreira (2012).

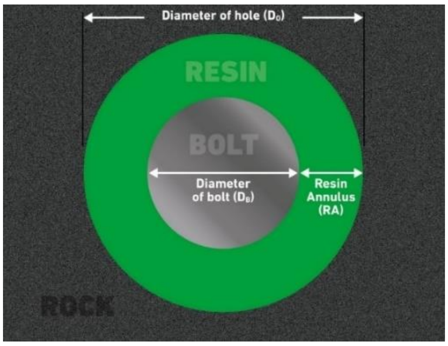

Figure 1. Definition of resin annulus

Industry testing in soft rock applications has concluded that the optimal annulus range to maximise the bond strength of conventional ribbed bolts lies between 2.5 mm and 4.5 mm as illustrated in Figure 2, Canbulat et al (2015) and Mark et al (2003). Laboratory testing using internally threaded pipes, which approximate hard rock applications, has confirmed that the optimal annulus for resin bolting is approximately 2 mm – 4 mm, Snyman et al (2011).

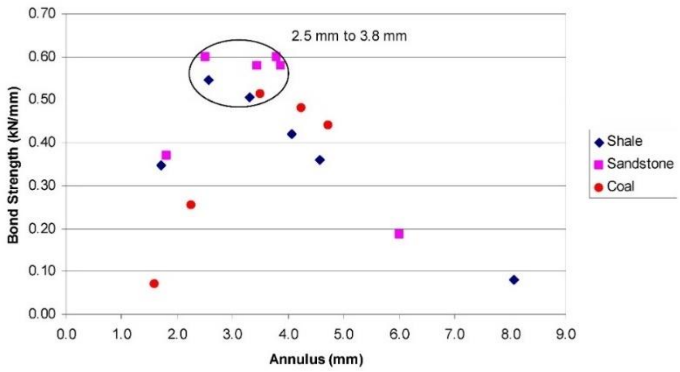

Figure 2. Effect of annulus on bond strength

South African hard rock mines commonly use Ø 34 mm drill bits with pneumatic rock drills when drilling support holes. Measurement of 37 holes found the drilled hole diameters varied from Ø 32 mm to Ø 37 mm (See Figure 3), Crompton (2007). Although the average support hole diameter measured was Ø 35 mm, 30% of the measurements exceeded Ø 36 mm. Factors such as age and wear of the drill bit, adherence to discard criteria, condition of the rock drill and the quality of the compressed air supply all impact on the hole diameter.

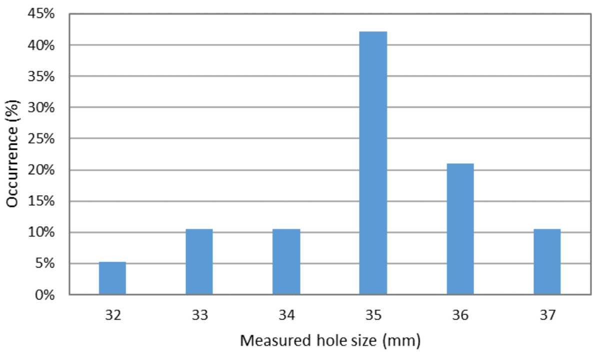

Figure 3. Support hole diameter with Ø 34 mm bit in hard rock

Given the recommended resin annulus range of 2 mm to 4 mm for resin bolting in both soft and hard rock applications, Table I below indicates the mis-match between common diameters of rock bolts and the range of support hole diameters.

Table I. Applicability of ribbed bolts in different diameter holes

Bar Ø (mm)	Hole diameter (mm)			
	32	34	36	38
18	7	8	9	10
20	6	7	8	9
22	5	6	7	8
25	3.5	4.5	5.5	6.5

To alleviate the restrictions imposed by resin annulus, a number of tendon designs are available with altered geometry in the anchoring portion of the tendon. This is typically achieved by the use of paddles or by increasing the diameter of the bolt.

