An Approach to Identifying Geological Properties from Roof Bolter Drilling Parameters

Gerald L. Finfinger, Senior Scientist
NIOSH - Pittsburgh Research Laboratory
Pittsburgh, PA

Syd Peng, Chairman and Charles T. Holland Professor
Quanzhong Gu, Graduate Research Assistant
Department of Mining Engineering
West Virginia University
Morgantown, WV

Gene Wilson, New Product Development Manager
J.H. Fletcher & Company
Huntington, WV

Bob Thomas, President
Structured Mining Systems
Canonsburg, PA

ABSTRACT

Identifying the properties of overlying rocks in underground mining operations is important to ensure the appropriate roof support design is used to maintain stability of the mine entries. Recently J. H. Fletcher & Co. developed a monitoring and control system for roof bolters for the underground mining industry. The system records the drilling parameters used during roof bolt drilling and the information can provide insight into the physical properties of the roof strata. The parameters include thrust, rotational speed, torque and velocity and the measurements are collected every 0.1 second during the operation.

The drilling parameters were analyzed to determine the application of identifying the strength of rocks being drilled from the measurements. The data was converted into the specific energy of drilling which is a measure of the amount of energy required for removing a given unit of rock during a drilling operation. The laboratory studies completed to date indicate a fairly high correlation between the specific energy of drilling and the unconfined compressive strength of the rocks that were drilled. Additionally, the drilling parameters were shown to be effective for identifying the presence of fractures or bed separations between rock layers. The thrust, torque and specific energy of drilling were all good indicators for identifying the fractures or separations. Regardless of the drilling parameters used during the drilling experiments, the location of the fractures were identified.

In order to determine the application of the drilling parameters for identifying roof rock properties, two series of experiments were conducted. The first series of experiments used three "manufactured" roof layers that had various rock samples embedded in concrete blocks. The rock samples included three types of sandstone, marble, and argillite. Another concrete block was poured with foam inserts to simulate large bedding separations (2 to 8-in). Two other manufactured blocks were constructed using high-strength concrete with cardboard layers embedded to simulate smaller fractures or bedding separations. The size of the cardboard layers varied from 1/8- to 1-in thick. One of the blocks had the cardboard layers embedded at an inclined angle to determine the effect of the orientation on the drilling parameters. A series of experiments was conducted with the rotational speed and the penetration rate held constant and the thrust and torque allowed to vary. The information collected from the experiments is used to determine the application of the drilling parameter measurements for identifying rock properties, fractures and bedding separations.

INTRODUCTION

There has been considerable interest in the past for using drilling parameters to determine geotechnical properties of rocks. Most researchers have focused on methodologies for determining the strength of rocks with unconfined compressive strength being the most common. As early as 1926, Protodyakonov (*1*) proposed and studied methods for determining mechanical properties of rocks by measuring drilling parameters. Following this early research, there were a widespread number of studies conducted by other researchers on drillability rock measurements (*2, 3*). The interest for determining the rock properties primarily lies in the area of improved drilling efficiency. Improved efficiency would increase penetration rates, decrease drilling times, increase bit life and ultimately reduce the cost of operation. Researchers followed the early investigations with studies relating the drilling parameters to the competency of the rocks being drilled with a focus on both drilling efficiency and structural integrity of the rocks (*4-5*). The structural integrity of the rocks has a direct bearing on the stability of the rocks for mining and construction purposes and for rock removal determinations such as blasting or cutting operations. In 1965, Teale (*6*) developed his concept of the specific energy of rock drilling where the drilling parameters of thrust, torque, penetration rate and rotational speed were used to determine the compressive strength of rocks. His research showed a close correlation between these parameters and compressive strength of the rocks. The U.S. Bureau of Mines, Spokane Research Laboratory conducted research on using the drilling parameters and Teale's methodology for determining the competency of roof rocks in underground mines as a design methodology for roof support (*7-9*). The Bureau's research was focused on improving safety of underground mining operations using drilling measurements collected from roof bolt machines. In the early 90's, Itakura, et al, (*10, 11*) studied the use of drilling parameters as a means of determining bed separations and fractures and developed a methodology for identifying the size and orientation of these discontinuities. All of the above researchers relied primarily on laboratory instrumentation experiments although some conducted a limited number of field investigations to evaluate the practicality of their approaches. In 1999, J. H. Fletcher & Company, in concert with Structured Mining Systems, developed a computer-control/monitor system for underground roof bolting machines that enhances the bolting operation (*12*). The roof bolting operation is enhanced by a feedback system that controls the drilling operation, automatically installs resin bolts to manufacturer specifications for hold and spin times and reduces operator fatigue. The drilling operation is controlled to match the conditions of the roof rocks being drilled with the intent of improved speed of drilling and reduced bit wear. The successful development of this system permitted the implementation of a research program for determining the application of drilling parameter measurements to identify rock properties by detailed laboratory and field experiments. The system is approved for use in underground coal mines and studies can be conducted as part of the normal drilling operation with minimal impacts to the mining cycle. The remainder of this paper will report on the results of the laboratory experiments using the computer control/monitor system on the Fletcher roof bolter machine.

