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APPLICATION OF HELICAL DRAG BIT TECHNOLOGY FOR MINING OPERATIONS

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Abstract

This paper discusses the Helical Drag Bit (HDB) and its rock drilling applications with an emphasis on use in mining operations. The HDB is a drilling tool that employs cutting members arranged in a pattern to form a helical groove or thread within a borehole. This pattern of cutters can be used for several purposes including roof bolting in mining, interpretation of the lithology of the strata being drilled and low energy consumption drilling.

Laboratory and field experiments have consistently shown increase of roof bolt-anchoring capacities in weak rock of more than 100% using the short encapsulation pull test method when boreholes are conditioned using the HDB. In 2004 a series of tests conducted in mines with weak roofs demonstrated the benefits of HDB technology for roof bolting applications in mining.

HDB technology offers opportunities for new and beneficial approaches to interpret the geology of roof strata. During conventional drilling, traditional approaches to determine rock properties require simultaneous measurement of several parameters such as thrust, rotational velocity, torque and penetration rate. The unique geometry of the HDB possesses a characteristic that allows determination of the mechanical properties of the rock being drilled by measuring torque as a single drilling parameter. This capability greatly simplifies the process of determining rock properties and provides reliable results.

Additionally, HDB technology has been demonstrated to offer significant advantages for rock drilling. A substantial portion of the rock is removed by the fracturing of the internal thread created in the rock bore by the tool taking advantage of the weakness of the rock in tension. Because the rock chips obtained in this process are relatively large, savings in energy are realized when compared to traditional drilling technologies.

Introduction

The HDB concept was developed by UTD Incorporated in the mid 90’s in response to a program of the Gas Research Institute aimed at maintaining a portfolio of products and technologies for low-cost drilling. After several stages of development from theoretical analysis to laboratory demonstrations, the HDB was demonstrated to be a technology capable of reducing drilling costs by increasing productivity.

Two characteristics of HDB technology are low energy consumption per distance of advance and low reaction force drilling. These characteristics were identified as being compatible with NASA’s requirements for exploration of extraterrestrial bodies. A Low Reaction Force Drill (LRFD) prototype for deep drilling on Mars was developed under NASA sponsorship. The drill proved successful during laboratory tests in limestone rock. Because the drill reaction forces are contained within the borehole, the drill is low weight and has low energy consumption, and drilling speeds are comparable with those of more traditional heavy drills.

During the course of HDB development new applications have been identified. For example, investigators noticed during the LRFD program that torque measurements were consistent and depended only on the type of rock being drilled. This observation pointed at the possibility of being able to determine rock characteristics by measuring only the torque during drilling with the HDB. A comprehensive test program is currently under way for refinement of this application.

Another promising application for the HDB is in the area of roof bolting in mining. An R&D effort currently in progress is aimed at employing the HDB concept to create rifled borehole geometries and to quantify the anchorage improvement realized by this process. It has been widely accepted that a rifled hole would provide better anchorage for fully grouted roof bolts than a smooth bore drilled hole. However, there have been no studies quantifying the improvement in anchorage when using rifled holes or the characteristics of the rifling needed to produce this anchorage improvement. Previous attempts to produce rifled holes have proved impractical.

HDB Description and Operation

Traditional drilling systems employ roller cone bits or drag bits. Both systems have advantages and disadvantages. Roller-cone bits work by crushing the rock and producing large chips. Although effective, the crushing action requires a premium in energy and equipment since rock is typically resistant to crushing. On the other hand, drag bits work by shearing and pulverizing the rock. Rock is less resistant to shearing thus requiring less energy and allowing the use of lighter drilling equipment. When used for drilling, the HDB combines the advantages of the shearing action of the drag bit and the large chip production of the roller bit. The result is a low energy consumption drilling system.