GLOVING

Gloving occurs when the plastic cartridge of the resin capsule partially or completely encases a length of the tendon during installation. Gloving is typically accompanied by poor mixing of the resin surrounding the rockbolt. Gloving is a problem common to all resin and bolt manufacturers, and occurs in all rock types and can happen whether the resin bolt is installed with hand held or mechanised equipment, Campbell, Mould and MacGregor (2004). Despite continued research into improving the effectiveness of resin bolting systems, gloving continues to be a widespread occurrence in industry, Purcell et al (2016). Figure 4 shows an extreme example of gloving from dynamic laboratory testing of a resin rock bolt conducted by the authors when testing a 2.4 m sample of a common paddle- type tendon with a 45° cropped tip installed in a steel pipe.

Figure 4. Gloving of common resin bolt geometry

The prevalence of gloving within resin bolt installations poses a risk in terms of both immediate support capacity of the installed rockbolts as well as the long-term corrosion protection of the steel tendons.

CORROSION PROTECTION

Corrosion of steel rock bolts can be problematic given the potential long-term exposure of the resin bolts to corrosive elements and actions in some installations, Aziz et al (2013). This is particularly noticeable in certain shafts where accelerated corrosion is evident on all steel products in use (See Figure 5).

Figure 5. Visible corrosion on steel support products

Resin bolts can offer excellent protection from corrosion if the tendon is fully encapsulated by the cured resin. However, when the resin is compromised with voids, poor mixing, eccentric bolt position or cracks, the tendon can be exposed to ground water and other corrosive elements. Contact between steel and certain rock types may also result in galvanic corrosion of the steel, Chandra and Daemen (2009). Correctly installed resin can create a barrier between the tendon and surrounding rock preventing this, providing that the resin completely surrounds the tendon.

This paper describes the practical approach taken to further investigate the acknowledged constraints for resin bolting applications and the development of a new resin bolt design to compensate for these.

LABORATORY INVESTIGATIONS

To better understand the effect of different resin bolt designs on the quality of installed ground support, four key aspects of the performance of several tendon designs were investigated in the laboratory. Testing required the installation of a large number of resin bolt samples. In order to eliminate variability arising from inconsistencies in the installations, all samples tested were installed using an automated bolt installation machine. This maintained consistency during installation by automating installation factors such as rotation speed, feed speed, mixing time and hold time.

Figure 6. Automated bolt installation machine

Findings from the laboratory testing are discussed in more detail below.

Centralisation of resin bolts

Centralisation of a resin bolt in a support hole encourages consistent mixing of resin during installation, the even distribution of stress from the tendon into the resin annulus under tensile loading, and it maximises the corrosion protection ability of the resin by fully encapsulating the tendon. In order to assess the centralisation of available bolt designs, Ø 20 mm paddled bolts were manufactured with 45° cropped tips and also with split tips (See Figure 7), and installed into steel pipes internally threaded with a resin annulus of 9 mm.

Figure 7. 45° tip and split tip configurations

Once the resin had cured sufficiently, samples were sliced at 50 mm intervals along their length so that the cross-section of the rock bolt and resin could be analysed. This helped determine the degree of eccentricity for both tip designs. The tests found that neither the 45° cropped tip nor the split design ensured centralisation of the rock bolts during installation. Figure 8 shows the 50 mm segments cut from the distal 300 mm, the critical anchoring zone, of the resin bolts. The eccentric location of each rock bolt is sufficient to allow the rock bolts to contact the test pipe (and therefore the borehole underground) which is not desirable for corrosion protection.

Figure 8. Eccentricity of Ø 20 mm paddled bar with 45° tip

Closer analysis of the test samples showed how the eccentric location of tendons within a larger diameter borehole increased the likelihood of gloving, voids and unmixed resin (Figure 9). The large annulus to one side of the off-set tendon provides a space for the resin capsule to move into without being fully shredded and mixed by the tendon.

