Abstract

The use of high-pressure waterjets as a method for enhancing the performance of mechanical cutting tools has been well documented over the years. However, concurrent with this development for drag bit tools, there has been some evidence that the combination was not an effective one.

By using sectioned samples of rock indented with a spherical indentor (of the type used in percussive drilling) the reason for the critical positioning of the jet at the rock, tool interface is shown to be due to the very limited gap through which access to the crushed material is available. Further, the gain to be achieved when the jet is played into the crushing zone as it develops, rather than later, is also evident from the experimental work. As with other forms of waterjet assist it is shown that even in rock as hard as basalt a jet pressure of 400 bar is sufficient for effective performance enhancement.

In the second part of the paper tests are described in which the combination of a waterjet playing on a single indentor are extended into the behavior of the indentor as a component in a rotary percussive drill bit. The change in the performance
levels of the separate components of the forces driving a rotary-percussive bit (i.e., cutting, thrust and impulse forces) is evaluated with the addition of a waterjet stream to the cutting process.

1. INTRODUCTION

Drilling is a fundamental part of many aspects of the geotechnical world. However, while the use of waterjets for enhancing the performance of drilling tools has been an ongoing effort for over the past twenty years, there has been little impact on the industry as a whole. In fact, although there is some ongoing research in both Australia and the United States, the progress of this technology in general has been lacking. A major portion of the reason for this relates to the lack of need for such a product. For a number of years the need to drill faster, in most of the common rock found in excavations, has not been pressing, relative to other needs that the industry has. Within the envelope of current performance the rates of drilling in soft and medium strength rock is largely adequate for industrial needs, and increased drilling rates, above those now available, does not often justify the costs of developing such a change (Pierce, Finger and Livesay, 1995).

In contrast, however, in harder rock, rates of penetration of current drills are still slow. In such conditions improved drilling rates can provide a significant benefit, justifying the costs and effort required both developing and introducing such tools. This is particularly true in the Geothermal industry where the costs of drilling and completions of the wells can account for 25 – 50% of the cost of the electricity which they produce (ibid.).

Drilling such rock is, however, by its nature, more difficult than is the case with the softer material. Forces needed to penetrate the rock are higher, and when the cutting tool is dragged over the surface of the rock, the resulting friction can generate high levels of heat. As a result, when this is not immediately removed, the cutting material weakens and is rapidly worn, requiring an expensive replacement. The use of a high pressure waterjet stream to provide cooling was the original justification under which Dr. Hood first added waterjets to assist in the cutting of the hard rocks in the gold mines of South Africa (Hood, 1976). This technology can also be applied in a drilling operation.
The harder rocks types which are the subject of this investigation are generally much more brittle in response than the softer rocks of the more general drilling case. Thus, over the years, it has been found more practical to drill in these formations with a percussive drilling tool, rather than relying on the rotation of a quasi-sharp cutting edge across the surface. In softer rock the percussive blows can be enhanced by rotating the bit, under thrust, to remove ribs of material between adjacent blows, and a rotary percussive drilling system has evolved. In harder rock, the forces required for straight rotary drilling are not always available to achieve significant penetration with a conventional carbide chisel shaped bit, which rapidly blunts and thus, requires increasing levels of force.

An alternative cutting surface has become available over the past twenty years, and this is the use of a polycrystalline diamond coated insert. There are several ways in which these inserts can be identified. For the purpose of this paper they will be referred to as a PolyCrystalline Diamond (PCD) insert. In other publications they are either referred to in this way or as PDC inserts. In general the terms can be interchanged. In a simplified description, one can understand that in such an insert the outer surface of the tool has been coated with a thin coherent layer of diamond. This provides a hard surface, much more resistant to wear, and the benefits of this tool are such that it has been reported that up to 30% of the mining drilling now uses this cutting surface as a replacement for tungsten carbide.

Diamond cutting tools are most widely used for rotary drilling and cutting operations, since the nature of the diamond makes the surface wear resistant. The diamond penetration of the material is shallow, and thus, the bit must rotate at relatively high speed if it is to achieve a satisfactory ROP. In softer rock this is often achievable. In harder rock, however, the thrust required to achieve the necessary penetration is greater, and at the higher rotation speeds, will generate high friction, heat that will, as with the carbide, weaken and enhance the erosion of the PCD surface.

