Mem. Natl Inst. Polar Res., Spec. Issue, 49, 99–112, 1994

LOW POWER DIAMOND ROCK CORING PARAMETERS

Zhengwen WANG, Jesse COLLINS and Scott L. HUANG

Department of Mining and Geological Engineering, University of Alaska Fairbanks, Fairbanks, Alaska 99775-1710, U.S.A.

Abstract: An experimental rock coring study was conducted on a low power diamond drilling system. In this laboratory experiment, two surface-set and two impregnated diamond bits were tested on six types of rock ranging from granite to limestone under the same conditions. In this paper, authors present the testing equipment, rock strength and index tests, and the result of the coring test.

1. Introduction

The GISP-2 program is an ice coring project with great climatological significance. The ice cores from Greenland inland ice allowed a study of global climate changes in the past ten millennia. From the perspective of a geoscientist, the project gives an additional excitement. The borehole through the thick ice sheet into the underlain rocks will no doubt contribute significantly to the understanding of the geology in this region.

Rock coring, as always, is a high cost engineering activity. The extremely cold weather, the lack of information about the bedrock geology, the great depth of the borehole (over 10000 ft), and the great difference in material properties of ice and rock, make even greater challenges in obtaining rock cores from underneath the Greenland ice sheet. In a rock coring project it is desirable to have a prior knowledge of the performance of a selected drill. As part of continuing research on the performance of a low power cable suspended drill, the authors of the Department of Mining and Gelological Engineering at the University of Alaska Fairbanks undertook the task of quantifying the rock coring parameters. A laboratory drillability assessment and simulation was designed. A systematic drilling simulation under a controlled laboratory environment, it was to assess the field performance of the intended drill system. The following sections discuss the testing equipment and results of this laboratory study.

2. Testing Equipment

The Rock Coring Laboratory of the Department of Mining and Geological Engineering was used to perform the investigation. In addition to the drill used, the laboratory is also equipped with a rock core surface polishing machine for preparing samples for standard triaxial tests.

2.1. Core bits

In the laboratory testing program, four types of diamond core bits (*i.e.*, AQ1, BQ1, AQ2, and BQ2) were employed to core the rocks. AQ1 and BQ1 are surface-set diamond core bits, with four steps of diamond profile. AQ2 and BQ2 are impregnated diamond core bits with a "V" groove in the matrices (Fig. 1). The major difference between the surface-set bits and the impregnated bits is that the diamond sizes of the impregnated bits are much smaller than that of the surface-set bits. The basic dimensions of the four bits are summarized in Table 1.

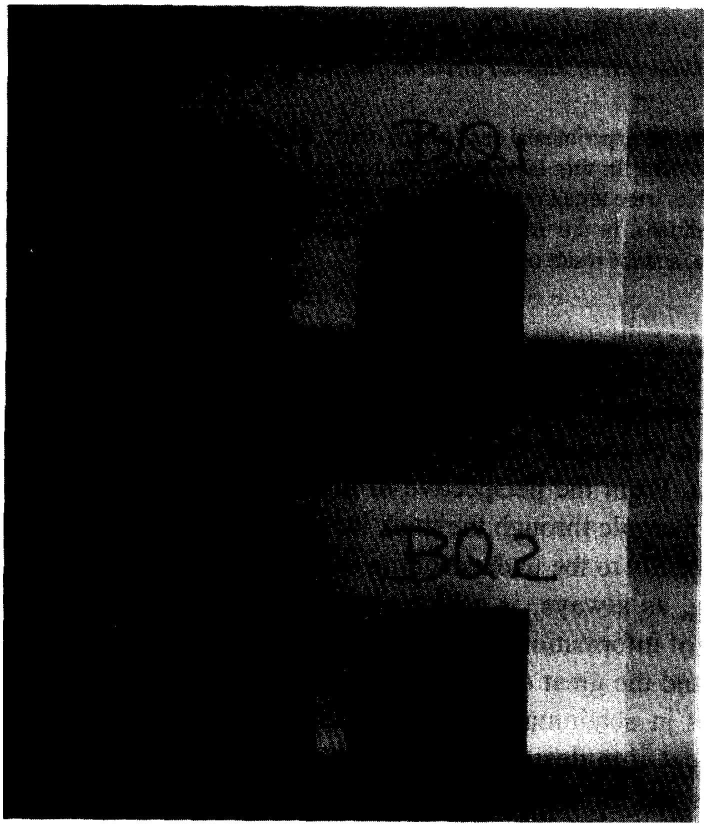

Fig. 1. Diamond bits tested.

Table 1. Dimensions of the bits tested.

Bit	Outer diameter (cm)	Inner diameter (cm)	Cross-section area (cm^2)
AQ1	4.747	3.000	10.630
AQ2	4.763	3.015	10.678
BQ1	5.974	4.044	15.184
BQ2	5.994	4.064	15.246

2.2. Drilling system and measuring devices

In operation, a bit was mounted vertically on a 20-inch clausing drill press (Fig. 2) which was modified slightly for this rock drilling and coring study. The power output of the motor is 0.56 to 1.12 kW (0.75 to 1.5 horsepower), and its rotational speed ranges from 150 to 2000 rpm.