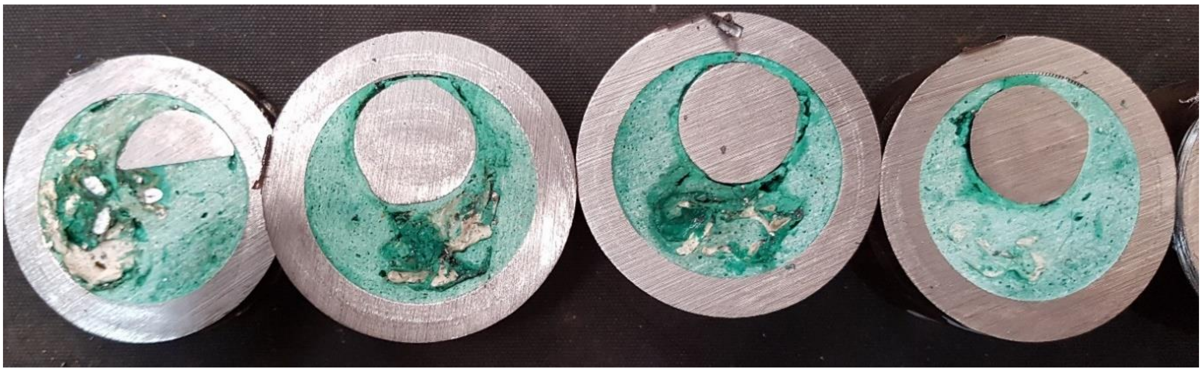

Figure 9. Poor resin mixing due to eccentric bolt location

Testing was then conducted on round and ribbed bar designs by installing samples into transparent tubes with an internal diameter of Ø 35 mm. Installing the samples into transparent tubes allows for observation of the tendon and resin during the installation and mixing process.

After installation, the samples were removed from the tubes (See Figure 10), so that the installed resin bolts could be assessed for centralisation, quality of mixing, gloving and voids. Immediately noticeable was the eccentric location of each sample and a line of voids along the resin/interface on the side where the tendon contacted the tube wall. These voids resulted in an inconsistent coating of the rock bolt by the resin with the steel being exposed in several places along the length of the sample.

Figure 10. Eccentric location of Ø 20 mm ribbed bolt in Ø 35 mm tube

In practice it is almost impossible to achieve a concentric alignment of the tendon and the borehole during installation. The effect is that while the tendon is rotating around its axis (shown in red in Figure 11), it is also rotating around the axis of the borehole (shown in blue in Figure 11). During installation, the tendon constantly rotates around the perimeter of the borehole and scrapes resin off this surface.

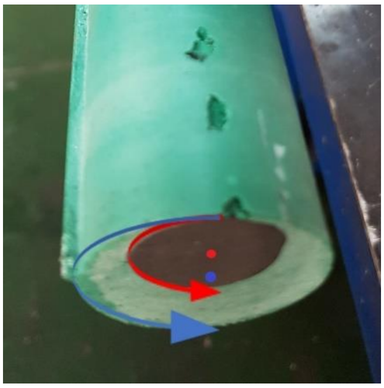

Figure 11. Eccentric location of Ø 20 mm ribbed bolt in Ø35 mm tube

The still frame from an installation video seen in Figure 12 illustrates this phenomenon, with the ribs of the tendon visible as a line of black marks along the length of the borehole while being installed.

