Use of Quality Assurance in Manufacturing Mine Roof Bolts for a Platinum Mine: Case study

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Abstract

As a result of roof bolts failures when supporting roofs during mining operations, there was need for quality assurance for the bolts to be investigated. The key bolt parameters were bolt length, diameter, rib angle, rib height, rib spacing and washer/plate thickness. Finite element analysis method was used to simulate, the failure was found to be due to high load. The new bolt design was generated and tested for the capacity of withstanding the load.

Keywords
Mining, roof bolts, quality assurance, design, load

1. Introduction
Roof bolts are the primary line of defense protecting mineworkers from the dangers of ground falls. Because roof bolts make use of the inherent strong point of the rock mass, they have many advantages when compared with earlier standing support systems. Due to their central importance, roof bolts have received more research attention than any other ground control systems. In South Africa, roof bolting is by far the most common support system used in underground mines (Altounyan et al 2007). Roof bolts are available in many forms, and the methods for attaching them to the rock mass are as varied, and the mechanical anchors are the most widely used roof bolting systems. The support capabilities of encapsulated bolts depend on the strength of the bond between the resin and the bolt, the strength of the bond between the resin and the surrounding strata, the strength and the modulus of deformability of the resin, the diameter of the bolt and borehole (including surface irregularities of the bolt) and, most importantly, the effective length of encapsulation (Aziz and Webb 2003). Investigations have shown that human error is the most common cause of roof bolting injuries. Human error probability estimation has become a critical issue for human reliability analysis (HRA) of roof bolting operation (Tu 2015). These are the five most important components of a bolting system (Bigly 2007): resin; bolt; hole; machinery equipment; and rock type. These five components are of equal importance, as failure of any of these will result in an inadequate support system. Therefore, as part of this study, all important parameters of these five components have been investigated in detail.

2. Justification

The study was motivated by a collapse of a platinum mine operation in July 2014, which was under the support roof bolts. During mining operations, the overhanging mass has to be supported; this is done by either the use of mine mesh or other bolts involving methods (Parker 2001). Stress analysis on a roof bolt and the use of key performance indicators (KPIs) in quality assurance; are useful in evaluating bolt properties in terms of material used, as well as component or system, efficiency and effectiveness. An investigation into stress analysis on a roof bolt using Finite Element Analysis (FEA); and quality control procedures of roof bolt support systems, quality control procedures for compliance with the design, support elements and quality of installation are done to come up with areas of improvement to avoid recurrence. Recommendations for improving quality control measures and for developing testing procedures for bolt system components, installation quality and resin performance are provided. Falls of ground (FOG) still account for around 35 per cent of all fatalities in underground Southern African mines. To help reduce FOG, appropriate support technology needs to be implemented, and a mindset and cultural change are required to make a significant change. Discipline plays a major role and needs attention, whilst appropriate first-world support technology is available to assist in the reduction of injuries and the improvement of productivity (Ferreira 2012).