During the drilling program, a constant load was applied onto the rock by employing a two-sheave block. The top sheave was attached at the top of a column which was encased in the column of the drilling machine. The lower sheave was mounted on the feed handle of the drill. Both sheaves were connected with a steel cable. When a weight is hung on the cable, this two-sheave block system will porduce a constant load on the bit.

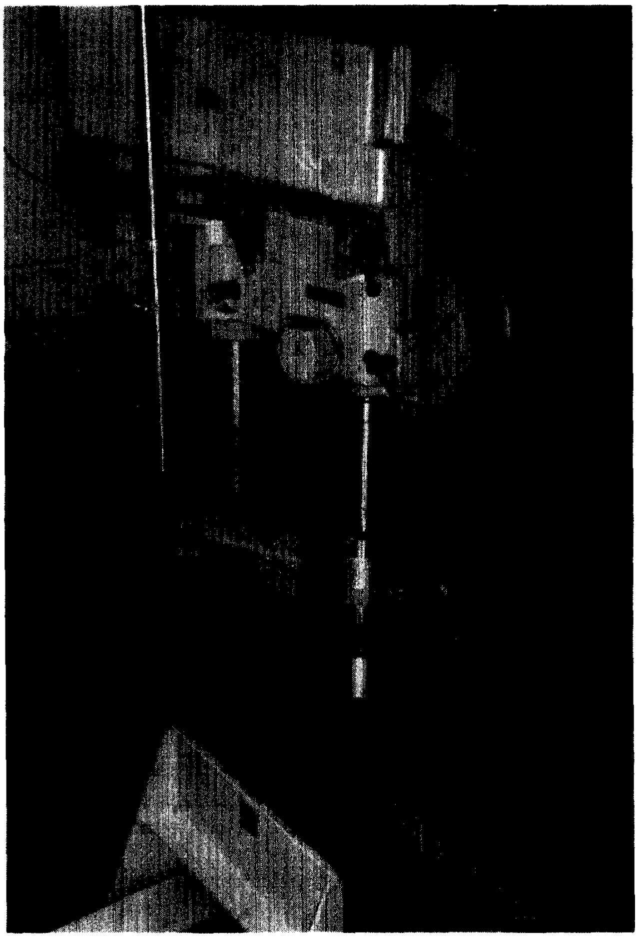

Fig. 2. A 20-inch clausing drill press.

The weight-on-bit, rotational speed, applied torque, penetration rate, and flow rate of circulating water are the basic drilling parameters monitored continuously throughout the tests. Three S. Himmelstein and Company (SHC) 2540 load cells were utilized to measure the weight-on-bit. The capacity of each of these load cells is 8896 N (2000 lb), and thus, the maximum load measurement is 26.7 kN (6000 lb). These three load cells were mounted to the base plate of the drill press.

The actual rotational speed of a bit and the applied torque to rotate it were measured by a SHC MCRT 2900T torque-and-rotational meter. This meter was installed between the drill spindle and the core barrel. The full scale of the torquemeter is 565 Nm (5000 lb-in) and the speed rating of the tachometer is from 150 to 10000 rpm.

The penetration depth of a bit is the distance from the rock surface to the cutting face of the hole. Axial movement was measured normal to the surface with a 60 cm (24 inch) full range SHC LVGT-600 Long Stroke LVDT.

Additionally, the flow rate of water was measured by a flowmeter. By controlling the water valve, the flow rate can be kept constant from 3.153×10^{-5} to 7.567×10^{-4} m^3/s (0.5 to 12 gpm).

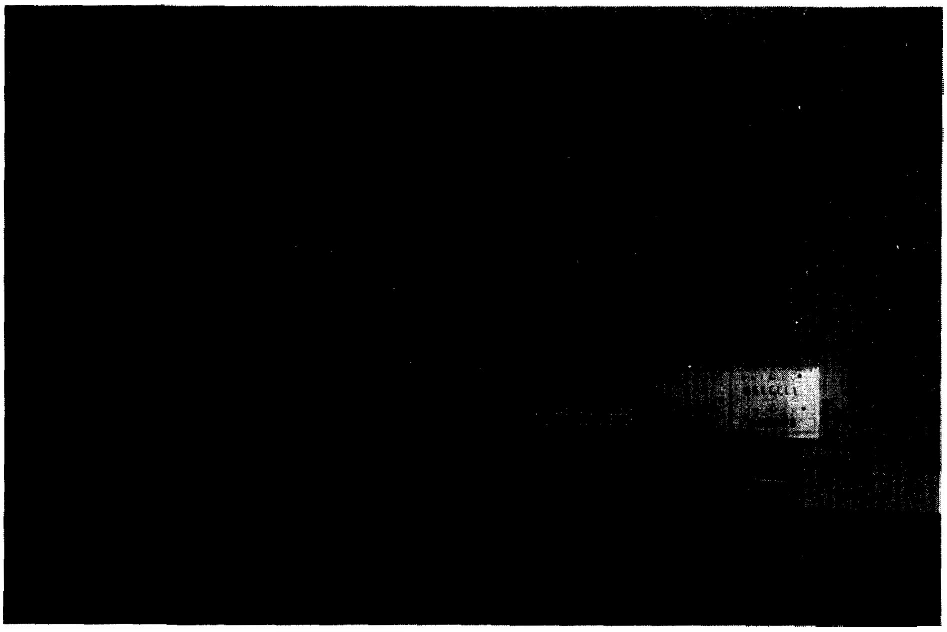

Fig. 3. SHC 6-488B data acqusition system.