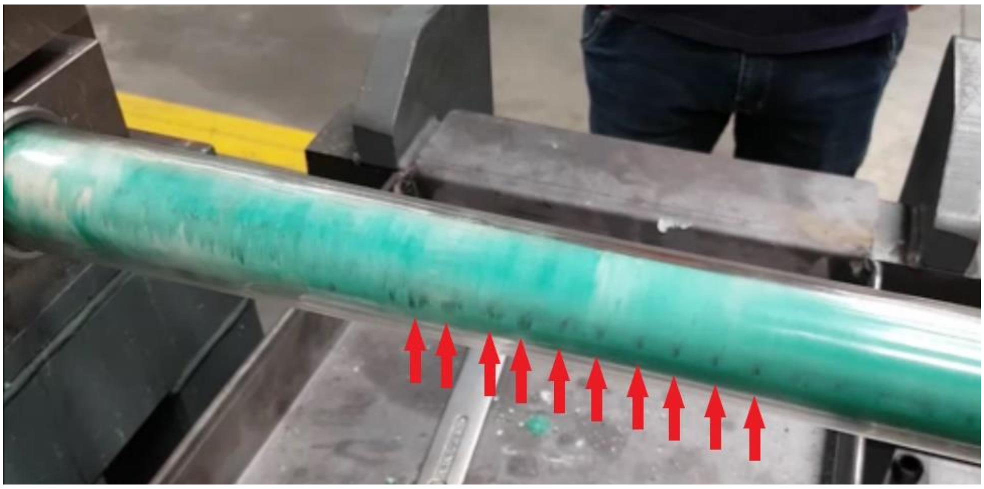

Figure 12. Scraping resin from internal surface of the borehole

Sample tendons were manufactured with a 32 mm tri-lobe tip on the distal end of the tendon (See Figure 13). The design is intended to optimise centralisation of a resin bolt in boreholes with a diameter range of Ø 32 mm to Ø 38 mm. Samples were again installed into simulated boreholes with an internal diameter of Ø 38 mm and then sliced into segments for analysis.

Figure 13. Tri-lobe tip design

The tri-lobe tip design showed a marked improvement both the centralisation of the installed tendons and quality of the resin mixing. Figure 15 provides a comparison between the same configuration tendon with a tri-lobe tip (upper row of segments) and a 45° cropped tip (lower row of segments).