3. Literature review

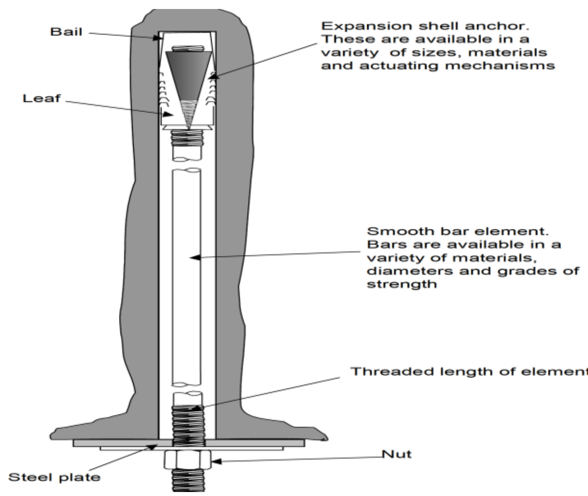
3.1 Overview

Roof bolting is the most common support system used in South African underground mines. Full-column single-resin bolts, full-column slow-fast combination resin bolts, resin point anchors, and mechanical anchors are the most widely used support systems (Campoli et al 2013). For many years the design of roof support systems was based on experience and the judgment of mining personnel. Although this approach was fairly successful, a more scientific approach based on sound engineering principles was required (Buttery 2009). Generally, the roof in South African platinum mines can be considered to consist of a succession of plates, due to the stratified composition of the sediments comprising platinum measures. If the length of an excavation is more than twice its width, the analysis can be further simplified to consider the behavior of beams, rather than plates.Roof bolting can be classified as one of most vital technological developments in the field of ground control in the whole history of mining (Canbulat 2004). It is an important component in the design of underground excavations and has been used to present an overall ground improvement scheme ever since the middle of the last century. Support is essential to improve both safety and output. Roof bolting has become the primary support system in the most mineral mining industry and all. Roof bolts dramatically reduce the number of fatalities each year and they were initially hailed as "one of the great social advances of our time" (Canbulat and Dlokweni 2003). Roof bolt- a bar inserted into the roof or side of a roadway which is used in conjunction with fully encapsulating resin or some other appropriate substance to provide reinforcement of the roof and sides of a roadway or working place in a mine (Mineral Beareu 2003). The three main types of roof bolts are: roof bolting, cable bolting; and ground anchoring. Mechanically anchored rock bolts are probably the oldest form of rock reinforcement used in underground mining and are still the most common form of rock reinforcement used in Canadian mines. In fact, if a bolt is overloaded, it usually fails in the threads at either the faceplate or anchor end rather than by anchor slip. Despite the safety consequences of ground instability, there remains a deficit of practical engineering understanding indicating how roof bolts provide reinforcement to the rock mass surrounding an excavation as mining proceeds. This applies particularly to ''fully grouted'' bolts which have gained popularity due to their superior performance compared to ''end-anchored'' bolts (Spearing eta al 2013).

3.2 Mechanical coupled roof bolts

The mechanical anchor bolt comprises of a flat bar with a wound anchor end. A mechanical shell anchor attached to the wound end of the bolt is used to anchor the system (Figure 1). When a torque is introduced to the bolt, the force drives a plug against the outer shell, which then enlarges and sets against the rock in the borehole walls. Once the anchor is set, the bolt is then tensioned. Ended time, the tension may be limited as a result of creep or failure of the rock around the anchor. For this reason the mechanical anchor bolt system should be installed in robust roof rock.

Figure 1 Mechanical anchor bolt (Canbulat 2003)



Van der Merwe and Madden, (2012) advocate that because of the long free stretch of the steel tendon, mechanical anchor bolts can spring when load is applied. It is therefore a soft support, although it is active by virtue of pre-tensioning. Wagner (2005) states that, due to of high contact stresses which progress at the position of the end anchor, mechanical anchors must be used in rock strata that contain uniaxial compressive strength of more than 55 MPa. The strength of rock necessary for mechanically end anchored bolts has also been examined by Windsor and Thompson (1997). They found that the mechanical presentation of the anchor may be estimated using the equilibrium of the forces on the components of the anchor system.

3.3 Resin point anchors

This designates that in areas where the rock is not resilient enough to empower mechanical anchors to be installed, point resin anchors may be implemented. Resin anchors necessitate more time and care to install in comparison to mechanical anchors. The advantages of point resin anchor bolts are that the anchor resistance can be amplified by making the anchorage measurement longer; and the changeover to full-column resin support, must it be required by varying conditions, is less disturbing because operators will already be trained in resin installation. Also other bolt types such as full column resin bolts are commercially available.

3.4 Current guidelines for the selection of roof bolt type

The selection of bolt type is determined by primarily the geological condition, the rooftop rock, and the mining technique. Despite the fact that mechanical anchor bolts are not operative in weak rock, Split sets are not suggestible in corrosive environments. For long-standing support, the resin/rebar bolt will always be an improved choice (Hagan 2003). Yasmeen (2013) prepared certain recommendations on the choice of bolt type. Mechanical bolts are recommended for

- Hard and tough rock as they can resist bit biting and keep the anchorage force;
- Impermanent reinforcement systems;
- Circumstances where bolt tension can be tested regularly;
- Rock that will not experience great shear force; and
- Zones away from blast sites where bolt tension may be affected.

