Frustum Bit Technology for Continuous Miner and Roadheader Applications

Submitted to:
Pat Willis
CSIR
The South African Institute of Mining and Metallurgy
Center for Mine Mechanization and Automation

Prepared by:
Brian Asbury
Levent Ozdemir
Tibor G. Rozgonyi
Colorado School of Mines
Mining Engineering Department

Synopsis

A new type of bit, that has been developed and is being evaluated, shows great potential in expanding the strength of rock that can be cut by continuous miners and roadheaders. This new style of bit is called the frustum. The tools tested in this program were developed, manufactured and patented by Briese Industrial Technologies, Inc. The frustum derives its name from the unique geometric shape of the cutter, or cutting insert. The frustum shape cutting tool has previously been proven as an effective cutting tool for machining metals, metal matrix composites and polymers.

The frustum rock bit has a very dense carbide frustum shape tip mounted on the end of a steel body similar to the conical bits typically used on continuous miners and roadheaders. In between the carbide frustum cutting tip and the steel body there can be a bearing that allows the frustum to rotate around the bit axis. When this bit is forced into the rock at a skewed angle, the frustum tip rotates as it travels. This rotation greatly reduces the cutting forces acting on the bit when compared to the current state of the art conical drag bits. This cutting force reduction, generated by the frustum's cutting action, allows for much harder and more abrasive rock to be cut without quickly wearing out the bit.

Full scale laboratory cutting tests have been performed with the frustum bit in direct comparison to the current state of the art conical bits. Field trials of the frustum bit are currently being planned. Test procedures, results and findings are presented.

Background

Currently, mining machines that utilize drag bits are limited by the toughness and abrasiveness of the rock being mined. This is because the fixed tip of drag bits generate a very large amount of friction between the cutting tip and the rock. When the rock becomes too hard or abrasive, standard drag bits fail quickly. This typically provides the economic limit of using currently available drag bits.

This limit of the drag bits has been surpassed by rolling cutters, such as single disc cutters and button rolling cutters. Since the rolling action of these cutters greatly reduces the friction between the cutter and the rock, these rolling cutters have the ability to cut extremely hard and abrasive rocks. The draw back of the current rolling cutters is that they require a large normal force, or thrust, to penetrate the rock. Therefore, the only machines with the ability to utilize the standard rolling cutters are heavy very large stiff machines with little mobility, such as Tunnel Boring Machines and Raise Borers.

A new type of bit, known as a frustum, is being introduced. The frustum style bit has been proven in the fields of machining hard metal and polymers. This type of bit shows great potential in expanding the hardness/toughness of rock that can be cut with currently available mining machines that have historically used pick cutters. This potential stems from the frustum's cutting action which uses a more tensile failure method associated with drag bits in conjunction with the mechanical advantage of a bearing, used in rolling cutters.

Objective

The frustum bit is new to rock cutting. Therefore, its cutting action in rock must be understood in order to maximize its potential advantages. Given that the frustum works on a very different cutting action, the typical cutting geometries for existing bit types do not apply. This study begins the identification of the optimum cutting geometry for the frustum bit, as well as evaluating its survivability and performance compared to existing drag bits.

Frustum Bit Description

A frustum is defined as that part of a cone-shaped solid next to the base and formed by cutting off the top with an approximately spherical surface as can be seen in Figure 1. The tools tested in this current program have been developed, patented and manufactured by Briese Industrial Technologies, Inc.

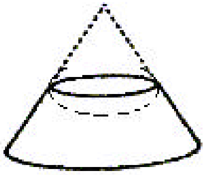

Figure 1: Geometric Frustum.

The bits evaluated in this program utilized a rotating frustum tip mounted on the end of a conical style bit body. The axis of the frustum bit body is skewed from the direction of travel to initiate rotation of the cutting edge. The bit is skewed to cut into the adjacent cutting path which has yet to be cut. This, in conjunction with a bearing installed in the body, allows a continuous rotation of the frustum cutting edge. Figure 2 shows a schematic of a frustum bit set up for full scale testing.