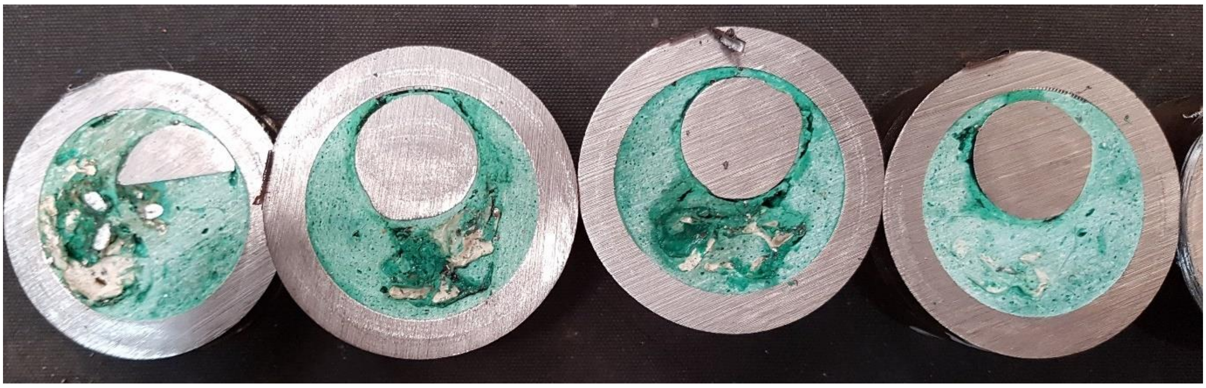

Figure 14. Eccentric location of bolt with 45° tip

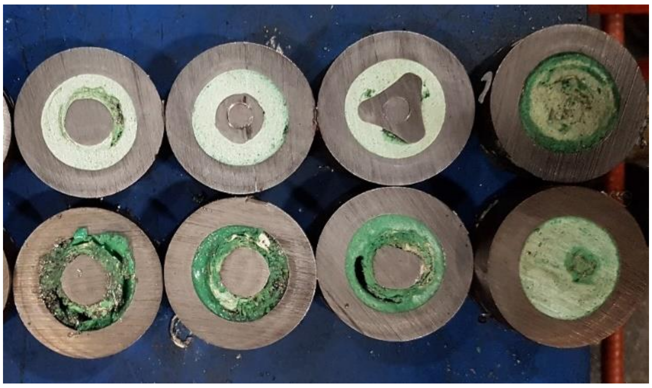

Figure 15. Resin mixing of Tri-lobe compared to 45° tip

Gloving and mixing

Gloving was prevalent in the tendons with the 45° tip with unmixed resin being noted along the entire length of the tendons. In several instances, the tendon was fully sleeved at points along the length of the anchoring zone, completely debonding the tendon from the resin in this critical region of the installed resin bolt (See Figure 16).

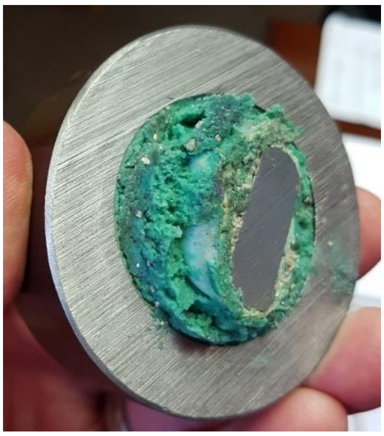

Figure 16. Gloving of test sample with 45° tip

By comparison, the tri-lobe tip design was found to pull almost the all of the capsule packaging to the distal end of the hole. This is done by the packaging wrapping around the very tip of the bolt as it shreds the capsule. Figure 17 illustrates this with a side-by-side comparison of two identical tendons, with the top tendon having a tri-lobe tip and the bottom tendon having a 45° tip. The tendon with the tri-lobe tip has well mixed resin along the entire length of the resin bolt with the capsule packaging wrapped up at the distal end of the bolt. Conversely, the bottom tendon with the 45˚ tip has poorly mixed resin along its length, unmixed catalyst visible, with gloving visible and unmixed resin at the distal end of the bolt.

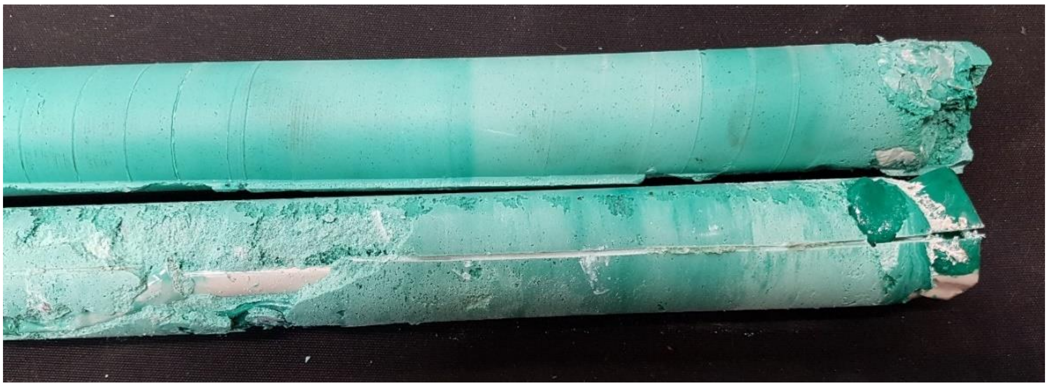

Figure 17. Comparison of tri-lobe tip design against standard 45˚ tip bolt

Voids in resin

To assess the efficiency with which different tendon geometries mix resin, split paddle and flat paddle designs were tested. As anticipated both designs improve the mixing of the resin, however, both exhibited voiding around the paddled sections of the tendons (See Figure 18). These voids result from curing resin being unable to flow and fill in around the rotating paddles faces during mixing. Whilst acceptable load capacity was still achieved when pull-testing these samples, the presence of voids may compromise the corrosion protection of the resin bolt.