3.5 Roof bolting design

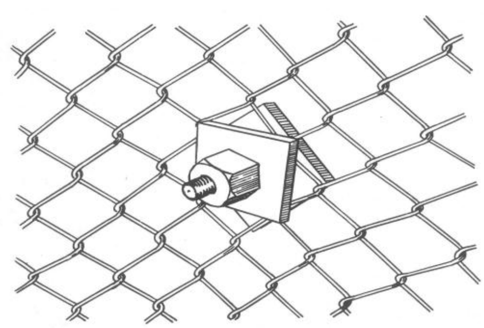
As in the design of other support systems, the design of a rock bolting system depends on: the nature of the discontinuities and the intact rock; the magnitude and distribution of the stresses induced; support requirements such as acceptable deformation and lifetime of the opening; and the size and shape of the openings. For a complete and appropriate rock bolting system design, the following parameters must be properly determined (O'Connor 2002): bolt type; bolt length; pattern and spacing of bolts; bolt diameter and anchor capacity; whether pre-tension should be applied or not. Roof support design based on geotechnical classification and rock mass classification systems have constituted an integral part of empirical mine design for over 100 years (Roberts 2002). The use of such systems can be explicit, and are traditionally used to group areas of similar geotechnical characteristics, to provide guidelines of stability performance, and to select appropriate support. It is suggested that, when platinum mine roof support is designed, 2.0 m of strata above the immediate roof should be tested. Plate loads can increase by a factor of ten or more in highly deformed ground (Roberts 2002). Plate load as a function of time in platinum mines was measured as part of this study. The choice of the type of support installed in a particular underground excavation depends upon the extent of the zone of loosened or fractured rock surrounding that excavation. Underground mines use two principal types of rock reinforcement – tensioned mechanically anchored rock bolts and not tensioned grouted or friction anchored dowels.

Tensioned rock bolts are most effective in retaining loose blocks or wedges of rock near the surface of the excavation. These blocks may have been loosened by intersecting joints and bedding planes in the rock or they may have been created by poor quality blasting. In either case, falls of loose rock create unsafe working conditions and some form of support is required. The need for mechanically anchored rock bolts is reduced significantly by careful blasting and by correct scaling. These techniques reduce the amount of loose rock which has to be supported and hence the need for bolts and mesh. One of the main disadvantages of mechanically anchored rock bolts is that, if the anchor slips or the bolt breaks, the capacity of the bolt drops to zero and the rock being supported can fall. This problem is less severe in the case of a fully grouted or friction anchored dowel because, even if slip does occur or if the face plate breaks off, the remaining length of the dowel is still anchored and will continue to provide support.

Figure 1 illustrates a number of components which can be used in different combinations. The expansion shell anchor is one of a large number of different types, all of which operate in basically the same way. A wedge, attached to the bolt shank is pulled into a conical anchor shell forcing it to expand against the drill hole walls. When grouting a bolt, the rubber grout seal is used to centre the bolt in the hole and to seal the collar of the hole against grout leakage. An alternative system is to use a quick setting plaster to seal the hole collar. The advantage of this is that the bolt can be tensioned immediately after installation using an impact wrench, torque wrench or hydraulic jack, and grouted at a later stage when short term movement shave ceased. This system provides very reliable anchorage in good rock and high bolt loads can be achieved. Mechanically anchored bolts without grout are widely used in mining.

Rock bolts in some circumstances is used to hold the mesh (Figure 2) in place. Mesh is useful for supporting small pieces of broken rock. Weldmesh is used traditionally as reinforcement for shotcrete, but is rapidly being replaced by steel fibre reinforced shotcrete. Mesh, like straps, is held in place with additional faceplates or washers and nuts on rock bolts or using separate pins.