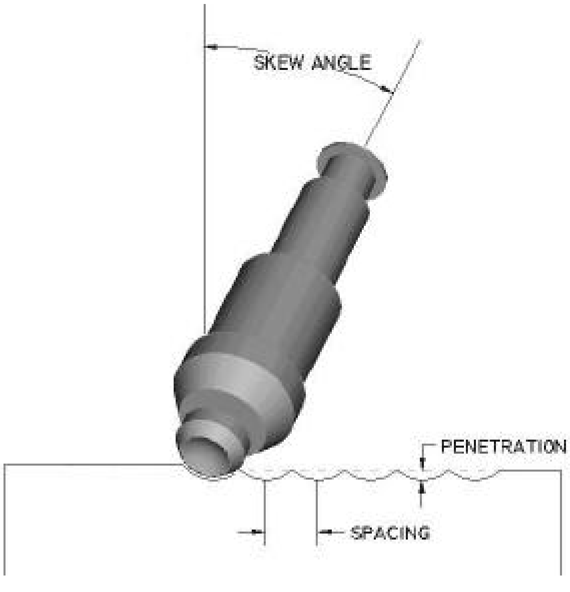

Figure 2: Schematic of Frustum Operation. (Courtesy Briese Industrial Tech.)

TEST PROGRAM

Introduction

This test program consisted of full scale cutting tests using different bit types at differing cutting geometries in a strongly cemented high silica sandstone. The Linear Cutting Machine (LCM) at the Colorado School of Mines was used for the cutting tests. The LCM forces a large rock sample through an actual bit at a preset cutting geometry. The linear cutting tests measure forces acting on the cutter to ensure that the bits are operating as they would on an actual excavator while providing an acceptable level of production. This full-scale testing eliminates the uncertainties of scaling and any unusual rock cutting behavior not reflected by its physical properties. This is because the cutting action of the LCM very closely simulates the cutting action seen in the field. After each pass of cutting tests, muck samples were collected to determine the relative percentages of respirable dust generated by cutting.

Linear Cutting Test Equipment and Procedures

The Linear Cutting Machine (LCM) features a large stiff reaction frame on which the cutter is mounted. A tri-axial load cell, located between the cutter and the frame, monitors forces and a linear variable displacement transducer (LVDT) monitors travel of the rock sample. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. A schematic drawing of the LCM is presented in Figure 3.

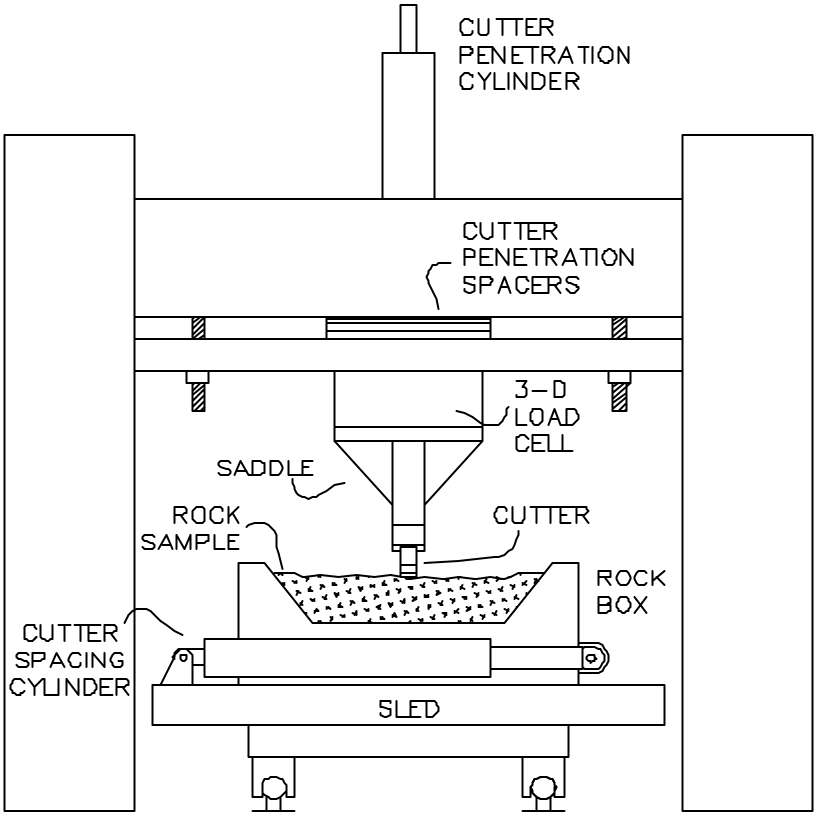

Figure 3: Schematic Drawing of the LCM Testing Stand.

A servo controlled hydraulic actuator forces the sample through the cutter at a preset depth of penetration, width of spacing and constant velocity. During the cut, the tri-axial load cell measures the normal, drag, and side forces acting on the cutter. After each cut the rock box is moved sideways by a preset spacing to duplicate the action of the multiple cutters on a mechanical excavator. A drawing of the three force components acting on a conical bit is shown in Figure 4.