The HDB drilling system incorporates a drill bit with cutting members arranged in a helical pattern on the periphery of a cylindrical surface. A standard drag bit is used to create a pilot hole. The HDB follows the drag bit and the helically arranged cutting members cut a "thread" within the pilot borehole. Several cutting members are typically incorporated into the HDB. Their function is to gradually increase the depth of the thread within the borehole until reaching the desired size. Figure 1 shows a model of the HDB and pilot bit. Figure 2 shows a photograph of the helical "thread" cut into a limestone block. Each successive cutter is designed with a longer radius arm that controls the depth of cut.

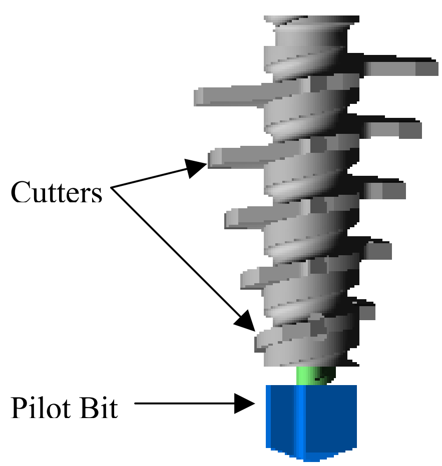

Figure 1 The Helical Drag Bit design is used to create grooves like those pictured in Figure 2.

Figure 2 "Rock Thread" cut in limestone using hardware developed for NASA's Low Reaction Force Drill.

Depending on the application, further steps can be included in the drilling process. When used for drilling, the HDB is fitted with wedge shaped members that follow the cutting members. The wedging action on the threads takes advantage of the inherent weakness of the rock in tension, breaking the thread at its base, effectively increasing the borehole diameter, and producing large rock chips that are subsequently removed. Since the rock is weaker in tension and shear than in compression, less power is required for drilling. The bit also pulls itself forward, so that thrust requirements are low. These features lead to improved efficiency, reduced surface equipment size, and lowered drilling cost. In horizontal and coiled tube drilling applications, the self-advancing feature of the bit can considerably extend the length of holes drilled and the useful life of components [1].

For exploration applications such as the Low Reaction Force Drill developed for NASA, it is desirable to recover larger rock samples for study. This is accomplished by adding scorer cutters that have the function of cutting at the root the rock spiral resulting from the HDB operation. Once the cutting members of the HDB have reached the desired depth, successive cutters will incrementally cut axially into the rock in order to produce a groove at the root of the resulting rock spiral until the rock spiral is detached from the main rock formation.

There are several operating variables that determine the resulting geometrical characteristics of the final borehole. These variables need to be optimized for each particular application. The key operating variables illustrated in Figure 3 are:

- Pilot hole diameter (D)
- Helical Pitch (P)
- "Thread" or groove depth (d)
- "Thread" or groove width (w)

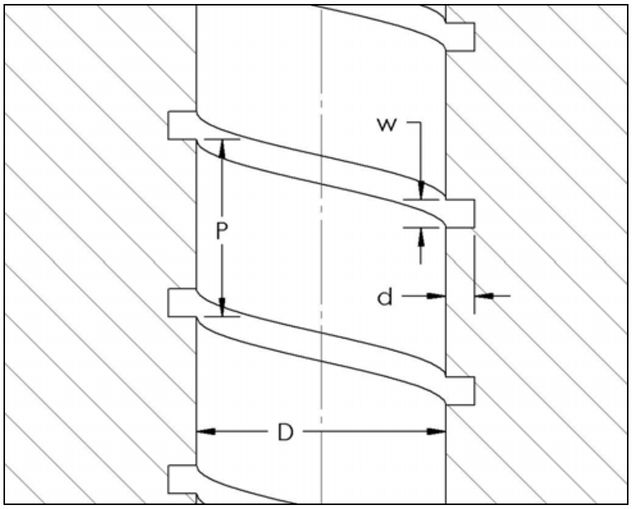

Figure 3 Section view of resulting borehole geometry after using the HDB.

Applications

Two new applications for the HDB have been developed and are currently in the testing stage.