Figure 2. Mesh (Roberts 2002)



Almost all platinum mine roofs are supported with roof bolts in South Africa. In the early years, the design of roof bolt patterns was based on local experience and the judgment of mining personnel. The suspension mechanism was the most easily understood and most widely used roof bolting mechanism. The design of roof bolt patterns has also been improved, and four main rock reinforcement techniques have been developed such as: simple skin control, beam building, suspension, and keying. Widespread instrumentation and vigilant visual observations are important for ensuring safety and stability in mines. While the effect of roof bolt diameter on support performance is well understood, there is still controversy over the length of the roof bolts. It has been shown that the probability of roof failures increases with decreasing bolt length (Hagan).

4. Methodology

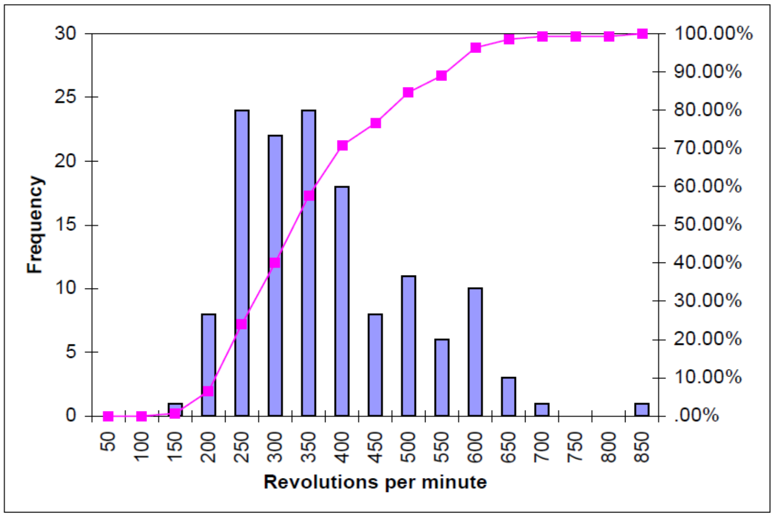
Rock Mechanics Technology (RMT) was used to test and evaluate the underground short encapsulated pull testing(SEPT) procedures; and the laboratory testing procedures as part of this study, specifications for roof bolts, quality of installation of a support system and the performance of the equipment used to install the bolts. The performance of bolting equipment was investigated as part of this study in order that the relative importance of the various machine parameters could be ascertained, as well as the range of values of these parameters as provided by the equipment. For the quality control procedures it was estimated that approximately 5 million roof bolts are installed annually in South African platinum mines. Although there are systems available to test the integrity of installed bolts, it is important to ensure that the roof bolts are installed in the best way possible.

5. Results and findings

5.1 Rotation speed during drilling

The results of rotation speed during drilling are presented in Figure 3. Drilling speeds for all machines show a similar trend to that of rotation speed, with the same shape distribution curve produced. As would be expected, the curve is shifted lower down the axis with the introduction of load to the system.

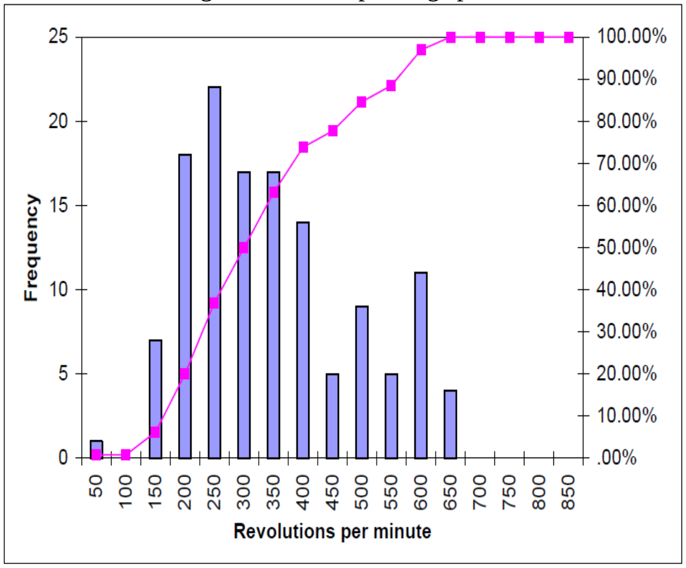
Figure 3. Drilling speed



5.2 Resin spinning speed

The speeds measured while spinning resin for various types of bolters, with data from Figure 4. Resin spinning speed shows a maximum speed of 643 rpm and a minimum of 45 rpm.