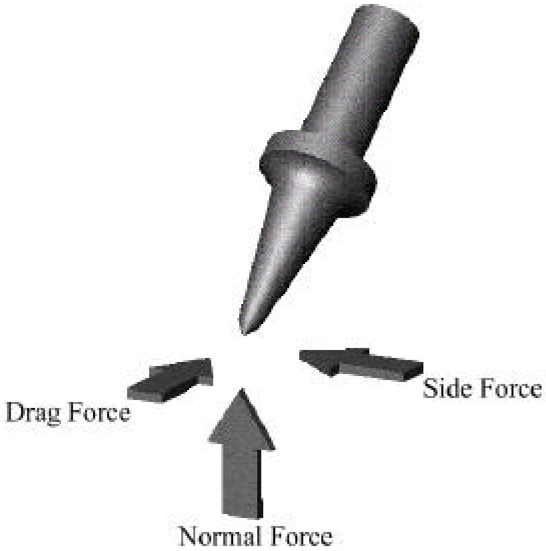

Figure 4: Schematic Drawing of Forces Acting on a Conical Bit.

In field excavation, the individual cutters on the machine always operate on a rock surface damaged from the previous cutting action. This scenario is duplicated in the laboratory by thoroughly conditioning the rock surface before testing begins. This is accomplished by making several passes before data is collected. A schematic drawing explaining the nomenclature is presented in Figure 5.

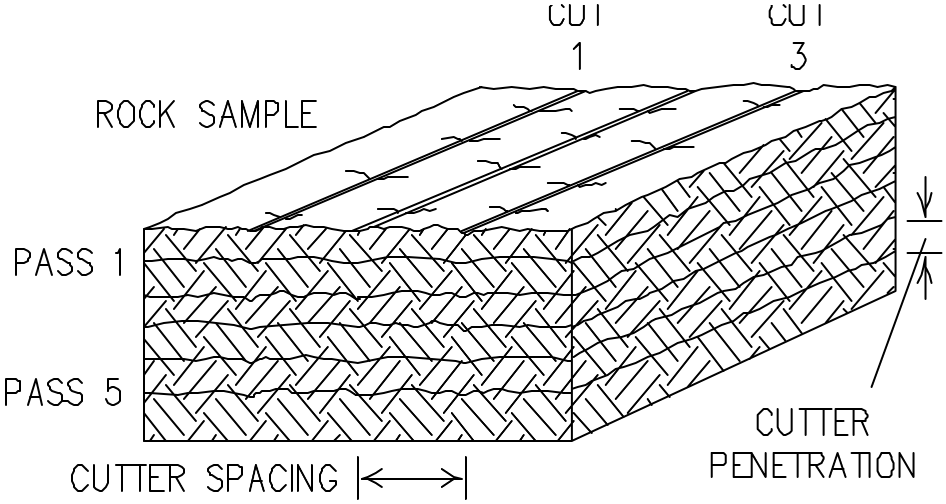

Figure 5: Schematic of a LCM Sample and Nomenclature.

Bit Types

A total of 4 different bits were tested in this study. Two were frustum bits and two were commercially available conical bits. The main difference between the two frustum bits was the aperture of the frustum. One of the frustum bits had an aperture of 19mm and the other was 38 mm. The 19 mm diameter frustum was approximately 3.2 mm deep with an outer diameter of 25 mm. The 38 mm frustum was approximately 6.4 mm deep with an outer diameter of 48 mm. Both of the frustum bit had a gauge length of 84 mm and their tips were made from tungsten carbide. Figures 6 and 7 show line drawings of the tested frustum bits.