- Lithology Identification
- Roof Bolt Installation

Lithology Identification

Laboratory tests have demonstrated the ability of the HDB to interpret the compressive strength of the rock being drilled for some types of rock. This ability to interpret lithologic changes or encountered foreign objects during drilling is of great benefit to drilling operators.

Recent studies have been published reviewing advances in lithology characterization during conventional drilling [2,3,4,5]. Unfortunately, in conventional drilling several drilling variables must be simultaneously monitored in order to interpret lithologic changes including thrust, rotational velocity, torque, percussion rate and penetration rate. This is true because the amount of material removed with each rotation of a conventional bit is a function of all those variables. In the case of the HDB, the geometry of a helical cutter is such that cutters on the opposite side balance the normal force on each cutter. Every rotation of the HDB results in a prescribed advance into the rock and the depth of the "thread" or groove is defined only by the initial borehole diameter, the pitch of the cutters surrounding the central hub, and the geometry of the individual cutters. Ultimately, the HDB can interpret lithologic changes based only on measuring torque by the following equation that correlates the measured torque to the compressive strength of the rock:

$$q_u = \frac{t_c}{K_{SE} \bullet d \bullet w \bullet r_c}$$

Where:
q_u = Unconfined Compressive Strength (UCS)
t_c = Torque per cutter
K_{SE}= Coefficient of proportionality between Specific Energy and q_u
d = Depth of cut
w = Cutter width
r_c = Distance of tip of cutter from center of rotation for each cutter

The above equation presents the torque contribution from each cutter. A typical HDB can have a number of cutters and the total torque is the summation of the contributions from each cutter.

Cubic blocks 2 feet on each side of four different types of rock were initially tested using the HDB with the purpose of validating the theoretical approach. The rock types and their corresponding compressive strength are shown in Table 1.

Table 1. Rock types tested and their compressive strength.

Rock Type	UCS (Psi)
California Limestone	3,500
Shale	5,200
Indiana Limestone	5,500
Sandstone	10,000

Three one-inch diameter pilot holes, with a depth of 12 inches, were drilled into each of the rock blocks. The torque required to cut a "thread" by using the HDB was measured with an electronic torque sensor. The data was collected using a data acquisition system and stored on a laptop computer for analysis.

Results show that the torque required for cutting the "thread" has little variation for each type of rock and that the torque values measured remain within a well-determined range for each material. Figure 4 shows the average measured torque values for each hole grouped by rock type.

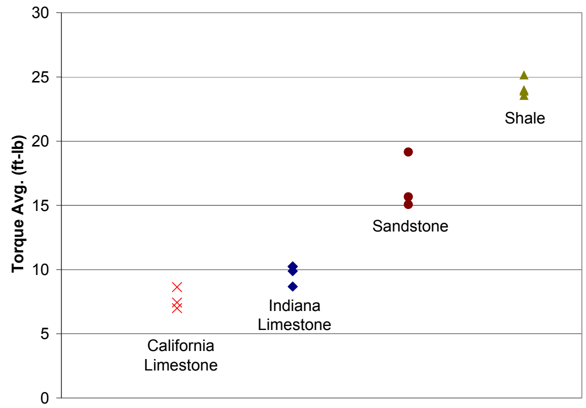

Figure 4 Average measured torque of cutting using the HDB show consistent results for all rock types

When torque values are averaged for each material and then plotted against compressive strength there seems to be a good degree of correlation for sandstone and limestone. The shale sample however, does not follow the same trend, perhaps due to its internal structure. Although all of the rocks tested are sedimentary, the shale is highly laminated. This may affect the mode of failure during cutting and ultimately the torque needed to cut the "thread" in the rock. Figure 5 shows a plot of torque vs. compressive strength for all materials tested. Figure 6 shows a similar plot excluding shale.