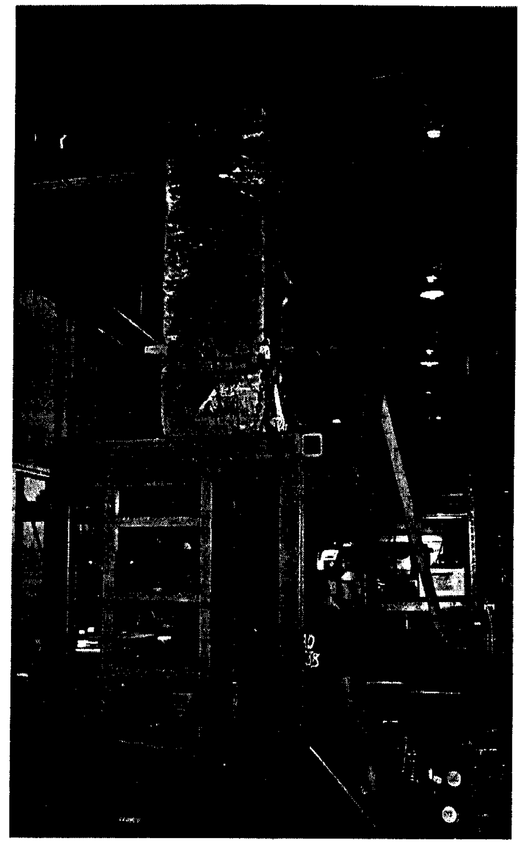

Figure 1. Set-up for drilling parameters experiments using a twin-boom roof bolter with Feedback Control System

DESCRIPTION OF EQUIPMENT

The drilling experiments were conducted using the J. H. Fletcher & Company arm feed style twin head roof bolter fitted with a dedicated intrinsically safe processor (figs. 1 and 2) (*12*). The processor monitors the drilling parameters of thrust, torque, penetration rate, and rotational speed. Additional conditions are monitored by the system but were not part of the research experiments. The system has the capability of being programmed for automated drilling operation (the feedback system) or for specifically designed control drilling. The controlled drilling approach was developed for the experiments conducted as part of this research. The drill bits used during the experiments were Kennametal's Dust Hog design including 1-3/8 and 1-1/32-in in diameter (fig. 3). The drilling operation was conducted using a vacuum recovery system for bit cooling and cuttings removal. The laboratory experiments were conducted at J. H. Fletcher & Company's Huntington, WV, facility. The same roof bolter and control system were used throughout the experiments.

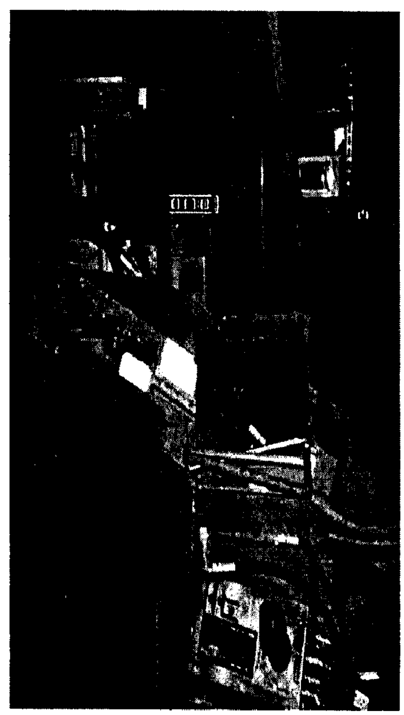

Figure 2. Close-up view of the Feedback Control System

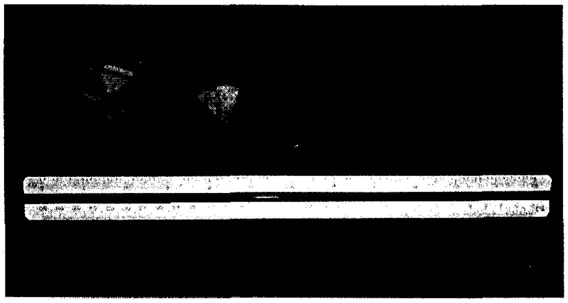

Figure 3. Drill bits used for drilling experiments

EXPERIMENTAL APPROACH

Rock Sample Blocks

The research project was designed to conduct a series of experiments in a laboratory setting as well as some field studies in operating underground mines. The laboratory experiments used the Fletcher roof bolter and a series of "manufactured" roof rock blocks. The manufactured roof rock blocks were designed and constructed by researchers at the Spokane Research Laboratory (SRL) and used a variety of quarried rocks embedded in poured concrete structures. Four blocks were provided by SRL for the drilling experiments and schematics of the blocks are shown in figure 4. Each of the blocks was 2 ft by 2 ft by 6-½ ft. Each block had four different layers embedded. Counting the concrete that was poured to embed the rocks, each block had 9 different layers. Block 1 had foam inserts to simulate large bedding separations. The foam inserts were 2, 4, 6 and 8-in thick. Blocks 2-4 had rock units embedded in them as shown in figure 4. The drilling experiments were conducted along the long axis of the blocks. The location of each embedded unit in the blocks was verified using a borehole video scope inserted into the drilled holes. The rock units were also visually observed with the video scope to determine the relative consistency of the rocks within the poured concrete. Additional confirmation of the embedded rock units was done by core drilling.

