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Low-load diamond drill bits for subglacial bedrock sampling

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ABSTRACT. Electromechanical cable-suspended drilling technology is considered one of the most feasible methods for subglacial bedrock drilling. The outstanding feature of this technology is that the bit load produced by the drill weight is usually within the range 1.5–4 kN while the recommended load for diamond drilling is 10–30 kN or even more. Therefore, searching for the diamond bits that can drill in extremely hard formations with minimal load and acceptable rates of penetration and torque is the necessary step to prove the feasibility of electromechanical subglacial drilling technology. A special test stand has been designed and constructed to examine the impregnated, surface-set, toothed and specially manufactured bionic drill bits. The results of experiments with ten types of drill bits show that the toothed diamond drill bit has the highest penetration rate of 3.18 m h^{-1} in very hard and abrasive granite under a 3 kN load. The torque (28.7 Nm) and power consumption (1.5 kW) of toothed drill bits are acceptable for cable-suspended drilling. The penetration rates of bionic drill bits may also be considered suitable and fall within the range 1.0–1.69 m h^{-1} under the lowest tested load.

KEYWORDS: glaciological instruments and methods, subglacial processes

1. INTRODUCTION

Understanding the role Antarctica has played in global systems over time will require a holistic study of both the thick ice sheets and the underlying rocks; however, the subglacial topography and geology of Antarctica is less well known than the topography of Mars (NRC, 2011). Study of the base of the Antarctic ice sheet is considered one of the most important scientific tasks for future decades and certainly will require bedrock sampling through the thick ice.

To recover subglacial bedrock samples, two types of subglacial drilling technology might be considered (Talalay, 2013): (1) commercial drill rigs with a conventional core barrel, or wire-line core barrel, or coiled tubing, and (2) electromechanical cable-suspended drilling with near-bottom fluid circulation. These drilling technologies have different concepts, limits, performance and applicable scopes.

To use commercial drill rigs in these heavy conditions, many components (e.g. hydraulic system, fluid processing system, etc.) should be largely redesigned as they are not able to work at low temperatures. Commercial drill rigs operate as outdoor machines, and use tents or primitive shelters that are not robust enough at extremely low temperatures and in storm winds in Antarctica. In addition, commercial drill rigs are still very heavy and power-consuming. They require a large logistical load to move and support, so using them in Antarctica is not only disadvantageous but also in some cases impractical.

In our opinion, the most effective method to penetrate subglacial bedrock is electromechanical cable-suspended drilling technology in which a winch with an armored cable is used instead of a pipe-string to provide power to the downhole motor system and retrieve the downhole drill. This was confirmed by four successful projects carried out by US and Russian specialists in Greenland, the Russian Arctic and Antarctica, completed by penetration into the bed (Table 1). It was found that the true bedrock included sedimentary rocks (e.g. siltstones, sandstones and mudstones), metamorphic rocks (e.g. weathered gneisses, granites and metabasalts) and only once (at Summit–GISP2, Greenland) included igneous rocks (gray, medium-grained biotite granite).

The subglacial drilling experience showed that the nominal power of the driven motors (nearly 2.2 kW) is enough even for drilling in hard igneous rock of IX drillability grade. (The grade is the integrated rock characteristic combining many of the factors influencing the drilling performance; all rocks are rated within 12 grades; a low drillability grade denotes easy penetration at a fast penetration rate (Ryabchkov and others, 2010).) Drilling in very hard and extremely hard rocks (fine-grained granite, granite-gneiss and granodiorite, jaspilite or quartzite) with X–XI drillability grade, such as researchers expect to find in the Antarctic subglacial environment (Tingey, 1991), may require uprating of the driven motor. This is undesirable as it requires not only increased motor sizes but also use of a stronger anti-torque system, oversized armored cable, a more powerful and larger winch, etc.

The outstanding feature of electromechanical cable-suspended drilling technology is that the bit load produced by the drill weight is usually within the range 1.5–4 kN (Augustin and others, 2007) while the recommended load for diamond drilling is 10–30 kN and even more (Core Drilling Tools, 2011). Most likely, the successful bedrock sampling of granites at Summit–GISP2 was predetermined by the heavy weight of the electromechanical drill (~7 kN). The adding of dead weights to lighter drills is possible, but only to a limited extent since it requires not only improving the power of hoisting equipment but also increasing the drill length and height of the mast.