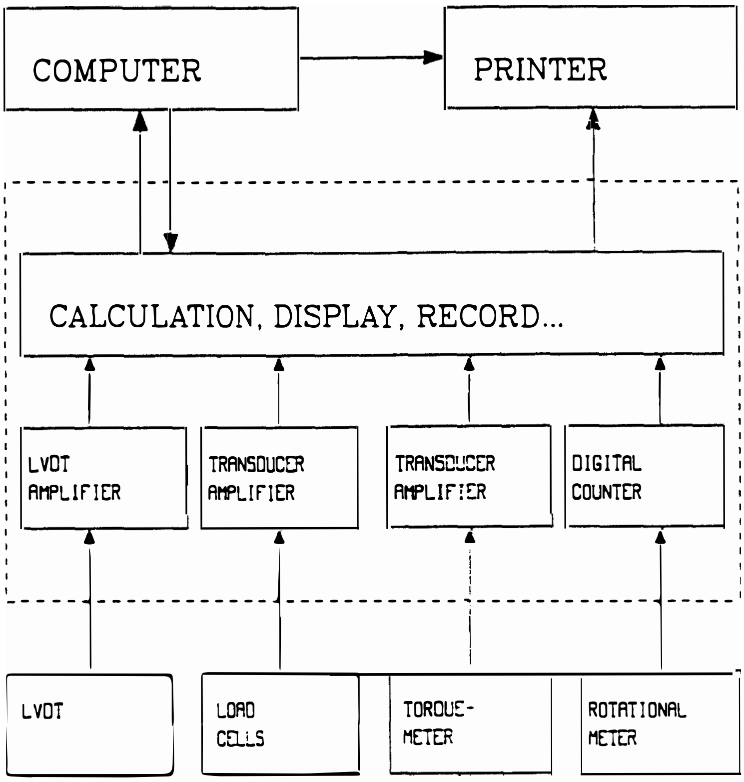

Fig. 4. Flow chart of laboratory testing procedures.

2.3. Data acquisition system

Measurements acquired by four transducers (*i.e.,* load cells, torquemeter, tachometer, and LVDT) are transmitted to a SHC 6-488B data acquisition system (Fig. 3). The SHC 6-488B is an advanced multi-channel, programmable device which provides fast, accurate data acquisition, processing and computer interfacing. It is housed in a standard System 6 cabinet. The upper two left module slots are occupied by LED numeric and alphanumeric displays, timers and interfaces. The keyboard occupies the lower two left slots. Four modules, namely Transducer Amplifiers 6-201 and 6-205B, Digital Counter 6-260B.2, and LVDT Amplifier, are installed in the remaining space at the right. Data recorded by the SHC 6-488B could be transferred to a computer or a printer. The flow chart of testing procedures is shown in Fig. 4.

3. Laboratory Experiment

3.1. Rock coring test

The drilling program used in this study included a total of 48 tests. Purpose of this test was to identify the optimum drill bits among the four bits tested. In this test, the four core bits were tested under the same condition. Performances of the bits on a given rock were compared among each other. Each of the four bits described in the previous chapter was tested on six rock types. A duplicate test was performed to reduce the possible laboratory error. Samples of the six rocks were collected from Alaska. They were rock A (sandstone from Healy), rock B (diorite from Aleutian Island), rock C (granite from Fox), rock D (schist from Aleutian Island), rock E (limestone from Livengood), and rock F (granite from Fox).

Throughout this laboratory experiment, the weight-on-bit was maintained at 2400 N (540 lb), and the rotational speed was maintained at 500 rpm. Additionally, the flow rate of the circulating water was maintained at about 9.46×10^{-5} m^3/s (1.5 gpm). Four direct parameter measurements (*i.e.,* weight-on-bit, rotational speed, torque, and penetration depth) were made at each time interval.

Based upon weight-on-bit, rotational speed, applied torque, penetration depth, and testing time, several drilling parameters including penetration rate, power input, specific energy, and friction coefficient can be calculated. These parameters were considered as the dependent variables in this study. Because weight-on-bit, rotational speed, and flow rate were maintained constant in the experiment, the two independent variables which might affect the drill performance were the rock type and bit type. Analysis of Variables (ANOVA) statistical procedure of the Statistical Analysis System (SAS) was subsequently performed to evaluate the significant effects of the bits on rock coring.