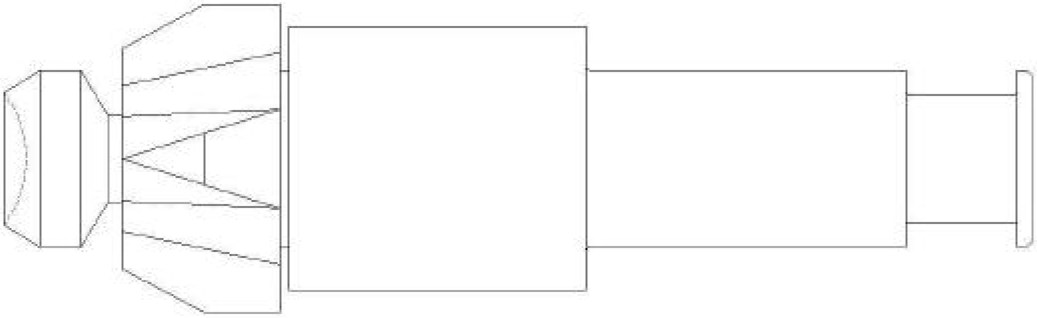

Figure 6: 19 mm Frustum Bit

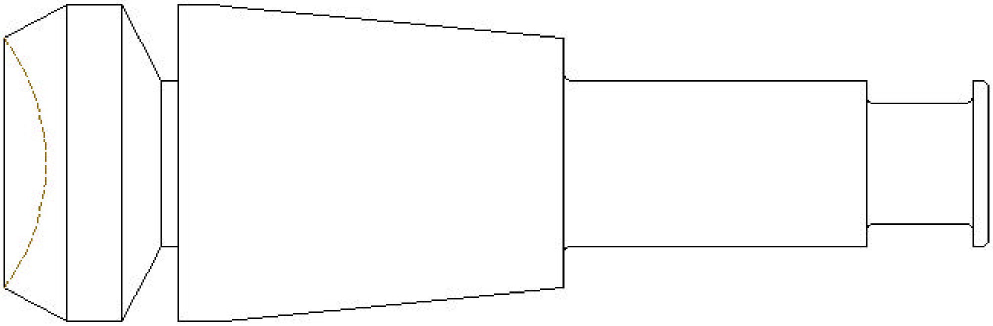

Figure 7: 38 mm Frustum Bit.

The two standard point attack conical bits tested in this program were the U-92 KHD and the U-94 (Figures 8 and 9, respectively), both produced by Kennametal. Both of these bits would commonly be used on continuous miners for producing coal, where harder coal measure rocks such as hard sandstone, in the floor or roof are encountered. The U-92 had a 16 mm diameter tip and the U-94 had a 19 mm tip. Both of the commercially available conical bits had a tip angle of 75 degrees.

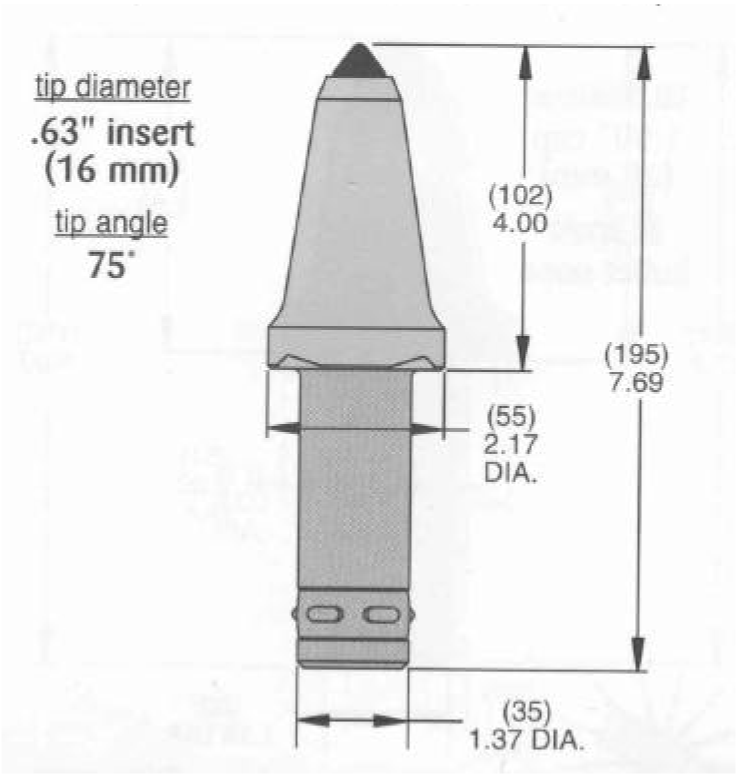

Figure 8: U-92, with a 16 mm Diameter Tip (Courtesy of Kennametal).