In the alternative approach to drilling hard rock, percussive bits are used, and, as the rock increases in resistance, the shape of the inserts changes from a sharp edged insert to a rounded surface, to increase the resistance to erosion. This current study began by examining hard rock failure under such an indenting tool, and then developed into the evaluation of a combination of PCD and high-pressure waterjet for rotary percussive drilling in harder rocks. For brevity, the studies reported herein will deal only with work on granite and basalt, out of a larger suite of rocks tested (Gertsch, 1998).
2. INDENTATION TESTING

Rock indentation tests on single inserts have provided fundamental information on tool behavior for over 40 years (Cheatham, 1958). By comparing the forces required to drive the insert into the rock, with the distance penetrated, a fundamental understanding of the interaction can be evolved. As part of a larger research project to investigate rock failure and to improve rock-cutting tools, a series of rock indentation tests began the experimental program. One novel addition to the test program was to section the indented rock samples, and to investigate the nature of the revealed failures.

While past force-penetration investigations have tended to concentrate on wedge-shaped indentors, this work deliberately was limited to spherical indentors. When a sharp indentor works on rock, it quickly assumes the lowest possible energy shape: a spherical cross-section. This tends to hold for drill bit inserts and other rock cutting tools such as disc cutters, particularly when working in hard rock. Because of this, most percussion bits have rounded inserts, and it was decided to limit the initial test program to such shapes.

3. EXPERIMENTAL PROCEDURE

Semi-spherical topped inserts of various diameters measuring up to 1.6 cm diameter were used in this program, with individual inserts being used to penetrate prepared core samples along the central core axis (Figure 1). The inserts (or indentors) were forced into core samples to a variety of set depths, monitoring the penetration force during penetration, from which one could calculate the required penetration energy.
Figure 1. Schematic of the test arrangement for low and high energy loading rates.

The complete test suite of rocks includes granites, basalt, quartzite, limestones, sandstones, and other igneous rocks. One major goal of the program is to find ways to improve the drilling rate of percussive tools in hard crystalline rocks.

The rock cores tested were nominally 54 mm (NX or 2-1/8 inches) in diameter and 76 mm (3 inches) long. Each core sample was cemented into a confining pipe section using a 63 MPa hydro-stone in a steel pipe 54 mm (2 inches) high with an inside diameter of 54 mm. Before cementing the sample in the pipe, each end of the core sample was ground flat with a diamond grinding wheel using a surface grinding machine and standard V-block holders. The core sample was cemented flush with the pipe on the end that was to be indented. On the lower end, the core protruded 2.5 cm beyond the jacket to ensure the core was always in sole contact with the lower loading platen (Figure 1). Observations from the test suite indicated that this lower test geometry had no influence on the results observed.

The confinement shown in Figure 1 is a passive system. There is no confinement on the sides of the sample until the sample is loaded. As a result, the rock sample
does not simulate the semi-infinite plane that a field drilling tool encounters. However, the confinement system was selected because:

- Testing core is a common geotechnical approach. Core preparation for this investigation was an inexpensive and readily available option.
- Core sized samples can be easily cut apart after a test and the internal failures evaluated.
- The passive system allows failure strains to develop outside the immediate contact point. One goal of the test program was to determine how the differences in strain failures related to the variety of rock properties in the sample suite.
- The results will be correlated with indentation data from tests on semi-infinite samples.

Two primary loading conditions were used:

1) For low velocity loading, a hydraulic test fixture was used to force the indentor into the sample to a set depth over a 1 to 2 second time frame, while indentor force was continuously monitored. For this low quasi-static loading rate, penetration depth into the rock was set to given values, penetration force measured, and penetration energy calculated.

2) For the high loading rate, a drop test fixture was built and power transmitted to the indentor by dropping a 68 kg (150 lb.) weight onto the holding fixture, which penetrated the rock at a much faster rate. For this dynamic load test, penetration energy was the set variable and was controlled by setting the drop height and weight, the penetration that resulted was then measured. The weight was dropped from various heights ranging from 0.3 to 1.8 m (one to six feet).

For both the low and high loading rates, the input energies to the indentors were adjusted to lie within the same range.

4. RESULTS

The first rock tested was fine-grained Dresser basalt with a uniaxial compressive of 479 MPa (69,500 psi.). In addition to its high compressive strength, this rock
tends to store a large amount of energy before and during failure. As shown in Figure 2, over 1,356 joules (1000 ft-lb.) of total energy was delivered during some of the indentation tests. This level of energy is higher than usually imparted through a drill insert; however, the polycrystalline diamond surface coating on the insert exhibited no wear over the full test suite.