Figure 18. Voiding around flat and split paddle designs

To overcome the voids arising from pure rotation of the resin during mixing, a design was then tested with the paddles on the bolt twisted on the axis of the bolt. During mixing the rotating paddles act like an auger (Figure 19), pumping the resin towards the distal end of the borehole during mixing and preventing the formation of voids behind the rotating paddles as can be seen in Figure 20.

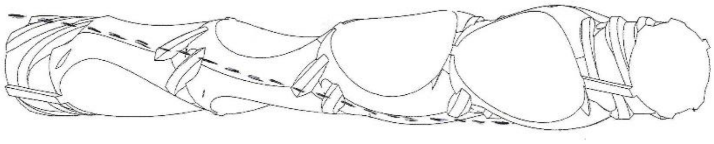

Figure 19. Voiding around flat and split paddle designs

Figure 10. Good resin fill with augured paddle design

LOAD TESTING

Laboratory Short Encapsulation Pull Tests

At each stage of testing, short encapsulation pull tests (SEPT) were conducted in the laboratory to quantify the change in the bond strength arising from each design iteration while allowing for the performance of the rock bolt to be incrementally improved with each modification. All tests were conducted in Ø 38 mm boreholes with an embedment length of 250 mm, including the tip of the tendons.

As illustrated by the performance envelopes (See Figure 21), the tendon design developed through the iterative development and testing appears to provide a more consistent and stiffer anchorage at 100 kN through a combination of the improved resin mixing and the tri-lobe tip design when compared to a conventional ribbed bar with cropped tip.

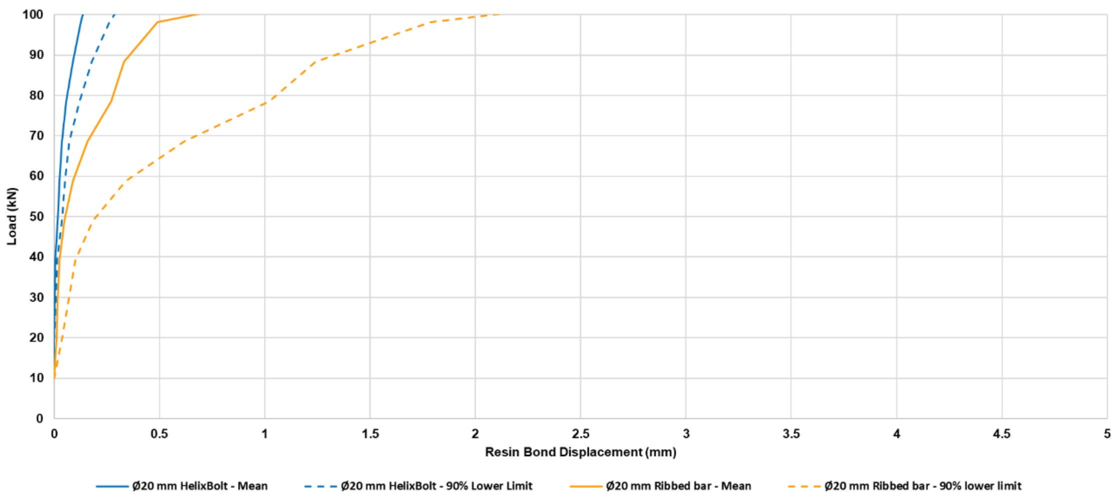

Figure 21. Laboratory SEPT results for Ø 20 mm standard resin bolt and HelixBolt in Ø 38 mm borehole

External third-party short encapsulation testing was conducted on the Ø 20 mm configuration of the tendon design with four different resins installed into Ø 38 mm boreholes. Ten HelixBolt samples were tested with each resin and the results show that the tendon design provides similar support capacity with all four resins up to 110 kN. Performance remained consistent for three of the resins to 180 kN Bierman (2018). Figure 22 is an overlay of the performance envelopes for the tendon with the four different resin types.