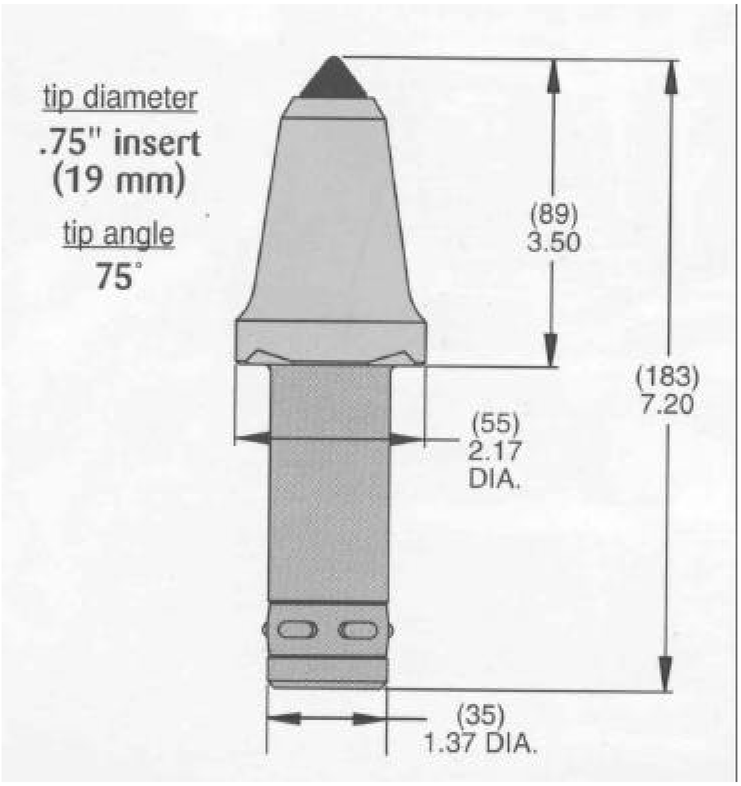

Figure 9: U-94, with 19 mm Diameter Tip (Courtesy of Kennametal).

Test Matrix

The frustum bit cutting tests were performed with the frustum edge cutting into the confined surface. This is defined as a negative skew angle and is illustrated in Figure 10. Attack angle is defined as the angle between the bit body axis and the cut surface. Attack angle is presented graphically with a conical bit in Figure 11. All of the frustum testing was performed with an attack angle of 45 degrees.

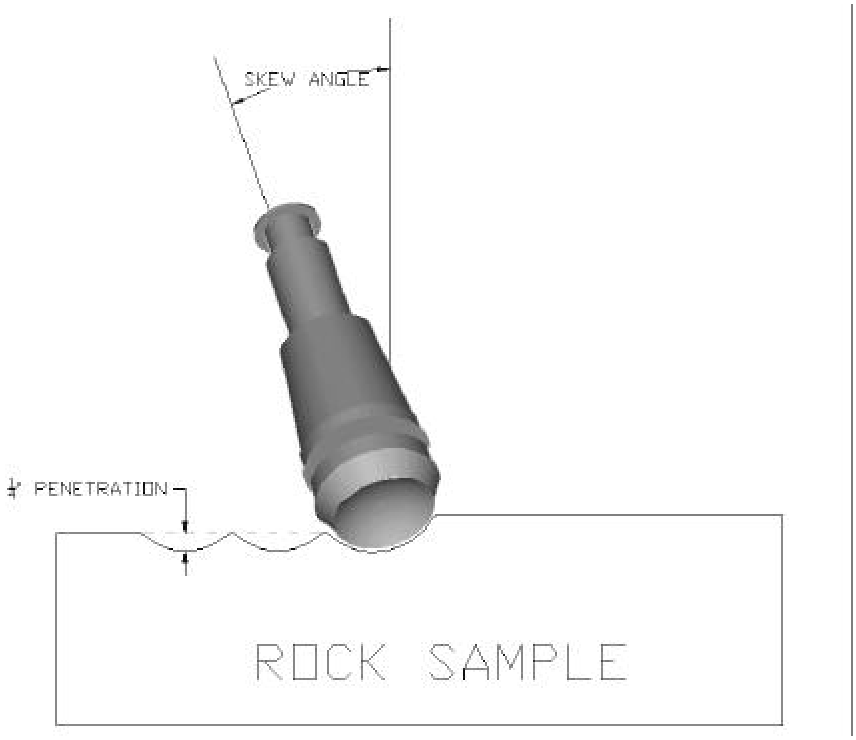

Figure 10: Negative Skew Angle of a Frustum Bit.