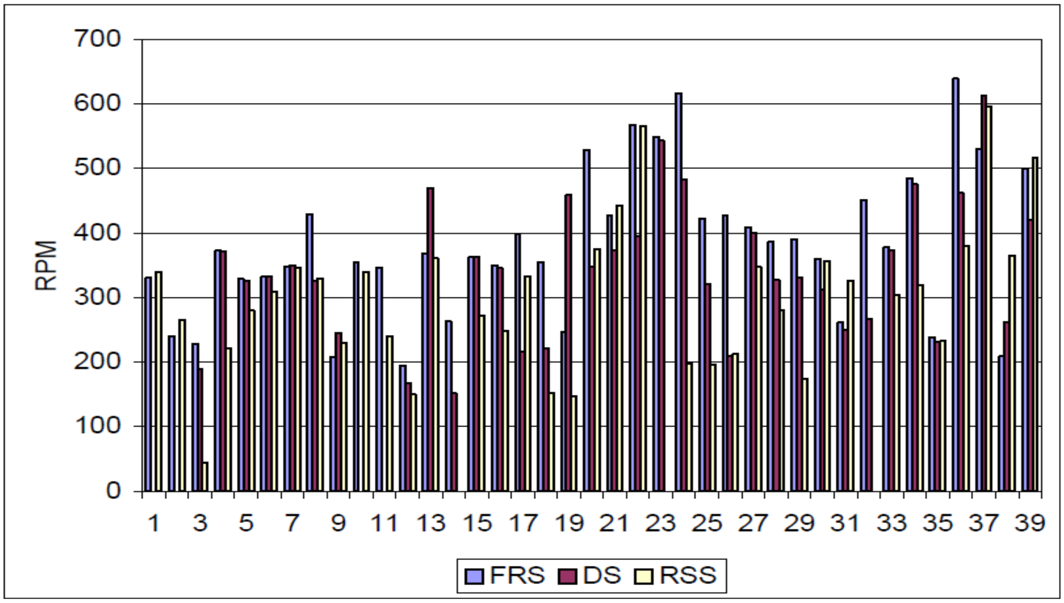
Figure 4. Resin spinning speed



5.3 Comparison of speeds

In order to compare free rotation, drilling and spinning speeds, these variables were plotted together in Figure 5. Note that FRS is free rotation speed, DS is drilling speed and RSS is resin spinning speed in the figure.