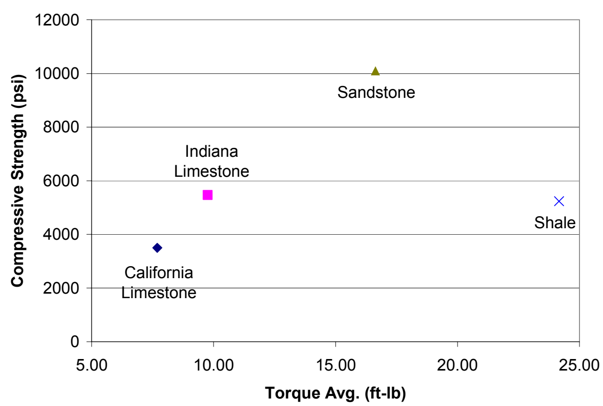

Figure 5 Shale does not follow the average torque vs. compressive strength correlation.

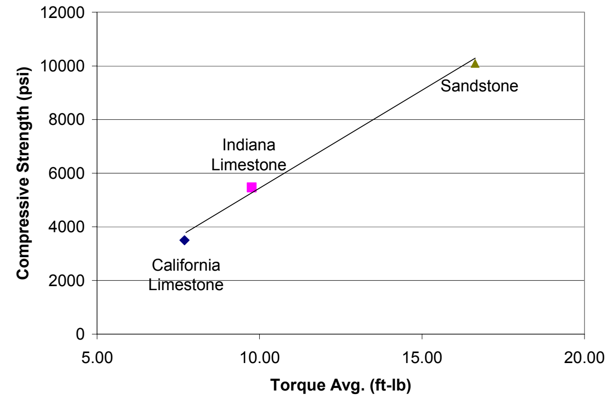

Figure 6 The average torque-compressive strength correlation becomes evident when shale is excluded from the graph.

Depending on the depth of cut, two modes of failure are possible when using a drag bit, ductile and brittle. The ductile mode occurs when the depth of cut is small so that the material removed flows in front of the cutter. In the brittle mode, the depth of cut is larger than a threshold that depends on the material structure and chips are produced by crack propagation under the cutter [6].

Results obtained demonstrate the relationship between the type of rock and torque measurements. Although not all materials fail in a similar fashion for a given cutter geometry, and therefore deviate from the theoretical approach, it is still possible to distinguish the material being drilled based on a calibration bore hole in the field. Additionally, a change in torque while drilling using the HDB would indicate a change of ground conditions. Further tests are in progress aimed at expanding the database of information and identifying the types of material that show the torque – compressive strength correlation when cut by the HDB.

Roof Bolt Installation

A new and promising application of the HDB is in roof bolting in mining. Rock bolts are a primary support technique used to stabilize rock against roof falls in coal and hard rock mines [7]. Installation of roof bolts involves drilling holes into the rock and establishing a firm anchorage in those holes. Approximately 80% of roof bolts use grout as a means of anchoring, with the vast majority of the remaining percentage of rockbolts using mechanical anchors [8]. The large use of grouted bolts is attributed to the fact that they distribute their anchoring load on the rock over a greater area and generally have superior anchorage capacity.

As major contributors to a roof control plan, rock bolts have been studied to determine optimum installation spacing and length, to match geologic conditions. The main ways rock bolts support mine roofs are: beam building (the tying together of multiple rock beams so they perform as a larger single beam), suspension of weak fractured ground to more competent layers, pressure arch, and support of discrete blocks. Cable bolting, where cables are used in place of steel rods or bolts, performs a similar function. It is important to note that while rock bolts play a critical role in mitigating rock mass failure, many other mine design factors come into play to create a stable mine environment including, but not limited to, opening dimensions, sequence of excavation, matching of bolt anchor and length with opening and geologic conditions, and installation timing. Notwithstanding the importance of these other factors, if the bolts used in rock stabilization do not perform well, miners are at risk.

Bolt installation characteristics near roof falls have been identified as contributing to failure [9]. One documented and regularly occurring rock bolt failure mechanism is loss of grout shear bond to the rock wall of the borehole [10]. Key contributors to the integrity of the grout interlocking with the rock mass are the diameter of the hole relative to the diameter of the bolt, type of grout (resin or cement), rock type, and condition of the hole.