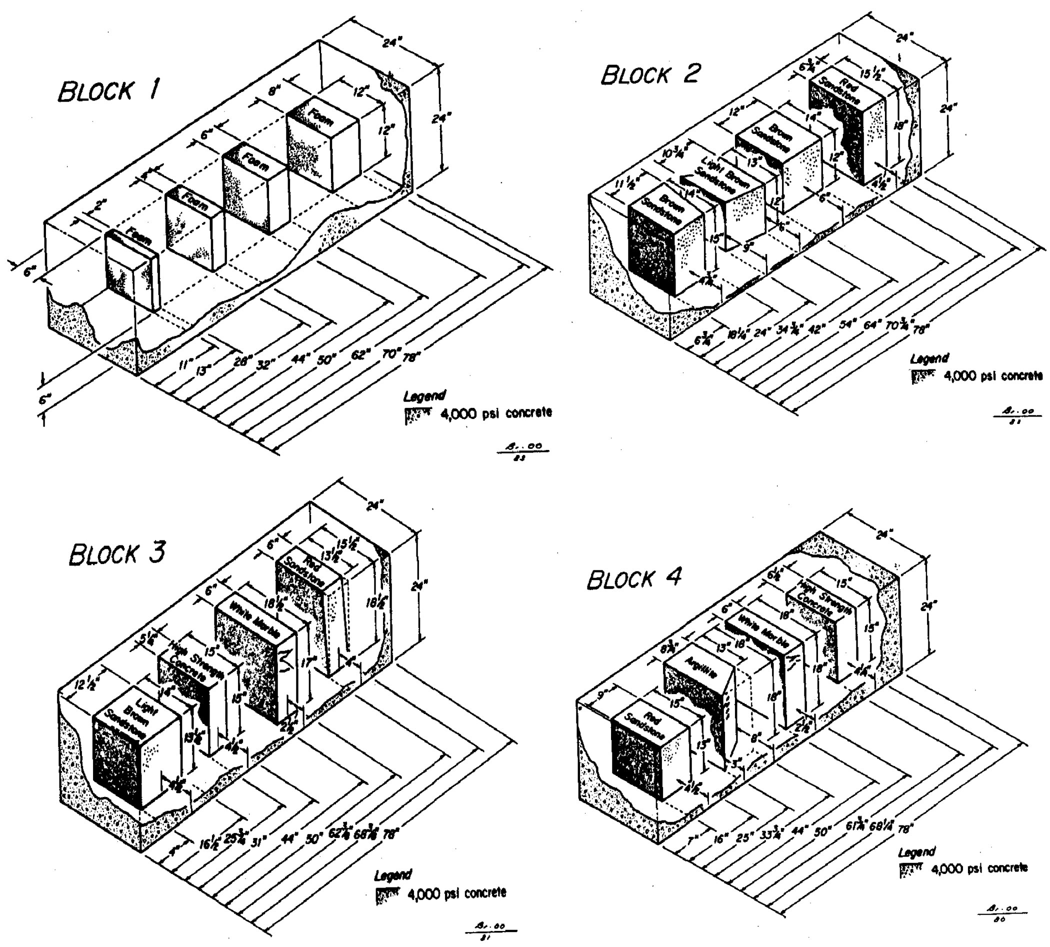

Figure 4. Schematics of the manufactured blocks. Block 1 has foam layers, Blocks 2-4 have rock layers

The physical properties of the rock units and the concrete of the manufactured blocks are shown in table 1. Depending on the number of samples available the number of tests per rock unit ranged from 2 to 9. The test procedure followed ATSM standards and was conducted on rock cores of 2- and 1-in in diameter. Two inch diameter cores were used when available. The average values of unconfined compressive strength (UCS), Brazilian tensile strength, Young's modulus and density are listed. The rock units were selected to include a variation of rock types and a wide range of compressive strengths. The average compressive strengths of the rocks varied from about 6,986 to 27,359 psi. The three sandstones (designated red, brown and light brown) were very consistent with no laminations or apparent bedding planes. All three sandstones are fine to medium grained. The white marble tends to have zones of voids and is discontinuous in many areas. The argillite, , a weakly metamorphosed shale, has zones of healed and open fractures. The high-strength concrete that was embedded as separate layers in blocks 3 and 4 had a compressive strength of 2,830 psi. While initially intended to be a high-strength concrete, these layers are the lowest strength units in the manufactured blocks. The concrete used for embedding the foam layers and the rock layers in blocks 1-4 had a compressive strength of 4,020 psi. Overall, the rock units and concrete layers in blocks 1-4 provided a series of drilling encounters simulating transitions from weak to strong and strong to weak rocks. The transitions were specifically designed to provide conditions similar to roof rocks found in underground mining operations.

Blocks 5 and 6 were designed to simulate fractures or smaller bedding separations and were constructed using a different high-strength concrete mix than what was used for the separate layers in blocks 3 and 4. This concrete mix had an average compressive strength of 12,329 psi. Blocks 5 and 6 were constructed in wood frames with a finished size of 36 by 49.5 by 60-in. The simulated fractures and bedding separations were constructed by embedding heavy weight illustration board (a dense cardboard) with a thickness of 1/8-in in the blocks. The simulated fractures covered the range of 1/8, 1/4, 3/8, 1/2, 3/4 and 1-in thick. For simulated layers thicker than 1/8-in, multiple sheets of the illustration board were used. One manufactured block had horizontal layers spaced every 12-inches in the block as shown in figure 5. An additional block was made with the simulated fractures oriented at an angle from the direction of drilling to determine if the orientation has an impact on the parameters or if the drilling parameters can be used to determine fracture direction (fig. 6). The inclined layers were intercepted by the drill bit at angles of 15, 30, 60 and 75°. To accurately determine the location of the simulated fractures, each hole was visually observed with a borehole scope after the drilling experiments were completed.