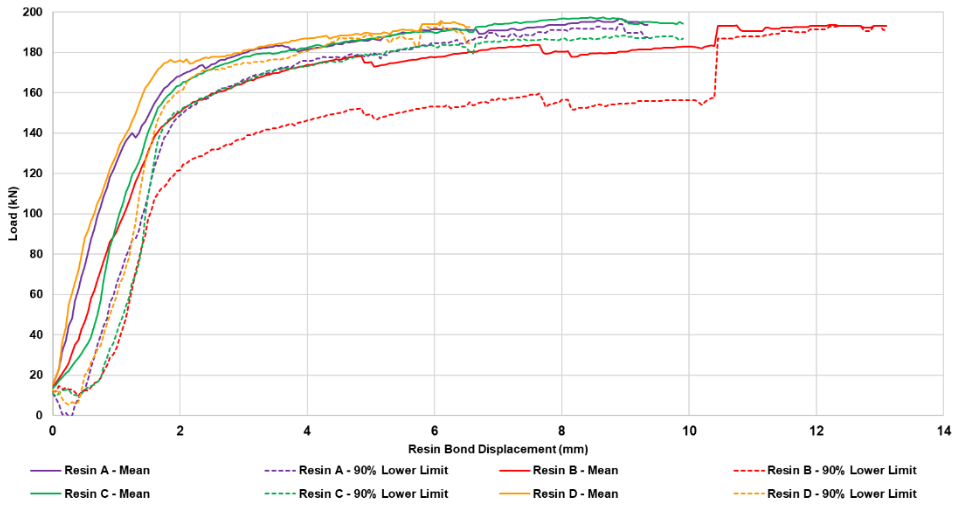

Figure 22. Laboratory SEPT results for Ø 20 mm HelixBolt with different resins in Ø 38 mm borehole

When designing, a higher resin bond stiffness is desirable in rock bolting as this prevents the opening of joints or fractures in the rock mass Pariseau (2007). Laboratory testing of Ø 16, Ø 18 and Ø 20 mm variants of the design showed that the stiffness of the resin anchored rock bolt installed in a Ø 38 mm hole is similar for all diameters when loaded up to 140 kN (See Figure 23). The Ø 16 bolt exhibited the lowest stiffness as expected, however, the Ø 18 mm bolts appeared to be slightly stiffer than the Ø 20 mm bolts This discrepancy is believed to be a result of test variability rather than bolt performance

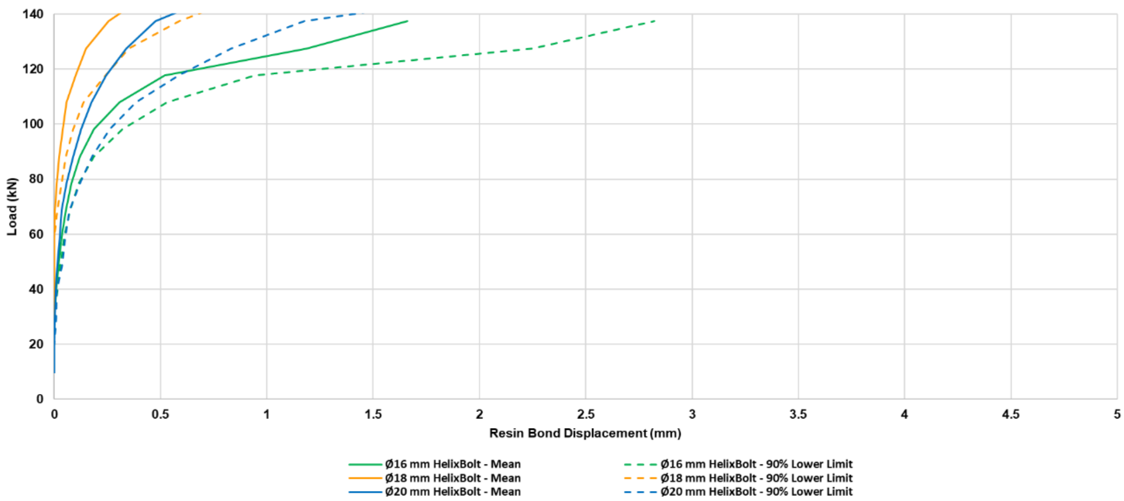

Figure 23. Laboratory SEPT results for different diameter HelixBolts in Ø 38 mm hole

The authors attribute the consistent resin bond stiffness to the consistent geometry of the tri-lobe tip for all bolt diameters.