3.2. Rock index test

Cores obtained from the coring program were tested to determine rock strength properties and several drillability indices. Point load test (*e.g.,* diametric and disc), Schmidt hammer hardness test (on both core and bulk specimens), Shore Scleroscope Hardness test, and rock density test were conducted. These material and strength properties were related to the drilling parameters as well.

4. Results and Discussions

4.1. Rock index tests

Among all rock strength properties and indices, the uniaxial compressive strength is the one which has been often suggested by different authors (KARPUZ *et al.*, 1990; HOWARTH, 1986) as the quantitative index of rock in drillability study. It is, however, difficult to perform in the field.

An alternative is the point load strength. The point load test was first introduced to predict uniaxial compressive strength and later was used for a rock strength classification. The point load strength is much easier and quicker to perform than the uniaxial compressive strength. It is also reliable when properly conducted (BROOK, 1977). In this study, procedures of point load test were adapted from the ISRM suggested method (ISRM: Point Load Test, 1985). The tensile strength of the rock was estimated from point load test.

Another alternative is the Schmidt rebound hardness test. This test was originally developed to estimate the compressive strength of concrete. It is now being used for rock hardness determinations as well (ISRM: Hardness and Abrasiveness Determinations, 1977). This test, similar to the point load test, is simple and fast to perform both in the laboratory and in the field. It could be a good alternation for uniaxial compressive strength test for medium hard rocks (CARGILL and SHAKOOR, 1990).

The third rock index test performed in this laboratory was a Shore Scleroscope hardness test. In this test, rock hardness can be obtained based upon individual mineral grains. The test is repeated in a random pattern and the result indicates the average hardness of various mineral grains in a rock sample. It is also easy to conduct in both laboratory and field conditions.

Results from the above rock strength and index tests are summarized in Table 2. Rock density was measured by the weight-and-volume method. Regression analyses were performed to relate these properties. Results indicated that the Shore Scleroscope index was directly related with the Schmidt indices (R^2=0.618 for core specimen and R^2=0.663 for bulk specimen). In further analysis, a rock strength property-cube compressive strength computed from the Schmidt hammer test on bulk samples was chosen to represent the rocks used.

Table 2. Rock strength properties and indices.

Property	A	B	C	D	E	F
Density (g/cm^3)	2.62	2.66	2.58	2.69	2.67	2.60
Shore scleroscope index	65.63	79.75	75.65	59.25	41.28	62.78
Schmidt index (Core)	41.54	38.60	41.24	39.08	31.60	38.50
Schmidt index (Bulk)	49.80	62.24	53.79	47.34	43.45	58.15
Point load index, psi	1188	2158	1384	2034	911	2078
Tensile strength, psi	1650	2940	1850	—	—	—

4.2. Rock coring test

In this rock coring test, the six rock samples were tested by the four coring bits (*i.e.,* AQ1, AQ2, BQ1, and BQ2). The weight-on-bit was maintained at 2400 N (500 lb) throughout all tests, and the rotational speed was kept at 500 rpm. The circulating water flow rate was kept at 9.46 × 10^{-5} m^3/s (1.5 gpm) for all tests. The four measurements included applied torque, rotational speed, weight-on-bit, and penetration depth which were recorded at a 2-s interval. The variations of these four measurements of a test were plotted. Figure 5 shows an example of these plots. Because of the vibration of the machine during drilling and the possible drift of the electronic devices, the recorded penetration depth fluctuated. However, the linear R^2 of those curves ranged from 0.96 to 1.00, indicating a steady penetration rate of drilling.

Because the weight-on-bit, the rotational speed, and the flow rate were constant, the two independent variables were rock type and bit type. Based on the measurements recorded by the data acquisition system, penetration rate, power consumption, friction coefficient, and specific energy, can be calculated. A statistical analysis of variables was conducted. F-values from this analysis indicated the significance of a variable affecting the observation. Table 3 presents results of this analysis.

The critical F-value of this test at 95% confident level is 2.84 for the type of bits and 2.45 for the type of rocks. Therefore, both bit type and rock type had significantly influenced all the measurements included in Table 3.