Table 1. Average rock mechanics properties of rock units in the test blocks.

Unit	Location, block and unit	Unconfined compressive strength		Brazilian tensile strength		Density, lbs/ft^3	Young's Modulus, 10^6 psi	Comments
		psi	Samples tested	10^3 psi	Samples tested			
Red sandstone	Block 2-unit 4 Block 3-unit 4 Block 4-unit 1	6,896	3	1.05	3	149	2.77	Consistent
Light brown sandstone	Block 2-unit 2 Block 3-unit 1	27,359	4	1.93	3	158	2.34	Consistent
Brown sandstone	Block 2-unit 1 Block 2-unit 3	9,995	2	0.93	2	160	1.94	Consistent
White marble	Block 3-unit 3 Block 4-unit 3	17,418	5	1.37	4	171	2.48	Vuggy
Argillite	Block 4-unit 2	20,445	5	1.04	5	182	4.24	Discontinuous
Hi-strength concrete	Block 3-unit 2 Block 4-unit 4	2,830	3	N/A	N/A	159	20.7	Grainy
Embedding concrete	Block 1-4	4,020	9	0.47	9	132	0.65	Standard Concrete
Embedding concrete in blocks with fractures	Block 5, 6	12,340	6	0.43	6	N/A	2.47	High strength concrete

N/A = Not available.

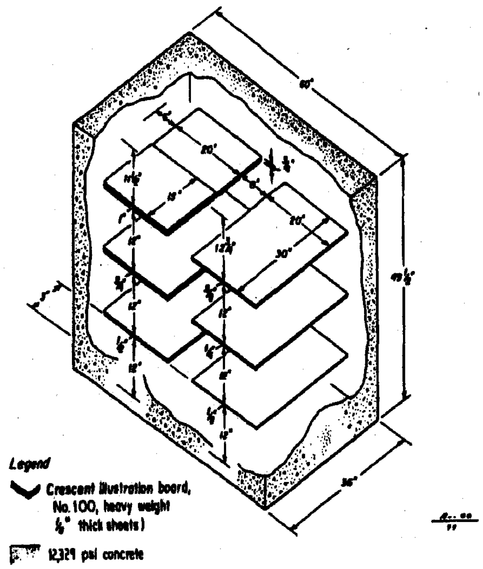

Figure 5. Manufactured block with simulated horizontal fractures

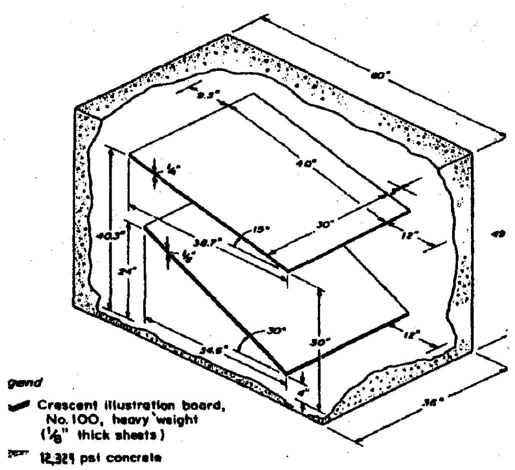

Figure 6. Manufactured block with simulated inclined fractures

Laboratory Drilling Experiments

The drilling operation was conducted by constructing a drilling frame above the roof bolter and drilling in a vertical direction (fig.1). The 6 manufactured blocks were loaded into the supporting structure above the roof bolter and the system was programmed for the specific rotational speed and penetration rate desired. A new bit was added at the start of each hole and the parameters of thrust, torque, rotational speed, and penetration rate were recorded every 0.1 second throughout the drilling. The data was collected by connecting a computer to the feedback control system on the roof bolter. The drilling parameters were recorded directly on the computer and covered the complete drilling passes from hole collaring to break through on the other side of the manufactured blocks. The drilling experiments on blocks 1-4 were completed in two weeks. Drilling on blocks 5 and 6 was conducted several months after the drilling of the first 4 blocks. Drilling experiments on blocks 5 and 6 were conducted over a two week interval.

The manufactured blocks with the rock layers were drilled in the direction of the long axis (78-in) and required two drilling passes of the roof bolt feed arm due to the height restriction on the test frame. The bit was initially collared into the cement block at a distance of about ½-in and the holes was drilled to a depth of 60-in. The drill rods were removed from the hole, an extension was added, and the remaining 18-in was drilled. As mentioned before, the bit was replaced after each hole was drilled. For the holes drilled in the 78-in long blocks, two separate data files had to be merged to cover the complete drill distance of each hole. With the exception of the block with the foam inserts, drilling in the manufactured rock layer blocks was fairly smooth. Occasionally a problem occurred with plugged bits, worn bits, machine shut downs or inadequate drilling parameters for the rock being drilled. Since the temperature of the drill bit is often quite high, the foam layers melted and plugged the bit during a large number of holes drilled in block 1.