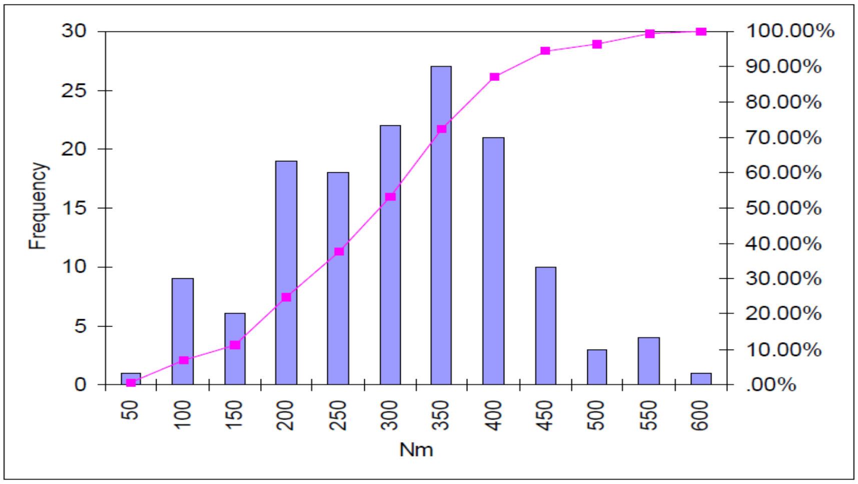
Figure 5. Speed comparisons



5.4 Torque

Currently, a bolter was expected to produce 200 Nm to 250 Nm torque at all times in order to tension the bolt to 5 tons (50 kN).In the drilling phase, enough torque is required to allow the bit to penetrate whatever rock type may be present in the roof and pass through harder layers with the same efficiency as through soft. The results from the torque measurements are shown in Figure 7. These figures indicate that the torque on all machines ranges from a maximum of 560 Nm to a minimum of 50 Nm. Figure 6 indicates that only 26 per cent of all bolters had torques within the 200 Nm to 250 Nm range.

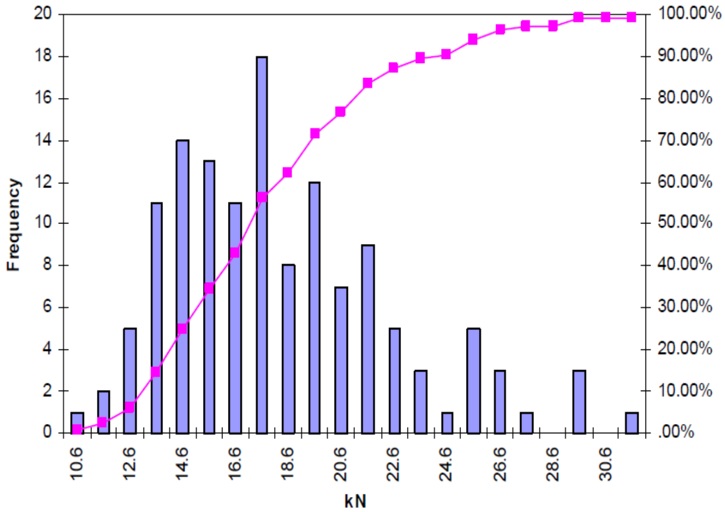
Figure 6. Torque



5.5. Thrust

Thrust is the axial force exerted on the drill steel by the machine. Thrust varies a great deal, from as little as 10 KN to 32 KN, with an average of around 18 kN. The results are presented in Figure 7.

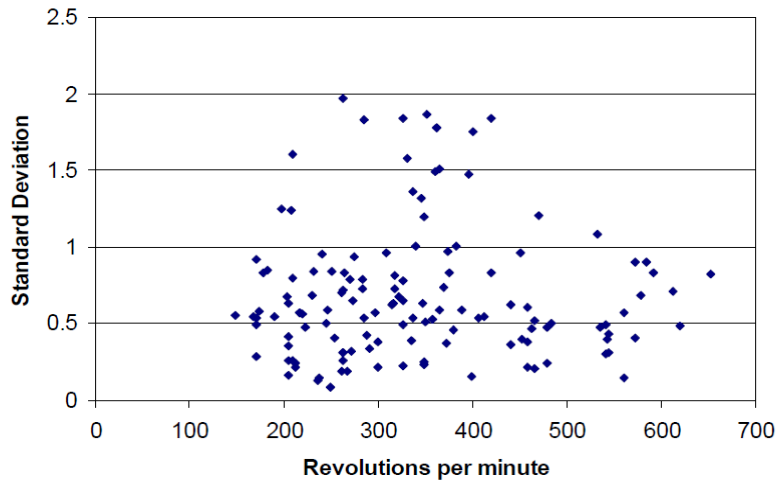
Figure 7. Thrust



5.6 Hole profile

The hole-profile is also a fundamentally important parameter, as it determines the bonding quality between the resin and rock. A smooth-walled hole will exhibit far lower bond strength than a hole-wall that is serrated or 'rifled'. Currently, there is no suitable tool available to determine the hole-profile, apart from over coring. However, over coring is very expensive and cannot practically be used for a large-scale experiment applied to all available bolters. Therefore, the hole-profile is measured by taking a number of hole diameter measurements at regular intervals along the hole. As shown in Figure 8, the largest percentage (approximately 80 per cent) of standard deviation on all holes, drilled by all machines, in all different roof types, is less than 1.0 mm diameter over the entire hole-length. Although 1.0 mm may seem insignificant, the fact remains that most 25 mm drill bits are shown to be drilling 27 to 28 mm diameter holes. This indicates that most 20 mm bolts are being installed in a hole with an annulus of up to 10 mm, when the worst case example of almost 2 mm standard deviation is taken.