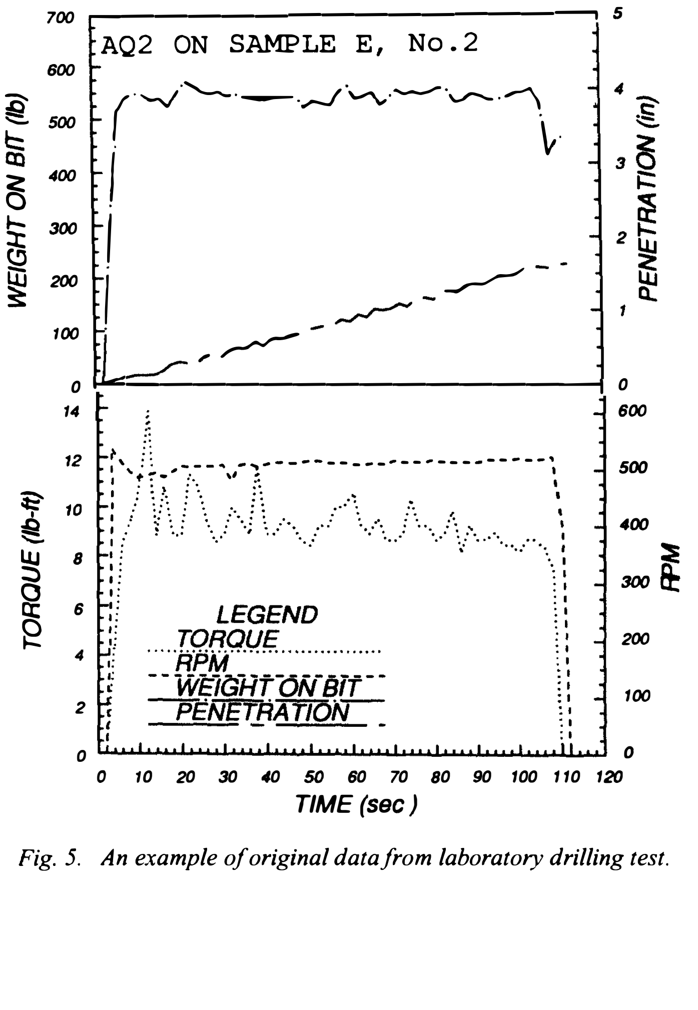

Fig. 5. An example of original data from laboratory drilling test.

Table 3. ANOVA of the rock coring test.

Measurements	F-value for bits	F-value of rocks
Penetration rate	51.63	9.50
Applied torque	85.51	38.23
Power consumption	80.06	35.40
Specific energy	19.05	7.05
Friction coefficient	74.58	33.30

a) Axial penetration rate: The axial penetration rate of a bit was defined as the slope of the penetration depth-time curve. Two penetration rates for the same testing condition were averaged. Figure 6 presents the average penetration rate of each bit versus the cube compressive strength of rock. From the figure it is noted that the average penetration rate decreases when the cube compressive strength of rock increases, and the penetration rates of the two surface-set diamond bits (*i.e.,* AQ1 and BQ1) are significantly larger than that of the two impregnated diamond bits (*i.e.,* AQ2 and BQ2). For the rocks D (*i.e.,* schist) and E (*i.e.,* limestone), the penetration rate of AQ1 bit is about twice as much as that of BQ1 bit. For the rocks A (*i.e.,* sandstone), B (*i.e.,* diorite), C (*i.e.,* granite), and F (*i.e.,* granite), the penetration rate of AQ1 bit is smaller than that of BQ1 bit. This might have been caused by the different diamond sizes of the two bits.

From Fig. 6 it is also noted that the penetration rates achieved by the smaller diameter impregnated bit (*i.e.,* AQ2) are 1.712 m/h (1.123 in/min) for rock D and 1.561 m/h (1.024 in/min) for rock E. With a penetration rate of 1.561 m/h, the AQ2 bit can achieve a penetration of 1.5 m (5 ft) of rock in about an hour in a soft rock stratum like limestone.

It is further noticed that the penetration rates of the two impregnated bits AQ2 and BQ2 were relatively small for the four hard rock samples (*i.e.,* A, B, C, F). If the impregnated diamond bits are to be used to drill hard rocks, the weight-on-bit might have to be increased to a higher level.

b) Applied torque: The applied torque is the torque needed to overcome the resistances of cutting and fluid. The torque required to overcome the resistance of fluid was minimal in comparison with cutting. The measured torque is thus considered solely as a function of friction and abrasion at the bit-rock interface. Figure 7 graphically shows the changes of applied torque as a function of cube compressive strength of rock. It was noted that the torque requirements of the two surface-set bits were significantly higher than that of the two impregnated bits. Furthermore, the torque requirement of the larger diameter surface-set bit (*i.e.,* BQ1) is larger than that of the smaller diameter surface-set bit (*i.e.,* AQ1). By averaging the six torque measurements of each bit, it was found that the ratio of average torque requirement of BQ1 bit to the average torque requirement of AQ1 bit is equal to the ratio between the square roots of the cross-section areas of the two bits. A similar result was found by MELLOR (1976) for comparison of drag bits. On the other hand, torque difference between the two impregnated bits is small. It was further noted from Fig. 7 that the applied torque decreases with the increasing rock strength for all the four types of bit.