Therefore, searching for the diamond bits that can drill in extremely hard formations with minimal load and acceptable rates of penetration and torque is a necessary step to prove the feasibility of electromechanical subglacial drilling technology. Wang and others (1994) investigated the advances of the different diamond bits under the lower operating parameters, but the rock samples used in tests had medium to high drillability at most VIII–IX grades. This paper describes results from a series of experiments to investigate the low-load diamond drilling of rocks with very high hardness and abrasivity.

2. TESTING EQUIPMENT

2.1. Testing stand

The testing stand consists of the XY-1 type rotary drill rig located on a frame, PMB-50 mud pump, QDX sewage pump, rock box, mud tank and various sensors (Fig. 1). The tested rock block with dimensions approximately 300 mm × 200 mm × 300 mm is fixed in the steel box using two strong screw-bolts. The XY-1 drill rig drives the spindle pipe and single core barrel with an attached drill bit. The drilling fluid delivered by the PMB-50 mud pump from the mud tank into the spindle pipe passes continuously over the core inside the barrel down to the drill bit across the face and ejects the fluid with cuttings to the outside surface of the drill bit. Drilling fluid flows into the rock box, and after sedimentation of the rock cuttings the fluid is pumped back to the mud tank by the sewage pump installed inside the box.

The bit load, rotation speed and flow rate of the drilling fluid are controlled in real time. The bit load is produced by hydraulic cylinders of the XY-1 drill rig and handled by a flow-regulating valve on the rig control panel in the range 0–15 kN. Considering that the rotation speed of the spindle pipe is changed in discrete steps using the gear ratios of the gearbox, the frequency converter is additionally used to control the XY-1 drill rig motor so that the rotation speed of the drill bit can be smoothly regulated up to 1010 rpm. The nominal power of the rig motor is 11 kW, and torque on the spindle pipe is as high as 500 Nm. In the same manner, the drilling fluid flow produced by the PMB-50 horizontal single action pump can be adjusted by a frequency converter to a rate of up to 50 L min^{-1}.

Six parameters, i.e. the bit load, rotation speed, torque, flow rate, depth and rate of penetration, are continuously measured and recorded at 1 s intervals during coring runs. Two pressure sensors of SSI-P51 type are installed in the upper and lower chambers of the feeding oil cylinders of the drill rig to measure the pressure in the hydraulic system. The load is then estimated by dividing the pressure difference in the upper and lower oil chambers by the section area of the piston rod.

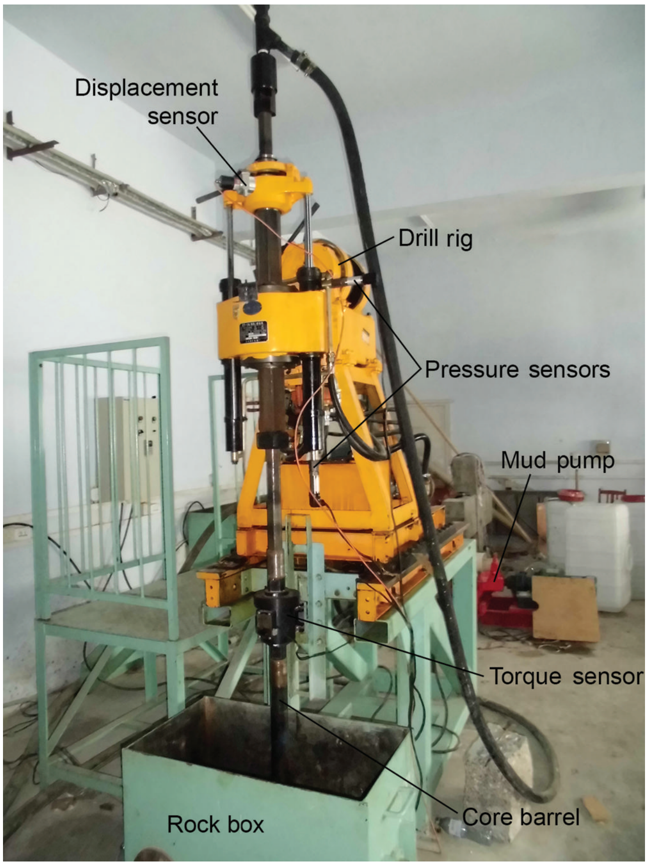

Fig. 1. Drill bit test stand.