A fully grouted bolt anchors itself by frictional interlock between the resin and the rock. Smooth boreholes consistently exhibit a reduced bolt load bearing capacity over rough walled holes because the interlocking effect is reduced. To address this, drill bit manufacturers intentionally use wide tolerances in manufacturing and offset bit cutter inserts in such a way as to induce a wobble during drilling which, when combined with loose bit mounting to drill rod, results in ridges being left on hole walls. This approach generally produces a sufficient wall roughness to increase anchoring capacity. However, even with these variations in borehole smoothness and anchorage capacity improvement, failure of the rock-grout interface is still common.

While considerable research into rock bolting has been conducted to date, gaps still exist in areas that could lead to vast improvements in rock bolt performance. For example, a significant number of pull-test studies have been performed to identify optimal hole diameter to bolt diameter ratios for maximum anchorage capacity. Hole condition has also been identified as an important contributor [10, 11, 12, 13, 14]. A bibliographic search on the topic led to the conclusion that no study has been conducted on the specific influence of modified hole condition by design to improve anchorage capacity.

Research dating back 30 years indicates that roof bolt anchorage failure is most likely when roof rock is weak, i.e. where roof support is most critical [15,16]. In view of the potential for improvement in rock bolt load bearing capacity with the use of the HDB, a testing program was developed to quantify the benefits of conditioning the borehole and to determine the optimal hole characteristics to maximize such improvement.

A HDB was designed that would cut a helical groove or “thread” to “condition” a standard 1 inch borehole. The helical pitch, and groove thickness were designed for weak rock with a compressive strength of about 500 psi and standard grout shear strength of about 2500 psi. The design values were such that the ratio of rock to grout area in shear is slightly larger than the grout to rock strength ratio of 5 to 1 therefore guaranteeing failure of the grout and not of the rock. The groove depth was limited by the amount of grout available in the cartridge. If the groove is too deep, the length of the grout cartridge required to fill the hole can be longer than the length of the hole. Figure 7 shows a picture of a conditioned hole in limestone resulting from use of the HDB.

Field-testing was conducted using the short-encapsulation pull test (SEPT) to make an evaluation of the effect of HDB hole conditioning on resin bolt anchorage. In a SEPT test, a roof bolt is grouted only in the top 12 inches, and then pulled using a hydraulic ram. The maximum load required to break the anchorage is recorded. The effectiveness of the bolt-rock-grout anchorage is measured by the “Grip Factor” which is defined as *the bolt’s resistance to pull out per inch of bolt length*. The Grip Factor is calculated as:

Grip Factor = Maximum SEPT load (tons) / 12 inches

A low Grip Factor (less than approximately 1 ton/inch) means that the bolt has low resistance to rock movement and is typical in mines with weak roof [12,16].

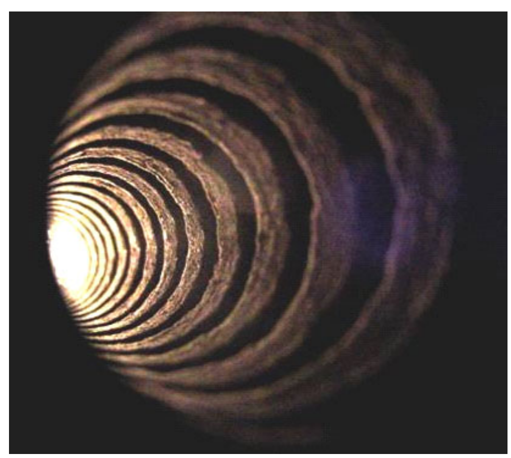

Figure 7 Conditioned hole obtained with the HDB

Two mines with low Grip Factor were selected for testing. Test site one was in the NIOSH Bruceton Mine in Pennsylvania, with an average Grip Factor of 0.69 ton/in.

Test site two was in the BHP Billiton San Juan Mine in Waterflow, New Mexico, with an average Grip Factor of 0.5 ton/in. Both Grip Factor measurements were documented for fully grouted headed rebar bolts using standard drilling techniques from previous studies conducted by others [12, 16].