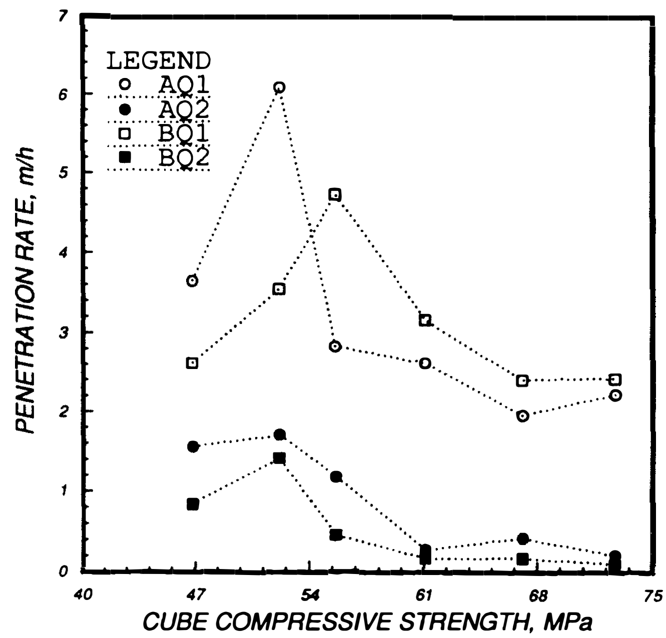

Fig. 6. Penetration rate vs. cube compressive strength of rock.

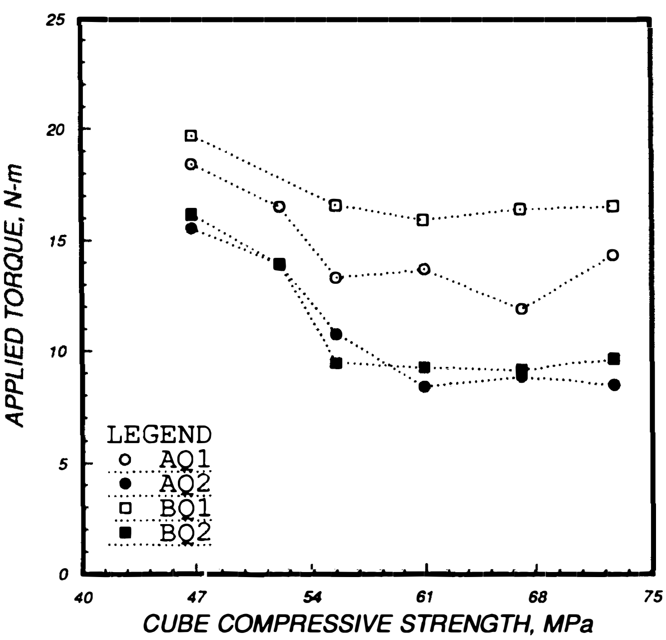

Fig. 7. Applied torque vs. cube compressive strength of rock.

CLARK (1979) pointed out that the torque increases with the friction resistance, which depends upon the strength and abrasivity of rock, the chipping depth (the depth of penetration of a cutter into rock surface) of the cutting tools, the number of exposed cutters, the amount of matrix in contact with the rock, the rotational speed, and fluid lubrication. In practice, there are some limitations on the operation of a drill with respect to the chipping depth. The first consideration is the chipping depth should be large enough so the rock can be cut at a reasonable rate. The cutting depth should not be so great that the cutter plunges so deeply that the motor can not supply enough torque to shear the rock, or produces chips that are too big for easy clearance in the annulus between the drill stem and the hole wall.

In operation torque was a function of weight-on-bit, which was normally exerted by the drill string to rock surface. In general, only a very small proportion of the rock surface is in contact with the core bit at any given time. This is necessary for an effective penetration under a limited weight-on-bit. On the other hand, an excessive weight-on-bit will cause parasite contact between bit matrix material and the rock surface, and consequently produce parasite friction and reduce drilling efficiency. If the torque requirement for drilling exceeds the torque capacity of the motor then the motor will stall.

c) Power consumption: Power consumption in this study is referred to as the power required to supply the bit with a rotational speed under a certain weight-on-bit. This is the power needed to overcome resistance and losses, with most of the resistance due to cutting. The power consumed by a bit is calculated as follow:

$$P = 2\,\pi T N,$$

where:

T is applied torque (N-m),

N is revolutions per second (rps), and

P is power input at the bit (W, or J/s).

Result of power consumption in the coring test is presented in Fig. 8. Because the power consumption by the bit is a direct function of the applied torque, the four bits tested and the six types of rock had a similar effect on the power consumption with the applied torque. At the same weight-on-bit (2400 N), rotational speed (500 rpm), and flow rate (9.46×10^{-5} m^3/s), the power consumption ranges from 0.37 kW (0.5 hp) for AQ2 bit to 1.12 kW (1.5 hp) for BQ1 bit.

d) Specific energy: The specific energy is the energy required to cut and remove a unit volume of material. It varies with bit characteristics, operating procedures, and material properties. In this laboratory coring test, the operating procedures, weight-on-bit, rotational speed, and flow rate are identical for all tests. The specific energy E_v, thus, is determined by the bit and rock types.