Table 1. Experience of subglacial bedrock penetration by electromechanical cable-suspended drills

	Drill type			
	CRREL	KEMS-112	PICO-5.2″	PICO-5.2″
Organization	US Army Cold Regions Research and Engineering Laboratory	Leningrad Mining Institute, USSR	University of Alaska–Fairbanks, USA	University of Alaska–Fairbanks, USA
Location	Camp Century, Greenland	Vavilov glacier, Severnaya Zemlya	Summit–GISP2, Greenland	Taylor Dome, Antarctica
Year	1966	1988	1993	1994
Bedrock interval (m)	1387.5–1391.0	457.1–461.6	3053.4–3055.0	~554.9–555.0
Type of rock	Metamorphic complex consisting of gneisses, granites and metabasalts	Frozen siltstones, sandstones and mudstones	Gray, medium-grained biotite granite	Sandstone and dolerite
Drillability grade (tentatively)	VIII	V	IX	VII
Type of drill bit	Toothed surface-set diamond bit	Tungsten-carbide bit	Surface-set diamond bit	NA
ID/OD of drill bit (mm)	114.3/155.6	93/112	34/NA	NA
Max bit load (kN)	8	1.2	7	7
rpm	225	230	100	100
Sources	Ueda and Garfield (1968); Fountain and others (1981)	Kudryashov and others (1994); Vasiliev and Talalay (2010)	Wumkes (1994); Gow and Meese (1996)	Wumkes (1994); Steig and others (2000)

Note: NA: data are not available.

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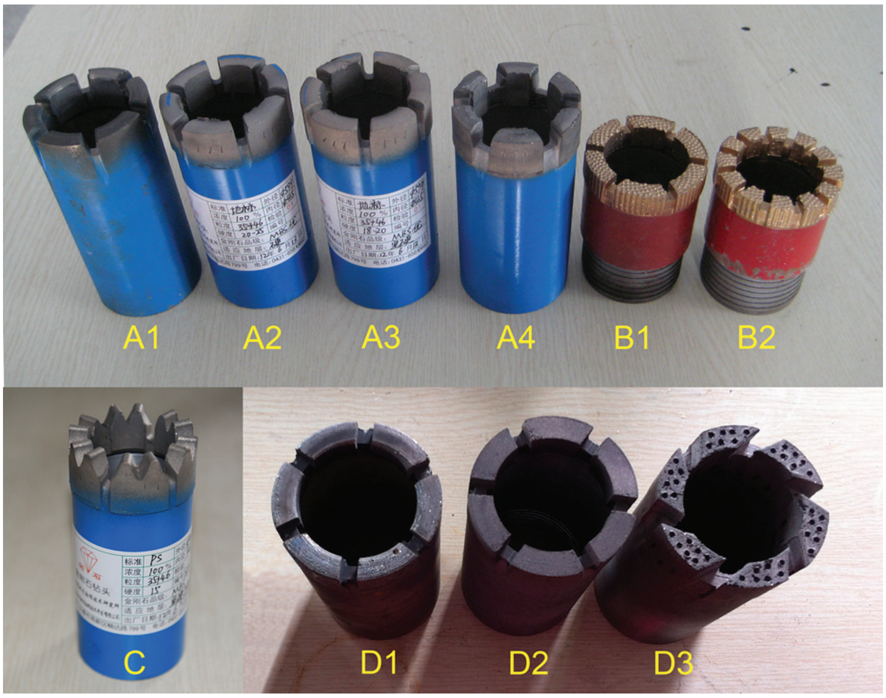

Fig. 2. Tested drill bits. A1–A4: impregnated bits; B1 and B2: surface-set bits; C: toothed impregnated bit; D1–D3: bionic impregnated bits.