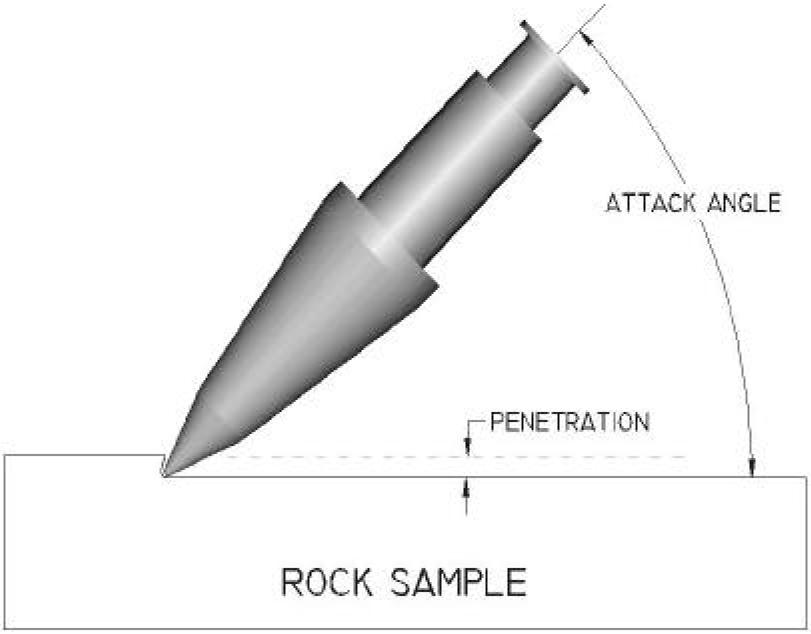

Figure 11: Attack Angle Description.

The conical bits were tested at cutting geometries that were expected to be required to most effectively mine the sample material given its strength and abrasivity. Table 1 provides the test matrix as tested to date for both the conical drag bits and the frustum bits.

Tool I.D.	Attack Angle	Skew Angle	Spacing (mm)	Pene. (mm)	S/P (ratio)
0.75" Frustum	45 deg.	20 deg.	13	2.5	5
0.75" Frustum	45 deg.	20 deg.	19	2.5	7.5
0.75" Frustum	45 deg.	15 deg.	19	2.5	7.5
1.5" Frustum	45 deg.	20 deg.	19	2.5	7.5
1.5" Frustum	45 deg.	20 deg.	25	2.5	10
1.5" Frustum	45 deg.	20 deg.	38	2.5	15
U94	48 deg.	0 deg.	13	2.5	5
U94	48 deg.	0 deg.	19	2.5	7.5
U94	52 deg.	0 deg.	13	2.5	5
U94	52 deg.	0 deg.	19	2.5	7.5
U92 KHD	52 deg.	0 deg.	13	2.5	5
U92 KHD	52 deg.	0 deg.	19	2.5	7.5
U92 KHD	52 deg.	0 deg.	25	2.5	10
U92 KHD	52 deg.	0 deg.	25	5.1	5

Table 1: Linear Cutting Test Matrix.

Rock Sample Properties

The rock used for the cutting test was Lyons Sandstone. This was a hard, abrasive sandstone that is similar to roof rock in many underground coal mines. It is representative of relatively difficult cutting conditions. The Lyons Sandstone had a compressive strength of 120 MPa and a tensile strength of 6.1 MPa. It should be noted that the Lyons Sandstone is a very abrasive rock, as can be seen by its measured Cerchar Abrasivity Index of 3.3. Physical property test results for the tested sample are presented in Table 2.

Density	Uniaxial Compressive Strength	Brazilian Tensile Strength	Cerchar Abrasivity Index	Elastic Constants	
				Young's Modulus	Poisson's Ratio
(g/cm^3)	(Mpa)	(Mpa)	(Index)	(Gpa)	(ratio)
2.39	158			36	0.17
2.40	109			37	0.17
2.39	92			35	0.18
		7.4	3.33		
		6.3			
		4.7			

Table 2: Test sample physical property test results.

Linear Cutting Test Results

All force data collected from cutting tests with the frustum bit were performed with an attack angle of 45 degrees and a skew angle of –20 degrees. Non-force data collecting attempts were made with a skew angle of –15 degrees, but rotation was not induced. All of the frustum testing with a -20 degree skew angle provided steady rotation throughout cutting with the frustum. Figure 12 shows the frustum bit set up for testing in the Lyons Sandstone.

Figure 12: 38 mm Frustum Cutting Lyons Sandstone.

For the Frustum bits, both the normal and drag forces increased with the increase in spacing. Table 3 presents the linear cutting test results for the frustum bit operating in Lyons Sandstone. Normal forces ranged from 2,500 to 12,000 N. Drag forces ranged from 1,500 to 8,100 N. It should be noted that the drag forces increased greatly when the forward apature of the frustum was exceeded. The drag force increasing faster than the cut spacing creates an increase in the specific energy requirement seen by the specific energy value increasing from 12 to 15 and then jumping to 23 kW-hr/m^3.

			Average Forces			Specific
Tool I.D.	Spacing (mm)	Pene. (mm)	Normal (N)	Drag (N)	Side (N)	Energy (kW-hr/m^3)
19 mm Frustum	13	2.54	2,518	1,517	254	13.1
19 mm Frustum	19	2.54	7,272	4,123	76	23.7
38 mm Frustum	19	2.54	2,898	2,073	567	11.9
38 mm Frustum	25	2.54	5,131	3,430	679	14.8
38 mm Frustum	38	2.54	12,049	8,144	-1,729	23.4

Table 3: Linear cutting test results for the rotating frustum bit.