The volumetric penetration rate, R_v (m^3/s), is determined by the axial penetration rate (R, m/s) and the cross-section area of the bit:

$$R_v = AR,$$

where A is the cross-section area of the cutting, and R is axial penetration rate. The cross-section area in core drilling is calculated as:

$$A = \frac{\pi}{4}\,(D_h^2 - D_c^2),$$

where :

D_h is the inner diameter of the hole (m), and

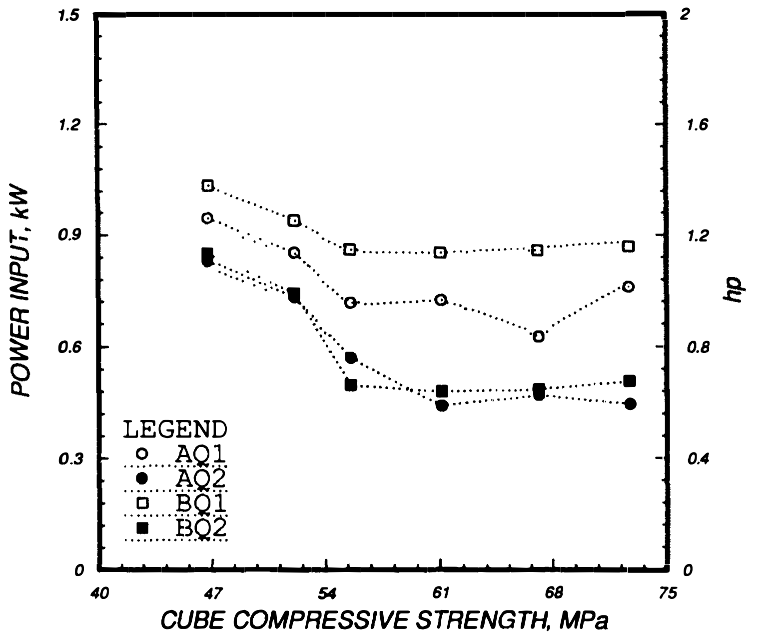

Fig. 8. Power consumption vs. cube compressive strength of rock.

D_c is the outer diameter of the core (m).

Therefore, the specific energy in terms of volume of rock removed, E_v, is as follow:

$$E_v = \frac{P}{R_v} = \frac{8TN}{(D_h^2 - D_c^2)R} .$$

Specific energy determined from this test is plotted against cube compressive strength of rock in Fig. 9. It was found that the specific energy of the two impregnated bits AQ2 and BQ2 increases with the cube compressive strength, whereas the specific energy of the two surface-set bits AQ1 and BQ1 did not change significantly with the cube compressive strength, and the difference of specific energy between the AQ1 bit and BQ1 bit was again small.

e) Friction coefficient: The friction coefficient is defined as the ratio of tangential force along the edge of the bit to the normal force. Theoretical analysis (MELLOR, 1976; CLARK, 1979) indicated that the cutting efficiency of a tool is determined by its shape and chipping depth, and the ratio of tangential cutting force to normal force, C_f, which incrases with the chipping depth. Therefore, the penetration rate of a bit must be related to the cutting force and C_f. Because the applied torque equals to the tangential force (F_t) times the radius of the bit (r), *i.e.*, $T = F_t\, r$, and the normal force (F_n) approximates the weight-on-bit (W), thus

$$C_f = \frac{F_t}{F_n} = \frac{T}{rW} .$$

The friction coefficient C_f is plotted against rock type for all the four bits in Fig. 10. It was noted that a decreasing trend of friction coefficient with an increase in rock strength

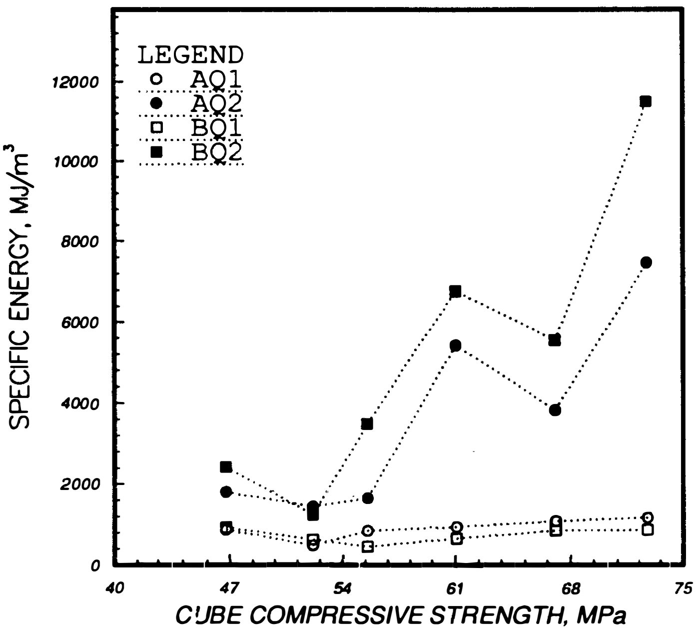

Fig. 9. Specific energy vs. cube compressive strength of rock.