The manufactured blocks with the cardboard layers to simulate fractures and bedding separations only required a single pass of the roof bolt feed arm since the drilling distance on these blocks was 49-1/2-in. This simplified the drilling and the data analysis operation since each hole drilled produced one data file. For most of the holes drilled in these two blocks, a new bit was used for each hole but there were several holes drilled with the same bit to determine the impact of bit wear. The biggest problem that occurred on drilling the blocks with the cardboard layers was bit plugging when the lower rotational speeds were used.

The blocks were drilled using various combinations of controlled drilling parameters. Table 2a shows the experimental design for the manufactured blocks with the foam layers (block 1) and the rock layers (blocks 2-4). Two sizes of bits, 1-3/8 and 1-1/32-in in diameter, were used during the drilling of blocks 1-4 to determine the impact of bit diameter. For the 1-3/8-in bits (indicated with an X in table 2a), tests were conducted using 5 levels of rotational speeds (range of 150 to 500 rpm's) and 3 levels of penetration rates (range of 0.6 to 1.5 in/sec). A total of 50 tests was conducted with 14 tests in the manufactured block with the foam layers and 36 tests in the blocks with the rock layers. For the 1-1/32-inch bits (indicated with an O in table 2a), 11 tests were conducted. Seven of the 50 drilling tests used the control system of the roof bolter ("Machine Control" in table 2). "Machine Control" refers to a proprietary feedback control system developed by J. H. Fletcher that automatically adjusts the drilling parameters as the bit encounters various conditions during drilling. The machine control system was modified to allow for specific control of rotational speed and penetration rate as needed for the experiments discussed in this paper. For each hole that was drilled in the manufactured blocks, a new bit was used to reduce the impact of bit wear on the drilling parameters and to simplify the data analysis. Bit wear was significant in a number of holes and, in some cases, the bit had to be replaced before the drilling could be completed through the block (78-in).

Table 2a. Drilling parameters used during laboratory experiments on manufactured blocks with rock layer.

	Rotational speed, rpm's	Penetration rates, in/sec			Holes drilled	Hole terminated prematurely	
		0.6	1.1	1.5		No.	Reason
Block 1	150	X			14	9	Bit plugged from melted foam
	200	X					
	300						
	400	X	X O	O			
	500	X	X O	X			
	Machine control	X X O O					
Block 2	150	X			9	6	Worn bits - 2 Broken bits - 2 Machine shut down - 2
	200	X O	X				
	300	X					
	400	X	X				
	500	X	O				
Block 3	150	X			13	1	Machine shut down
	200	X O	X				
	300	X	X	X			
	400	X	X	X			
	500	X	O	X			
Block 4	150	X			14	0	
	200	X	X				
	300	O	X				
	400	X	X	X X			
	500	X	O				
	Machine control	X X X					

X = 1-3/8-inch diameter bits. O = 1-1/32-inch diameter bits.

Table 2b. Drilling parameters used in the test program on manufactured blocks with fractures.

Fracture orientation	Rotational speed, rpm's	Penetration rates, in/sec					Holes drilled	Holes terminated prematurely	
		0.4	0.6	1.3	1.1	1.5		No.	Reason
Horizontal fractures (Block 5)	150	X	XXXX	XX		XX	69	39	Bit plugged Machine stopped
	200	XX	XXXX	XXX		X			
	300	XXX	XXXX	XXX	X	XX			
	400	XX	XXX	XXXXX	X	XX			
	500	XXX	XXX	XXX		XXXX			
	600	X	X	X	X	X			
	Machine control	XXXXXXX							
Inclined fractures (Block 6)	150						50	18	Bit plugged Machine stopped
	200								
	300	XXX	XXX						
	400	XX	XXXX XXX	XXXXX X	XXXXX				
	500	X	XXXX X	XXXXX	XXXXXXX XXXXX	X			

X = 1-3/8-in diameter holes.

Table 2b shows the experimental design for the two manufactured blocks with cardboard layers for simulating fractures and smaller bedding separations. The drilling experiments on the blocks with the simulated fractures were similar to the experiments on the blocks with the rock and foam layers. The rotational speed was controlled but varied between 150-600 rpm's and the penetration rate was controlled but varied between 0.4-1.5 in/sec. The manufactured block with the simulated horizontal fractures (block 5) had 69 holes drilled in it with 39 of them ending prematurely (before the hole could be drilled completely through the block). The majority of the holes ending prematurely were the result of bit plugging when the cardboard layers were intercepted. For block 6, which had the layers inclined, 50 holes were drilled through it with 18 of them ending prematurely. The rotational speeds were varied between 300-500 rpm's with penetration rates varying between 0.4-1.5 in/sec. The lower rotational speeds were not used while drilling block 6 since the bit plugged often at these speeds while drilling through the cardboard layers in block 5. The higher rotational speeds helped with cutting and removing the cardboard layers. All the holes drilled in the two blocks with the cardboard layers used the 1-3/8-in diameter bits.

In order to verify the location of the embedded rocks and the condition of the rocks themselves, each of the holes drilled in the blocks was observed with a borehole camera. The interfaces between the rocks and the embedded cement were measured and the condition of the rock units was recorded. Selected areas of the blocks were core drilled with a 1-in-diameter core barrel to collect rock and cement samples for physical property testing. Two-in-diameter cores were available for testing on 3 of the rock units (argillite, white marble and brown sandstone) and it was not necessary to collect 1-in-diameter cores on these units.