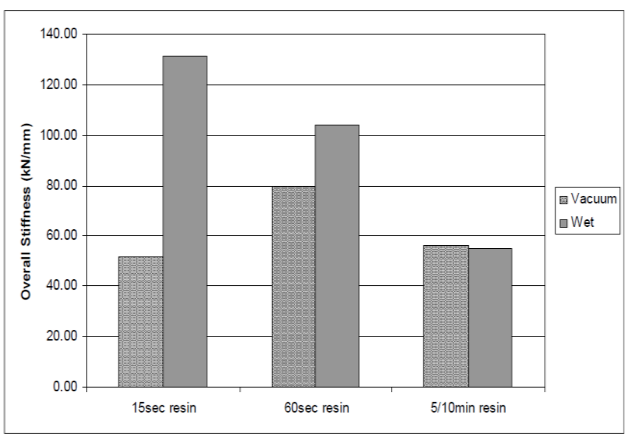
Figure 8. Drilling speed against hole profile standard deviation



5.7 Wet and dry drilling

A total of 24 short encapsulated pull tests were conducted to determine the effect of wet and dry drilling. This figure indicates that bond strengths for wet drilling are between 4 to 28 per cent greater than with dry drilling probably due to the fine particles which may be left behind after dry drilling.

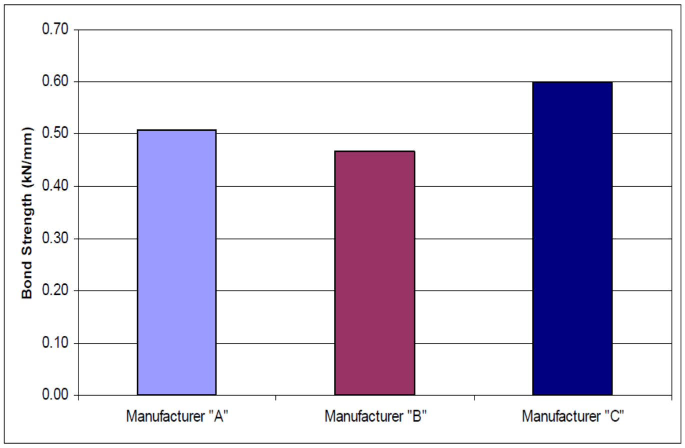
Figure 9. Effect of wet and dry drilling on overall support stiffness



5.8 Determination of roof-bolter performances using SEPT

In order to determine the influence that different roof-bolters have on the bond strength of roof bolts installed by the particular bolter, a total of 20 short encapsulated pull tests were conducted. Resin type, flushing type and bit type were kept the same in all tests. Three roof-bolters from three different manufacturers were evaluated. The results are shown in Figure 10.

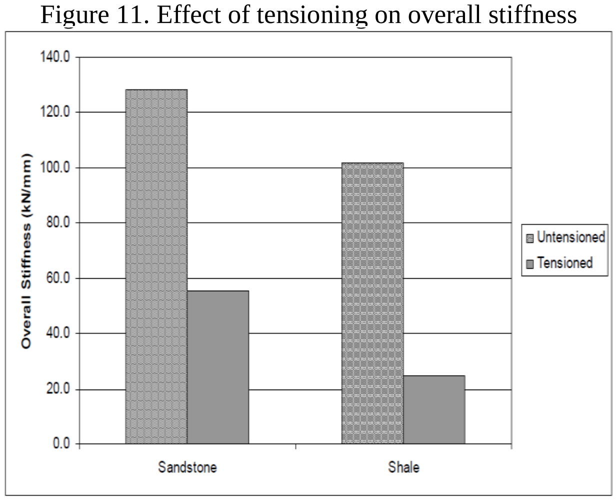
Figure 10. Performance of roof bolters using SEPT



5.9 Performance of roof bolts

The roof bolt profile plays a significant role in determining the pull-out resistance of roof bolts. Figure 13 shows tensioned versus non-tensioned roof bolts. An additional 25 short encapsulated pull tests were conducted to determine the effect of tensioning on bond strength. These tests were conducted in sandstone and shale roofs. Figure 11 shows the effect of tensioning on overall support stiffness. It is therefore suggested that a new testing procedure be developed to test the performance of tensioned bolts.