![Figure 2](image_url)

**Figure 2.** Comparison of total penetration with energy in Dresser Basalt.

The results obtained from the Dresser basalt, showed that the relationship between the energy input to the indentor and the penetration achieved was relatively linear. Regardless of penetration depth or loading rate, a given input
energy is necessary to achieve a given penetration (Figure 2). This energy: penetration relationship is confirmed by examining the load-penetration shown in Figure 3. As the indentor penetrated into the rock sample, no catastrophic failures are evident during the penetration history, which is confirmed by the steep rise of the force curve to 1.27 mm (0.05 inch) penetration, and the less steep but constant rise after that. The change in slope that occurs corresponds to an increase in the amount of fracture failure compared to the amount of crushing generated in the rock. The increase in fracturing lessens the bearing capacity of the rock, and less load is needed to achieve further penetration into the rock. The bearing capacity loss likely comes from reduced confinement around the indentation.

5. WATERJETS IN THE CRUSHED ZONE

If a waterjet-assisted system is to work the jets must strike the rock in the zone where the tool is crushing the material. Because the jets work at relatively low pressure when compared to the rock strength, it is futile to have the jets strike intact rock outside this zone, which is generally within two mm. of the tool impact zone (Figure 4). Thus, equipment which has been manufactured to use waterjets in which the jets strike the rock 4 mm from the impact point are inherently doomed not to work. Unfortunately this has not always been understood.

![Figure 4. Waterjets directed under an impacting PDC cutter.](image-url)
One problem with designing systems which combine mechanical and waterjets comes with the large quantities of water generated when a high-pressure waterjet flows continuously into the crushed zone. Such a flow is not always necessary, since the rock crushing process is itself quasi-cyclic. Thus, it should be possible to integrate a pulsating waterjet system into the cutting system to reduce the quantities of water used. A further advantage of pulsed waterjets is that less power is used in the jet assist when compared to a continuous jet, significantly lowering the power requirements of the drilling system.

In the design of the rotary percussive hammer, it has therefore, been decided to use the pressure pulses generated by the impacts of the hammer to provide the pressurized water for the flushing operation. This part of the program is being carried out by Novatek, under whose funding this program is being carried out. It is important to understand the role which the waterjet plays in the process of rock failure under the impacting bit. To illustrate the benefits, examples of the cores were sectioned along the line of the center of the indentation. Before sectioning the rock the site was impregnated with resin to hold all the fragments in place and thus, to more clearly show the pattern of damage under the insert.

![Figure 5. Indentation without waterjet impact.](image-url)
The benefits of adding the water, despite the limited role it plays, can be seen in three tests where a waterjet and PDC insert combination were used to penetrate a 479 MPa (70,000 psi) basalt. In the first example shown above (Figure 5) the indentor was struck with a given amount of energy, and without waterjet use. The bit penetrated approximately 1 mm into the rock. Underneath the bit a zone of crushed rock extended to at least this depth, but the rock has not only failed, but been recompacted by the bit. As a result a considerable amount of energy would be required to remove it. This can be seen in the next test (Figure 6). The indentor was driven into the rock with the same energy, creating the same pattern of damage, and then the cavity was washed with a 400 bar waterjet spray. The indentor penetrated the same 1-mm, and the waterjet washed out a cavity in the underlying crushed basalt an additional 3-mm deep. However, because the cavity was narrower than the indentor was, the indentor would need to re-indent the cavity to achieve the additional 3-mm of penetration. In the third test, (Figure 7) the 400 bar jet played along the edge of the indentor as it struck the rock. As with the previous test, the crushed rock was removed by the jet. In this case this occurred as the indentor advanced, and since the two events occurred simultaneously, the bit advanced the full 4-mm penetration with a single stroke.

While this illustrates the benefits of having the two events occur simultaneously, it also suggests that it is only necessary to have the jets acting on the bit when it is actively crushing the rock. For the remaining time it is unnecessary. Since this
requires the jet to operate for less than half the time involved with a continuous jet stream it provides an opportunity to develop of a tool which gives the same effect but at half the energy and with half the water usage. In some locations the second advantage is the greater of the two.