Experimental Results

The data collected during the drilling experiments was analyzed to determine the impact of the embedded units on the drilling parameters and to determine if changes in the parameters could be used to identify the material being drilled. Since all 6 blocks had multiple holes drilled through them, multiple data sets were obtained for each block and for each unit within the blocks. The procedure used for analyzing the multiple data sets included a pattern identification approach for variations in drill parameters and conversion of the drilling parameters to the specific energy of drilling (SED). The areas of greatest interest are those zones where the drilling transitions from one rock layer (or fracture) to another. The identification of these transition zones and the characterization of materials in each zone are of particular interest for characterizing roof rocks.

Variations in Drilling Parameters with Rock Types and Simulated Fractures

An example of the drilling parameters collected during the drilling of block 2 in the laboratory experiments is shown in figure 7. The penetration rate for the example was set at 0.6 in/sec and the rotational speed was 300 rpm's. Since the example shown is block 2, the total distance drilled was 78-in and is indicated by the depth on the left hand side of the figure. The variation of the penetration rate is similar to what was measured during all the laboratory experiments as it fluctuates considerably based on the mechanics of the drilling process. For this example, the penetration rate varied from 0.1 to 1.8 in/sec. The fluctuation was somewhat consistent when transitions zones between weak and strong rocks were encountered and the system often required several inches of drilling before the penetration rate returned to the programmed setting. The rotational speed remains fairly constant during the entire drilling operation but requires 4 to 8-in of initial drilling into the block before the programmed level is reached. Past researchers have reported similar results and have recommended not using the drilling data from the first 4 inches of drilling since it produces inconsistent results. The thrust and torque levels were not controlled but were allowed to change as needed to achieve the controlled penetration rate and rotational speed. The thrust levels shown on figure 7 varied from about 2,000 to over 8,000-lbs. The torque followed a pattern consistent with the thrust variations and has been shown in past studies to be directly related to rock strength. On the example shown, the compressive strengths of the embedded rocks ranged from 4,020 to 27,359 psi and the variation in thrust and torque levels would be expected for drilling through a sequence of rocks with a large variation in strengths.

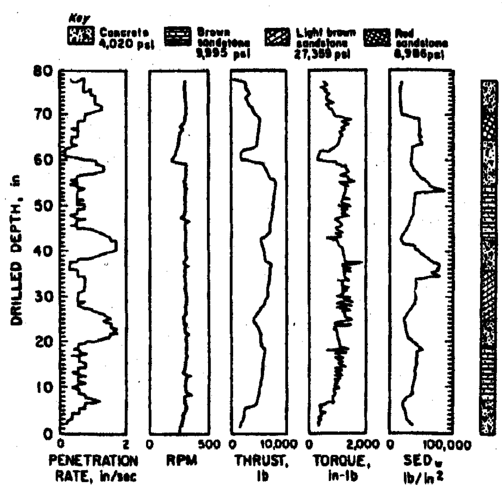

Figure 7. An example of the drilling parameters for manufactured blocks with rock layers. Controlled parameters of 0.6 in/sec penetration rate and 300 rpm rotational speed.

Patterns in the drilling parameters were also analyzed to determine trends as the drill bit transitioned from one rock layer to another. The patterns were identified on the basis of changes in the drilling parameters (thrust, torque, rotational speed and penetration rate) and the SED. Changes in the parameters and the SED were studied for the cases where the hole transitioned from strong to weak layers and weak to strong layers. The changes were noted as each hole was drilled and the frequency of occurrence for each pattern was counted. The patterns identified are listed in table 3a. Eight different patterns were noted when drilling transitioned from strong to weak rocks with pattern number 8 representing about 55% of the cases. This pattern had a decrease in thrust, torque and SED, an increase then decrease in penetration rate and no change in the rotational speed. Of the remaining 7 patterns, none had a frequency of more than 10%. For those transitions from weak to strong rocks, 9 patterns were identified. The dominant pattern, accounting for about 55% of the occurrences, is characterized by increases in thrust, torque and SED, a decrease in the penetration rate and no change in the rotational speed. Of the remaining 8 patterns, only pattern 8 occurred more than 10% of the time (12.9%).

Figure 8 shows the drilling parameters obtained during the laboratory experiments on block 5 to determine if fractures or smaller bedding separations could be identified. The distance drilled on this block was 49-1/2-in as indicated on the left side of the figure. For this example, the penetration rate was set at 0.6 in/sec and the rotational speed was set at 500 rpm's. While the penetration rate fluctuated during the drilling process it was more consistent than what was observed while drilling in the blocks with the rock layers. Block 5 was mostly composed of concrete with very small transition zones since the largest cardboard layer was only 1-in thick. The fluctuations in the penetration rate were possibly related to the concrete mixture itself since it contained aggregates (sand and gravel). The block had 3 cardboard layers embedded in it and the parameter that was most significant in identifying the layers was thrust. Referring to the figure it is easy to identify the "fractures" with the changes in thrust.

Variations in the drilling parameters were also studied to identify patterns that occurred as drilling transitioned from rock to fractures and from fractures back into rock. The patterns recorded during the drilling are listed in table 3b. For those cases where drilling transitioned from rock into a fracture, 6 patterns were identified. Pattern 6 was the dominant pattern accounting for about 65% of the cases. Pattern 6 is characterized by decreases in thrust, torque and SED, an increase in the penetration rate and no change in the rotational speed. For drilling transitions from fractures back into rock, 8 separate patterns were identified. Pattern 8 accounted for more than 60% of the occurrences and is characterized by increases in thrust, torque and SED, a decrease in the penetration rate and no change in the rotational speed.