A series of baseline tests were performed with state of the art conical bits suited for the difficult cutting conditions of the Lyons sandstone. The trends seen in the results for the conical bit testing were quite typical. The specific energy values for the conical bit ranged from 14 to 46 hp-hr/yd^3. The summary of the conical force results from the linear cutting tests are presented in Table 4.

				Average Forces			Specific
Tool I.D.	Attack Angle	Spacing (mm)	Pene. (mm)	Normal (N)	Drag (N)	Side (N)	Energy (kW-hr/m^3)
U94	48 deg.	13	2.54	9,298	5,365	2,802	46.2
U94	48 deg.	19	2.54	13,640	7,549	2,486	43.3
U94	52 deg.	13	2.54	6,358	3,724	1,321	32.1
U94	52 deg.	19	2.54	11,272	6,048	1,009	34.7
U92 KHD	52 deg.	13	2.54	4,207	2,931	383	25.2
U92 KHD	52 deg.	19	2.54	7,053	4,926	1,123	28.3
U92 KHD	52 deg.	25	2.54	11,066	7,583	-1,162	32.7
U92 KHD	52 deg.	25	5.08	8,850	6,613	-1,327	14.2

Table 4: Linear Cutting Results from Conical bits.

Muck samples from the linear cutting tests were collected to determine the relative percentage of respirable dust generated by cutting. This was done for both the frustum and the conical bits. A cut of size of 25 microns was used as a relative measure of respirable dust. The 25 micron material ranged from 7.6 to 9.7%, for the frustum bit. The percentages of dust generated by the conical bits were somewhat higher than the frustum results. The dust generation results for the 25 micron size material bit are presented in Chart 1.

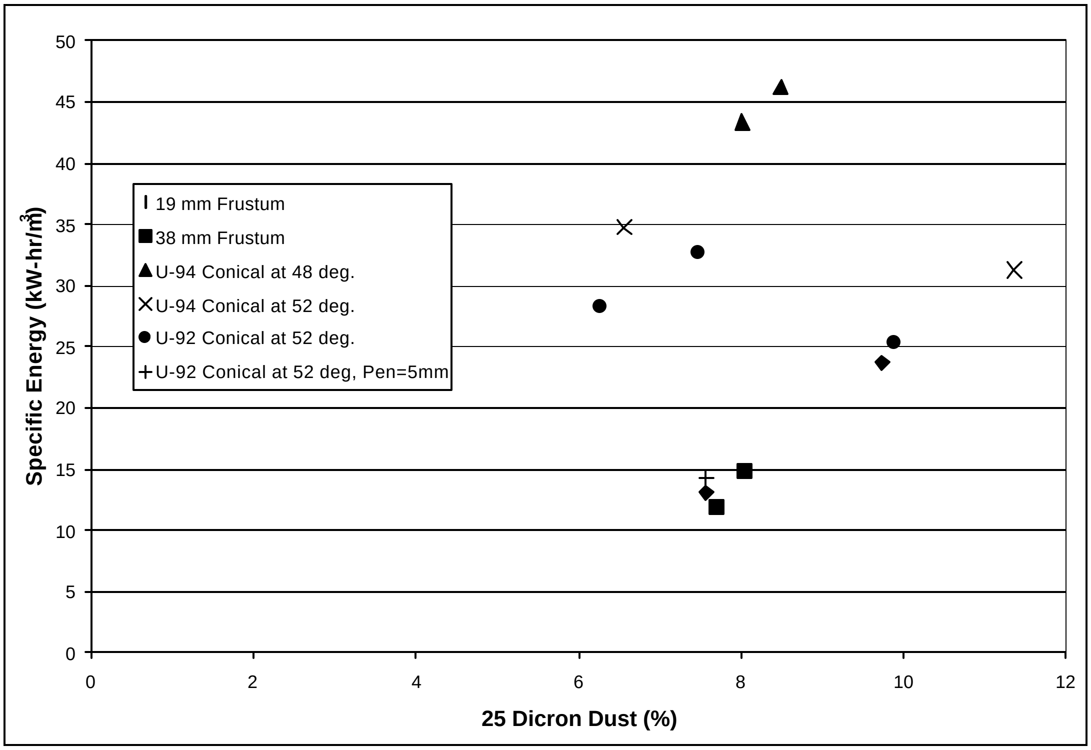

Chart 1: 25 micron dust results, all penetrations = 2.5 mm, except as noted.