UNDERGROUND SHORT ENCAPSULATION PULL TESTS

Subsequent to laboratory testing, underground short encapsulation testing was conducted to corroborate the laboratory results. These tests comprised Ø 16 mm, five Ø 18 mm and three Ø 20 mm samples. The rock bolts were installed into holes that ranged in measured diameters from Ø 34.4 to Ø 35.2 mm using a pneumatic rock drill mounted on an airleg to insert the bolts and mix the resin. The underground test results were corrected to account for stretch in the un-bonded length of steel under load and the performance envelopes derived from the results are presented in Figure 24. Note that that these underground tests were terminated when test loads reached 110 kN for the Ø 16 mm rock bolts, at 140 kN for the Ø 18 and at 150 kN for the Ø 20 mm rock bolts van Vuuren (2017).

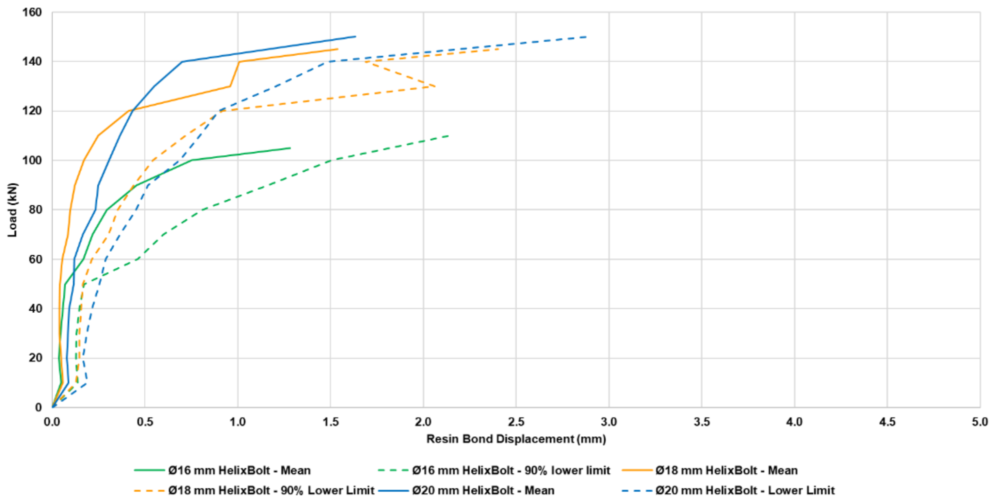

Figure 24. Normalised underground SEPT results for different diameter HelixBolts

Comparison of the laboratory and underground SEPT results (See Figure 23 and Figure 24), shows that the laboratory testing yielded higher load capacity with a less deflection than the underground testing. This is due to better control and repeatability of installation and testing parameters in the laboratory compared to testing underground.

CONCLUSIONS

The aim of this research was to investigate the effect on the bond strength of different tendon designs when anchored in larger diameter boreholes with resin capsules. Incremental testing and modification of tendon geometry led to a design that improved resin mixing, reduced the instance of gloving in applications with large resin annuli up to 11 mm (Ø 16 mm bolt in Ø 38 mm hole) and minimised voids in the resin annulus.

Laboratory and underground test results confirm that the derived rock bolt design can be installed in a resin bolting application with an 11 mm annulus and, with a 250 mm bond length, achieve loads in excess of 160 kN with an Ø 16 mm bolt, 170 kN with an Ø 18 mm bolt and 190kN with an Ø 20 mm bolt.

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