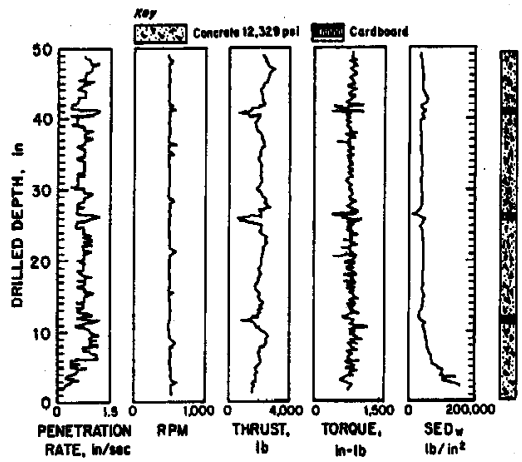

Figure 8. An example of the drilling parameters for manufactured blocks with simulated fractures. Controlled parameters of 0.6 in/sec penetration rate and 500 rpm rotational speed.

Table 3a. Variation trends of drilling parameters while drilling in manufactured blocks with embedded rock layers (Blocks 2, 3 and 4).

Transition	Pattern	Thrust	Torque	Penetration rate	RPM	SED	Frequency	Percentage
Strong to weak rock	1	1st ↓ then ↑	1st ↓ then ↑	↑	NC	1st ↓ then ↑	1	2.38
	2	↑	↓	1st ↑ then ↓	NC	NC	2	4.76
	3	↓	↓	↓	NC	↓	2	4.76
	4	1st ↑ then ↓	1st ↑ then ↓	NC	NC	1st ↑ then ↓	3	7.14
	5	↑	↑	1st ↑ then ↓	NC	↓	3	7.14
	6	↑	↑	↑	NC	↑	4	9.52
	7	↑	↑	↑	NC	↓	4	9.52
	8	↓	↓	1st ↑ then ↓	NC	↓	23	54.76
Weak to strong rock	1	↑	NC	1st ↓ then NC	NC	↑	1	3.23
	2	↑	↑	NC	↑	↑	1	3.23
	3	↑	*	*	NC	*	1	3.23
	4	↑	↓	↓	NC	*	1	3.23
	5	↑	↑	↓	↓	*	1	3.23
	6	↑	↑	↑	↑	NC	2	6.45
	7	1st ↑ then NC	↑	1st ↑ then ↓	NC	1st ↓ then ↑	3	9.68
	8	↑	↑	NC	NC	↑	4	12.90
	9	↑	↑	↓	NC	↑	17	54.84

Legend: ↑ = increase, ↓ = decrease, NC = no change, * = no dominant trend

Table 3b. Variation trends of drilling parameters while drilling in manufactured blocks with simulated fractures and bedding separations (Blocks 5 and 6)

Transition	Pattern	Thrust	Torque	Penetration Rate	RPM	SED	Frequency	Percentage
Rock to fracture	1	↓	↓	*	*	*	1	2.94
	2	NC	NC	*	*	*	1	2.94
	3	↓	1st ↑ then ↓	↑	NC	↓	1	2.94
	4	↓	NC	↑	NC	↓	4	11.77
	5	*	*	*	*	*	5	14.71
	6	↓	↓	↑	NC	↓	22	64.71
Fracture to rock	1	↑	↑	*	*	*	1	2.94
	2	↑	↓	↓	NC	*	1	2.94
	3	↓	↑	↑	*	↑	1	2.94
	4	↑	↑	↑	*	↑	1	2.94
	5	↑	NC	*	NC	↑	2	5.88
	6	NC	NC	*	*	*	2	5.88
	7	*	*	*	*	*	5	14.71
	8	↑	↑	↓	NC	↑	21	61.77

Legend: ↑ = increase, ↓ = decrease, NC = no change, * = no dominant trend

Correlation of Rock Strength with Specific Energy of Drilling (SED)

The specific energy of drilling (SED) as defined by Teale (*6*) was used for conversion of the drilling parameters. His definition of the specific energy is defined as the work done per unit volume of rock excavated. The specific energy is dependant upon a number of factors including rock properties, the mechanics of the drilling operation and the chip removal process. According to Teale (6), as the efficiency of the drilling operation increases (appropriate thrust and rotational speeds are reached) the specific energy value decreases until it approaches a near constant value. The specific energy of drilling is determined by the following:

$$e = \frac{F}{A} + \frac{2\pi NT}{Au} \qquad (1)$$

Where:

e = specific energy of drilling, psi
F = thrust, lbs
A = cross-sectional area of the hole, in^2
N = rotational speed, rpm
T = torque, in-lbs
u = penetration rate, in/sec

The specific energy of drilling (SED) for each data point along the hole length was computed for each hole (see Fig. 2). The SED for each rock type that was embedded in the manufactured blocks (Blocks 2 - 4) in all holes was then computed, summarized, and its average SED determined. This average SED was compared to the average strength of the rocks based on the unconfined compressive strength tests (UCS). The maximum, minimum and average values of the SED and the UCS are listed in table 4. Comparing the average SED to the average UCS for the rock types, the SED was 1.9 to 4.5 times greater. The variation in the minimum and maximum values of the SED was much greater than the variation in the UCS of the rocks. This variation is the result of the drilling process and is related to discontinuities, drill cuttings removal and drilling inefficiencies such as binding of the rods and dulling of the bits.