Discussion of Test Results

As can be seen in Chart 2, the specific energy requirements for the frustum bits were substantially lower than those of the conical bits. This means that a mining machine properly utilizing frustum bits would be able to excavate the Lyons sandstone considerably faster than the same machine using conical bits.

The optimum cutting geometry for the frustum bits has not been completely identified. But it is believed that the cut spacing for the frustum bits should be slightly less than the forward aperture of the frustum. This means that a cutterhead using frustums would have considerably more bits than a cutterhead using conical bits. This, combined with the fact the force requirements of the frustum bits are substantially lower than the conical bits, means that the summed forces acting on the cutterhead would be better balanced. Therefore, less vibration would be transferred to the mining machine, reducing maintenance and downtime.

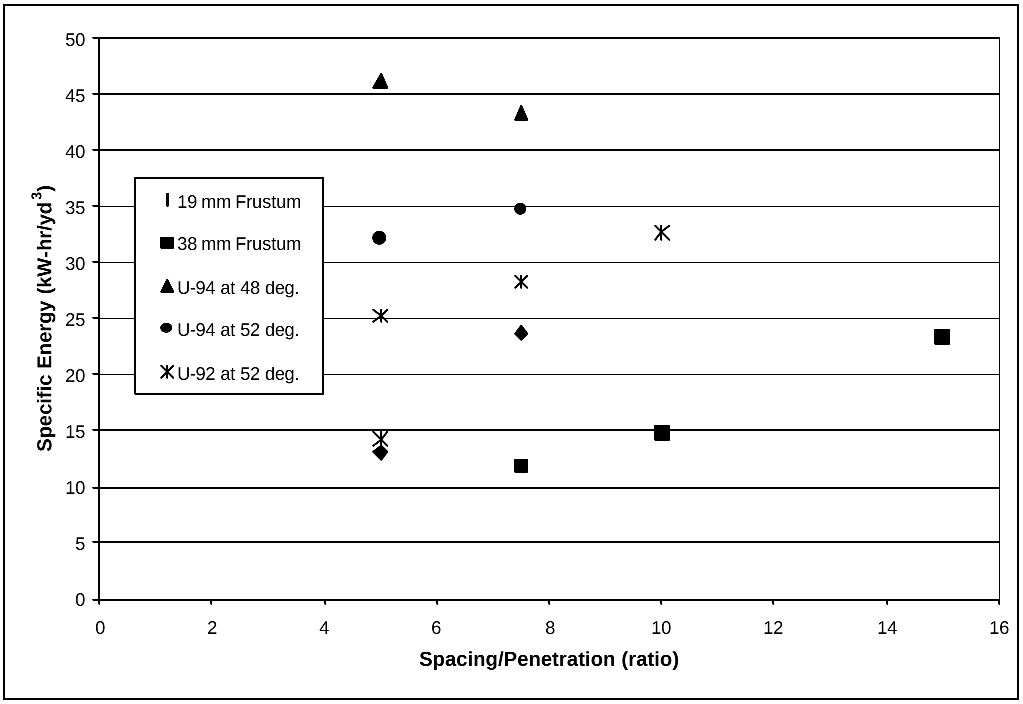

Chart 2: Linear Cutting Results for the Frustum and Conical Bits.

A substantial observation regarding bit wear was made during this study. The rotating frustums showed little to no abrasive wear, while the conical bits experienced a great amount of steel wash in very little cutting time in the same rock. Figure 13 shows the U-92 conical bit after approximately 10 linear meters of cutting and the 19 mm frustum after almost 100 meters of cutting. It can clearly be seen that the conical bit has lost much of the steel supporting the carbide tip, and the 19 mm frustum bit remained relatively unchanged. The test results show that the frustum bit has great potential to reduce bit cost, as well as improve utilization, by reducing down time for bit changes while cutting hard, abrasive rocks, and extend the mobile mechanical rock excavation technology to the hard or even very hard and abrasive rocks category.

Figure 13: U-92 Conical and 19 mm Frustum Bits After Testing.

CONCLUSIONS

The frustum bit presents great potential for increasing the strength and abrasivity of rocks that can be economically cut in mining and construction applications. Its rotation allows hard abrasive rocks to be cut with minimal wear while also greatly reducing the cutting forces and specific energy requirements. The frustum's low cutting force requirements lend itself to application with existing mining machines such as continuous miners, roadheaders, drum shearers and surface miners.

Before field trials are performed, the frustum's optimum cutting geometry will be identified through further linear cutting tests. By doing so, the cutterhead could be designed to properly match the mining machine to the rock being excavated.