Test site one: 16 bolts were installed, 8 using a traditional or “standard” drilled hole and 8 using the HDB to condition the hole. Bolts used were 79 inch-long, #6, Grade 60, with a minimum nominal yield load of about 26,500 lb. They were installed in alternating standard and HDB conditioned holes, all in close proximity to each other to minimize the effect of any variation in anchoring horizon.

Results from site one were consistent, showing an average increase in load capacity of 66%, with a maximum increase of 107% between the bolt in the standard hole with the lowest load capacity and the bolt in the conditioned hole with the highest capacity. The average grip factor (GF) was 0.66 (ton/in) for standard holes vs. 1.1 (ton/in) for conditioned holes. These results are presented in Figure 8. Even though the GF standard deviation was nearly the same for standard and conditioned holes, in relative terms standard holes had a 9% variation in load capacity while only 5% variation was encountered with conditioned holes. This suggests that bolts installed in conditioned holes might have more consistent maximum load capacities than bolts installed in standard holes. Half of the bolts installed in conditioned holes exceeded the nominal yield capacity of the bolt, while all of the bolts installed in standard holes exhibited a maximum load that was below 67% of the nominal yield load of the bolt.

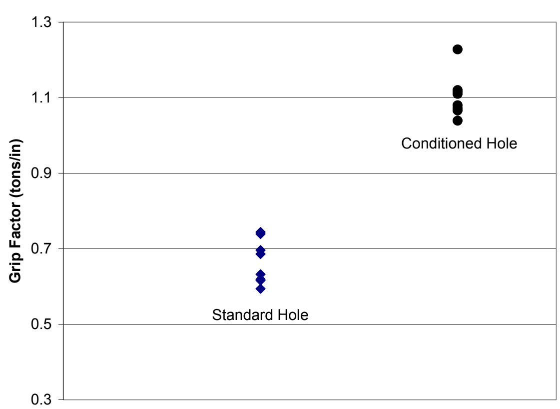

Figure 8 Comparison of Grip Factor between bolts installed in standard holes and bolts installed in HDB conditioned holes.

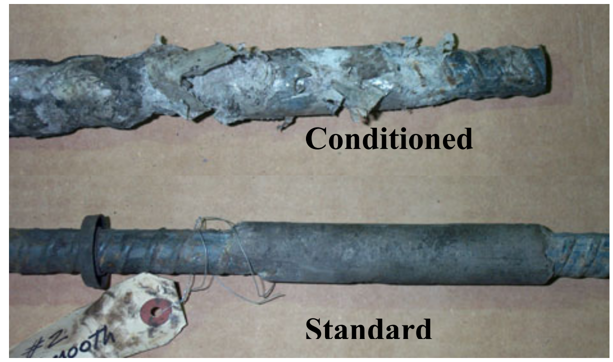

Figure 9 Bolts recovered from the test site. One was recovered from a “conditioned” hole (top) and the other was recovered from a standard hole (bottom).

Two bolts were completely extracted for study, one from a standard hole and one from a neighboring conditioned hole (Figure 9). The bolt from the conditioned hole exhibited some gloving and yet its load capacity was 82% higher than that of the neighboring standard hole, which had no signs of gloving. One possible explanation is that, since friction between surfaces is not the main bolt loading mechanism in conditioned holes, gloving does not present a problem affecting the load capacity of the bolt, provided there is adequate mixing of the grout.

Test site two: Results at site two also showed a dramatic increase in load capacity when boreholes were conditioned using the HDB. 26 bolts were installed; half of them using standard, and the other half using conditioned boreholes. In contrast to test site one, four different bolt lengths were used in order to determine the effect of conditioning the holes in various anchoring horizons. Bolts used were #6, Grade 60, with lengths of 4, 5, 6 and 7 feet. Bolts were installed in alternating standard and conditioned holes, in groups of equal length to ensure similar anchorage horizons. Cores were obtained near each group of bolts in order to characterize roof composition. The 4-foot bolts had an anchorage horizon in a region consisting of carbonaceous mudstone and shale with abundant coaly stringers. The 5-foot bolts found anchorage in a region with weak grey mudstone rich in clay. The 6-foot bolts had anchorage horizon within a combination of rock types. From the bottom to the top, there were 5 inches of coal, 2 inches of carbonaceous mudstone, and 5 inches of fine-grained sandstone. The 7-foot bolts had an anchorage horizon in fine-grained sandstone.