6. ROTARY PERCUSSIVE TESTING

It is evident from the above results that the combination of waterjets with PCD inserts can have benefit during the percussive phase of the drilling operation. The next question to investigate was whether it could also enhance the rotary portion and the combined cutting operation. In order to make this evaluation a new testing frame was constructed. This frame (Figure 8) is made up of moving table, driven by an underlying hydraulic cylinder. This allows a measure of the cutting force to be obtained during rock removal. A platform is then set over the rock sample, and two thrust cylinders can be used to set up a known penetration of the insert into the rock. To provide an impact force, the platform with the insert is set under a weighted rod. The rod is raised and dropped using a shaped guide rotated by an electric motor.
Figure 8. Rotary percussive test rig (artists rendering to show the components).

It should be noted in the above figure that the cutting tool is actually located directly under the pulsating load rod, but is dragged along by two instrumented bolts shown next to the connecting point. During a test the penetration depth is set, and the rock moved under the bit. The percussive motor is started, and, at a defined frequency, the weight drops onto the inset, creating an additional penetration of the rock at defined intervals.

It was originally anticipated that the tests would be carried out at a number of different conditions, both with and without the use of the high-pressure jet stream. For these tests a jet pressure of 42 MPa was used since it has been found both at UMR and extensively elsewhere, that this pressure is effective in removing the crushed rock around the impact point. The initial tests were carried out using a cylindrical insert, with a slightly rounded edge, set into the holder at a positive rake angle of 45°. This is not the forum for an extended discussion as to why this angle was chosen. However, a brief comment is appropriate. In cutting soft rock a negative rake angle, which in coal mining is around 30°, is often most effective. However, in harder rock, it is important to have a sufficient body of material behind the cutting edge to support the forces imparted, and with the type of insert required this mandated that the angle be positive. Since the insert was being driven into the rock with contact on both sides of the cutting edge, and the bit thus wears on both the front and back faces; a 45° angle seemed an appropriate starting point for the tests.

The initial blow energy for the drop weight was set at 68 joules (50 ft-lb) and the spacing at around 2-cm between adjacent blows. The initial penetration of the rock was set at a depth of around 1.5-mm. Initial evaluation of the performance of the loading frame was carried out on concrete samples, given the high cost of rock. The first actual cutting tests were then carried out on a red granite sample block. The granite is the local Missouri Red.

Table 1. Relative depth of cut into the rock from a test run across the block measured a distance of some 30-cm.

<table>
<thead>
<tr>
<th>Depth without water (mm)</th>
<th>Depth with h-p water (mm)</th>
</tr>
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<tbody>
<tr>
<td>2.24</td>
<td>3.33</td>
</tr>
<tr>
<td>2.93</td>
<td>3.25</td>
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<tr>
<td>2.17</td>
<td>3.61</td>
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It was found, during the first test run of the insert, without high-pressure water added, that within two passes over the surface the bit was failing in shear. Two separate runs gave the same result. Tests with high-pressure water added to the bit (fed centrally down the cutting face axis to the point of contact) did not give the same immediate problem, and a series of six passes were made without failure. On a seventh pass again failed in shear. Examination of the penetration of the sample showed that there was a significant difference between the cut made with and without the jet (Table 1). The final runs were also made in cutting into rock which had been cut before and where the depth was no longer a constant, which may also have influenced the conditions at failure. Evaluation of the conditions of failure is still continuing.

Although these results are preliminary it is clear that, under the current conditions of testing, the operation of the bit will only work when the bit is flushed with high-pressure water during the impact stroke. It is currently believed that this is because of the way in which the rock fails under the bit. As the bit is driven down into the rock it crushes the material (as shown in Figure 5) with the crushed zone conforming to the shape of the tool. In the rotary percussive mode of the drill, the insert is immediately subject to the rotary or cutting force, forcing it into the solid rock ahead of it. The rock has been penetrated to a considerably greater depth than the bit is designed to fail under conventional cutting (in relative terms the conventional cutting depth is around 1-2 mm and the impact blow is driving the bit in an additional 2-3 mm). The increase in shear force on the bit face is thus, sufficient to fail the carbide support behind the bit.
In contrast, when the waterjet is applied to the bit, the crushed material is washed from the area as it is formed. The bit penetrates further into the rock, but without any confinement except only at the very extremity of the bit. And even here, in most cases, the underlying root crack has been exposed and washed clean in almost all cases. Thus, there is no confinement of the bit, and with free space ahead of the insert it has the opportunity to recover and return to the initial set depth of cut before it contacts solid rock. This largely removes the problem, although the current failure of one of the bits even in this condition suggests that considerable additional work is required to identify the parameters where this will hold true and what shear conditions the bit can withstand. Changes in angle and cooling conditions are also part of the current study, as well as changing the blow frequency and amplitude.

7. REFERENCES