Figure 9 shows a plot of the average UCS and the SED of the rocks and concrete used for blocks 2-4. Using the Teale equation for determining the SED, a linear regression was obtained with a correlation coefficient of 0.734. Given the wide variation in the rock strengths and in particular in the SED the regression equation gives a reasonable approximation of the data. In order to determine if the correlation could be improved, a statistical approach was used where the different drilling parameters were weighted to determine which had the greatest effect on reducing the variability of the SED. The two parameters which had the greatest effect were found to be the rotational speed and the penetration rate. The weighted SED using the rotational speed and penetration rate was obtained using the following:

$$SED_w = \frac{\sum SED \times \mu \times n}{\sum \mu \times n} \qquad (2)$$

Where:

SED_w = Weighted specific energy of drilling, psi
μ = penetration rate, in/sec
N = rotational speed, rpm.

Table 4. The maximum, minimum, and average values of SED and UCS for rock layers.

Parameters, psi	Concrete	Red Sandstone	Brown Sandstone	White Marble	Argillite	Light Brown Sandstone
Max SED	84,762	57,428	87,815	86,104	87,968	92,964
Ave SED	40,324	28,007	44,849	44,862	46,735	50,804
Min SED	15,943	15,265	20,197	20,983	13,489	15,934
Max SED_w	56,244	37,069	54,262	71,892	62,129	60,311
Ave SED_w	36,987	27,901	36,400	40,553	45,850	48,904
Min SED_w	24,549	20,920	23,952	24,081	11,154	37,293
Max UCS	6,468	8,098	12,070	19,226	28,011	34,696
Ave UCS	4,020	6,986	9,995	17,418	20,445	27,359
Min UCS	2,496	6,188	7,920	15,343	16,488	10,695

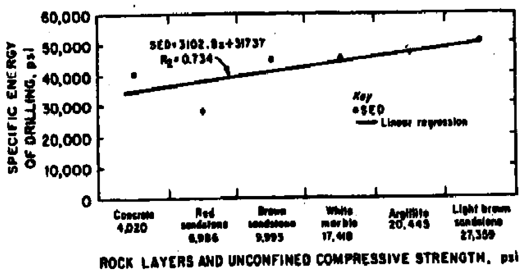

Figure 9. Correlation of specific energy of drilling and UCS for rock layers

This approach was used to reduce the variation in the SED caused by non-homogeneity of the rocks and drilling inefficiencies. Figure 10 shows the data points and the linear regression of the SED_w and the unconfined compressive strength of the rocks. The correlation coefficient for the linear regression is 0.841 a significant improvement over the SED without weighting.

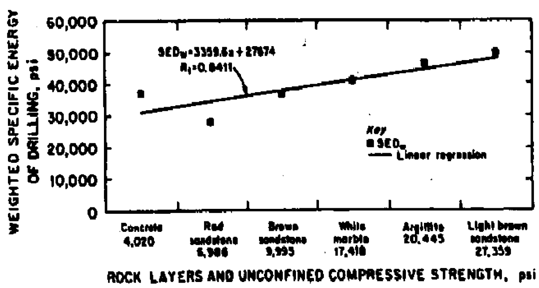

Figure 10. Correlation of weighted specific energy of drilling and UCS of rock layers

SUMMARY AND DISCUSSION

The data collected from a series of laboratory experiments using manufactured blocks for simulating rock layers indicates that drilling parameters collected during routine roof bolt drilling operations can be used to identify the relative strength of the rocks. The data was collected from a large number of holes drilled through 3 blocks that had rock samples embedded in them. The rock samples included marble, argillite, concrete and three different sandstones. All of the rocks drilled were sampled for physical property testing and the characteristics of the rocks were identified. The drilling experiments included a series of controlled tests where the penetration rates and rotational speeds were held constant and the torque and thrust were allowed to vary. The control parameters were selected to match what is normally encountered in underground roof bolting operations and the size of the bit and design of the laboratory drilling experiments simulated normal mining conditions. The specific energy of drilling, as defined by Teale, was found to have a good correlation with the unconfined compressive strength of the rocks being drilled. An approach using Teale's original equation with additional weight given for the velocity parameters of rotational speed and penetration rate was found to improve the fit between the SED and the unconfined compressive strength of the rocks. There is a large variation in the SED (table 4) even for a specific rock type drilled under laboratory conditions. Given this large variation it will be necessary to develop secondary and possibly tertiary parameters for identifying rock types during drilling. A series of patterns was identified during the drilling experiments for transitional zones from strong to weak rocks, weak to strong rocks, rock to fractures and fractures to rock. In each case a dominant pattern emerged and will be useful for developing the secondary and tertiary parameters.

Fractures and bedding separations can be positively identified by changes in the drilling patterns (most notably thrust) but additional study is needed to characterize the dimensions of the fractures (size and orientation). A significant amount of data has been collected from the drilling experiments and will be further analyzed for a more complete characterization of the fractures.

Field studies will also be necessary to investigate the application of the methodology for real-time identification of roof lithology and roof characterization. Preliminary studies have been completed in underground coal mines in Utah, Illinois and West Virginia but additional field studies are needed based on the findings of the laboratory experiments.

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