Figure 11. Effect of tensioning on overall stiffness



5.10 Variation in roof bolt parameters

In a support system, it may not be possible to control the hole diameter, because of many factors, such as the rock strength, bit type, drilling type, thrust of roof bolter etc. A total of 235 roof bolts from three different manufacturers were evaluated (approximately 80 roof bolts from each manufacturer). The effect of annulus size on support performance has been shown to be significant. Also, theoretically, a 0.6 mm reduction in bolt diameter can reduce the yield load of a 16 mm bolt by 7 per cent (assuming a tensile strength of 480 MPa). This highlights the need for quality control procedures to be in place at mines for checking the elements of a support system, which are part of the engineering design (roof bolt, and bits).

5.11 Stress analysis using finite element analysis

An analysis was conducted using solid works simulation package for the roof bolts. The results were obtained, and a conclusion was drawn with regards to these results. The current design was giving a maximum Von Mises stress of 1.09 x 10^{11} Pa but the yield strength of bolt material is 6.204 x 10^{8} Pa. This means that the design could easily fail hence there was the need for redesigning, and test the design using Finite Element Analysis (FEA). The bolt is made of alloy steel (cast steel) of the following properties Table 1

Table 1. Bolt steel properties

Name:	**Alloy Steel (CS)**
Model type:	**Linear Elastic Isotropic**
Default failure criterion:	**Max von Mises Stress**
Yield strength:	**6.20422e+008 N/m^2**
Tensile strength:	**7.23826e+008 N/m^2**
Elastic modulus:	**2.1e+011 N/m^2**
Poisson's ratio:	**0.28**
Mass density:	**7700 kg/m^3**
Shear modulus:	**7.9e+010 N/m^2**
Thermal expansion coefficient:	**1.3e-005 /Kelvin**

It was concluded that a maximum shear σ_b stress of 300MPa had been experienced according to the machines they used and the type of rock at the collapsed case study mine operation.

6. Recommendations

This study recommended that the rib geometry of re-bars be investigated so that the interaction between bolt and resin can be optimized as well as ensuring thorough mixing of the resin. The suggested thrust, rotation speed and torque values recommended for roof bolters have to be evaluated fo their effect on productivity and drilling rates. While SEPT was found to be appropriate, there was still need develop a series of quick-and-easy testing procedures to determine the performance of support elements; as well as improve the quality of installation of roof support; and develop new quality resin-testing procedures and techniques to ensure expected support performance. These are recommended KPIs are not the forte of the case study operations, however a continuous improvement strategy is critical to ensure the success of the platinum production in underground mining operations. Compliance with the design should be checked underground at least once every fourth week. Although there are systems available to test the integrity of installed bolts, it is important to ensure that the roof bolts are installed in the best way possible. Underground support installation is one of the most important aspects of support performance. The use of KPAs is necessary to manage performance. Only effective quality assurance would ensure the effective optimization of the mining processes.

7. Conclusion

The study was based on a maximum stress of 300MPa and through use of relevant equations, the following bolt parameters were settled for, these are: (a) increases of bolt length from 1,5m to 2m, bolt nominal diameter 15 to 27mm , rib thickness from 3,35mm to 5mm, thickness of the stress bearing plate from 10mm to 20mm; and (b) adjustments on rib spacing from 8,73mm to 5mm, rib angle $\propto$ from 72 to 50 degrees, bolt spacing from 1,5 to 1m. World class achiever identified controls, quality, cost, delivery, safety and morale as key measuring instruments for performance for mining operations.

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Biography

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