Pull test results are presented in Figure 10. Bolts installed in conditioned holes consistently exhibited higher load capacities than those in standard holes.

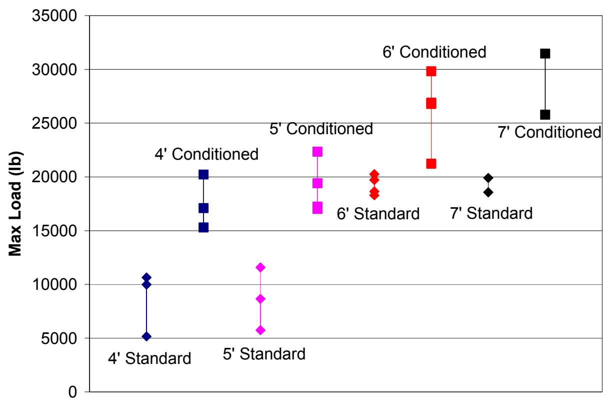

Figure 10 Comparison of maximum anchorage load between bolts installed in standard holes and bolts installed in HDB conditioned holes for the various anchorage horizons tested.

Calculation of the average Grip Factor for each group of bolts installed show consistent improvement in holes conditioned using the HDB. Results are shown in Table 2. Bolts installed in weaker rock, as evidenced by the low Grip Factors of the 4 and 5 feet anchoring horizons, saw the greatest percentage increase in load capacity. Bolts in the relatively more competent rock (6 and 7 feet anchoring horizons) saw a lower percentage increase in load capacity. The improvement however, was sufficient to bring the average Grip Factor above the threshold value of 1 ton/inch, which is the value under which a mine roof is classified as weak. Four of the bolts installed in conditioned holes exceeded their nominal yield capacity. One of them reached the ultimate strength, breaking at the base of the head, something never seen before at this mine during a 12 inch encapsulation test. These high anchorage loads were obtained with the 6 and 7-foot bolts that were anchored in a relatively more competent rock than the 4 and 5-foot bolts.

Table 2 Average Grip Factor for bolts installed in standard and conditioned holes for each of the anchoring horizons tested.

	4 feet	**5 feet**	**6 feet**	**7 feet**
Standard	0.37	0.36	0.81	0.8
Conditioned	0.75	0.81	1.11	1.19
% change	103	125	37	49

It is clear that dramatic bolt load capacity gains can be realized by conditioning the borehole. Mines with weak roof, where demonstrated load capacity improvements are greater, can benefit the most. Even mines with more competent roof could increase bolt anchorage capacity by reducing the negative effect of gloving. By applying borehole conditioning during roof bolting operations, roof support systems can be optimized leading to improved safety in the work environment.

Conclusions

This paper discussed the mining applications of the Helical Drag Bit (HDB). Investigations have demonstrated that bolt anchorage capacities can be substantially increased, by more than 120% in some cases, when the HDB is used to condition the boreholes during roof bolting. Development of a commercial version of the HDB is in progress. This version will be suitable for use in the mining environment, capable of single pass drilling to satisfy production requirements.

The unique geometry of the HDB could allow a drill operator to determine the characteristics of the rock being drilled by measuring only the torque of drilling. Initial testing has demonstrated that a correlation exists between the torque of drilling and the mechanical properties of the rock being drilled underscoring the potential for such application.

The HDB is an efficient drilling tool that can potentially compete with traditional drilling technologies used in the oil and gas industry. The HDB is also useful in environments where size, weight, and energy consumption are limiting factors.

Acknowledgement

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