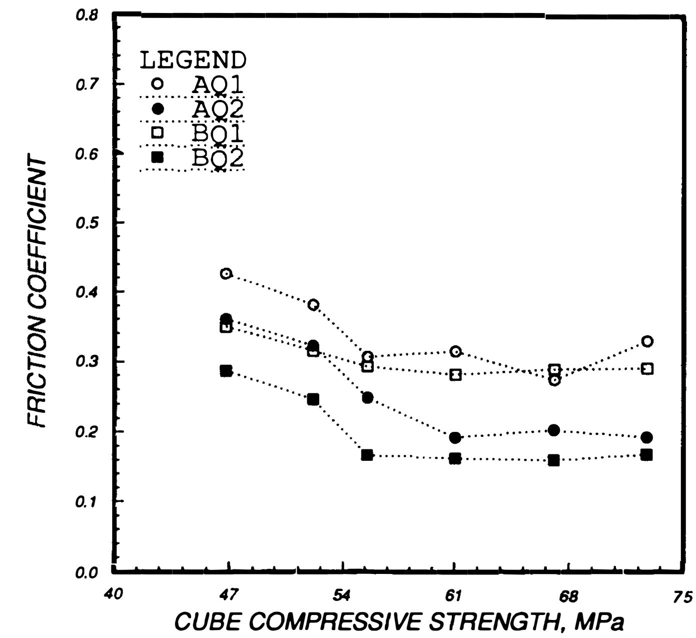

Fig. 10. Friction coefficient vs. cube compressive of rock.

existed. The friction coefficients of the surface-set bits are larger than that of the impregnated bits. It was also noted that the friction coefficient was diameter-related for the same type of bits. This is expected because the bit was not simply sliding on the surface of rock during an effective drilling process. When the same weight-on-bit is applied on different bits, the smaller the diameter of a bit, the deeper the cutting tools will plunge into the rock surface. Therefore, a larger tangential force is needed to shear or crush the rock in front of the cutting tools. That is why in Fig. 10 the larger friction coefficients are corresponding to the smaller bit diameters.

5. Conclusions

Several conclusions can be drawn from this laboratory experimental study:

1) Penetration rate, applied torque, power consumption, specific energy, and friction coefficient are found to be significantly affected by the bit and rock types in this test.

2) Penetration rate of the two surface-set diamond bits tested is significantly higher than that of the two impregnated diamond bits on all the rock samples.

3) Larger diameter surface-set diamond bit (*i.e.*, BQ1) performs better than the smaller diameter surface-set diamond bit (*i.e.*, AQ1) on hard rocks, while the AQ1 bit performs better than the BQ1 bit on softer rocks.

4) Impregnated diamond bits with smaller diameter can be used to drill in soft rocks and achieve a considerably high penetration rate (1.5 m per hour) at 2,400 N (540 lb) weight-on-bit.

5) Specific energies of the two impregnated bits (*i.e.*, AQ2 and BQ2) increase with the increase of the rock strength, while the specific energies of the two surface-set bits (*i.e.*, AQ1 and BQ1) do not change significantly with the rock strength. Furthermore, the specific energies of the two impregnated bits are significantly influenced by the diameters, while the specific energy difference between the two surface-set bits is small.

6) Friction coefficients of the four bits tested decrease with the rock strength, and the surface-set bits have higher friction coefficients than the impregnated bits.

Acknowledgment

Thanks are given to the School of Mineral Engineering at the University of Alaska Fairbanks for the support during this research.

References

BROOK, N. (1977): The use of irregular specimens for rock strength tests. Int. J. Rock Mech. Min. Sci. Geotech. Abstr., **14**, 193–202.

CARGILL, J.S. and SHAKOOR A. (1990): Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. Int. J. Rock Mech. Min. Sci. Geotech. Abster, **27**, 495–503.

CLARK. B.G. (1979): Principles of Rock Drilling. Colo. Sch. Mines Q., **79** (2).

DAVIES, O.L., ed. (1979): The Design and Analysis of Industrial Experiments. Longman Group.

HOWARTH, D.F. (1986): Review of rock drillability and borability assessment methods. Trans. Instn. Min. Metall. (Sect. A: Min. Industry), **95**.

ISRM (Int. Soc. for Rock Mech.), Comm. on Testing Meths. (1977): Suggested Method for Determining Hardness and Abrasiveness of Rocks. Committee on Laboratory Tests, Document No. 5.

ISRM (Int. Soc. for Rock Mech.), Comm. on Testing Meths. (1985): Suggested method for determining point load strength. Int. J. Rock Mech. Min. Sci. Geotech. Abstr., **22**, 51–60.

KARPUZ, C., PASAMEHMETOGLU, A.G., DINCER, T. and MUFTUPGLU, Y. (1990): Drillability studies on the rotary blasthole drilling of lignite overburden series. Int. J. Surface Min. Reclamation, **4**, 89–93.

MELLOR, M. (1976): Mechanics of cutting and boring. Part Ⅱ: Kinematics of axial rotation mechines. CRREL Rep., **76-16**.

RINALDI, R.E., KOCI, B.R. and SONDERUP, J. M. (1990): Evaluation of deep ice core drilling systems. Polar Ice Coring Office Tech. Rep., **TR-90-1.**

(Received July 4, 1993; Revised manuscript received July 15, 1993)