A torque sensor of LKN-205 type is installed between the spindle pipe and the core barrel to measure torque and rotation speed of the drill bit. The stator of the sensor is connected with a guide block located at the slot of the rig frame, so that it can only move up and down but cannot rotate with the drill pipe. The hole in the center of the sensor allows circulating fluid to pass down to the drill bit. The measuring limit of the torque sensor is 500 Nm with an accuracy of $\pm 0.2\%$.

A WEP-50 drawstring displacement sensor is installed on the shell of the drill spindle, and the end of the drawstring is fixed on the body of the drill rig. Thus, the sensor can move up and down with the drill spindle, while the end of the drawstring is stationary. The sensor measures the length of the drilled run, and the relative displacement is converted to the rate of penetration. The fluid flow rate is measured by a LDE-40L electromagnetic flowmeter with a measuring range up to 800 L min^{-1}.

All data are transmitted and stored in the computer, and the main parameters are displayed in graphic form on the screen.

2.2. Rock type

Granite with high quartz content was selected for this study. A standard WYY-1 tester was used to test the indentation hardness of the sample, and results indicate that drillability of the rocks is within the range of X–XI grades (Table 2).

Abrasivity of the granite samples was tested on a special apparatus modified from the bench drill. The rock sample is fixed in a sample holder on the bench drill table. A standard metal rod 8 mm in diameter and 70 mm in length made from tool steel with HB 250 hardness is mounted as the drill. Drilling was conducted for ~10 min for each metal rod under a constant load of 0.15 kN and with a rotation speed of 400 rpm. After each test the rock abrasivity is estimated by measuring the metal rod wear. Four rock samples were tested in this study, and the average abrasivity index is ~172 mg (10 min)$^{-1}$, which means the granite samples have the highest abrasive grade (Liu, 1991).

2.3. Drill bits

Ten types of diamond drill bit (Fig. 2) are employed to core the rocks: (1) A1, A2, A3 and A4 – standard impregnated

Table 2. Results of rock hardness test

Sample No.	Hardness					Average hardness value	Drillability grade
	Test point 1	Test point 2	Test point 3	Test point 4	Test point 5		
	MPa	MPa	MPa	MPa	MPa	MPa	
1	6755	6988	6289	6289	5357	6336	XI
2	5124	5357	5590	5590	6056	5544	X
3	5823	3960	5823	5590	4659	5171	X
4	5357	5590	4659	5124	5823	5310	X
5	6755	5357	6988	6289	5823	6242	XI
6	5590	5357	5590	6056	6056	5730	X
7	5823	5823	5590	4659	5357	5450	X

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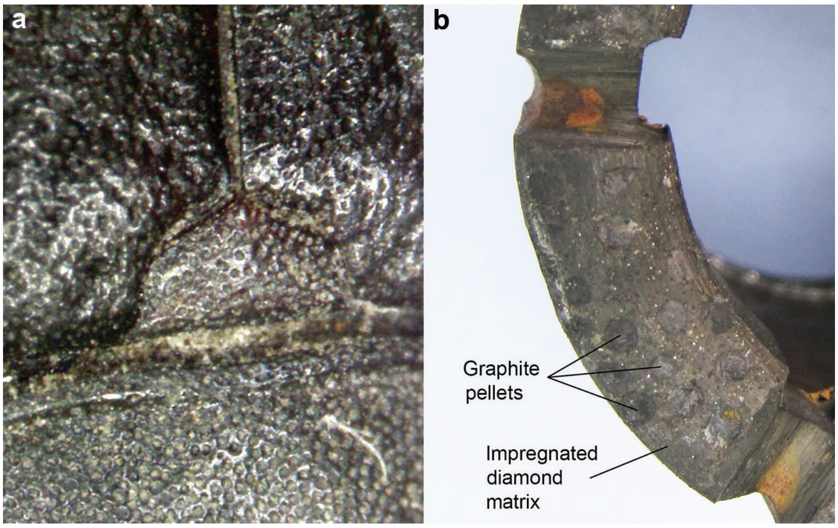

Fig. 3. (a) Armor surface of dung beetle (http://www.f1cd.ru/media/reviews/ks-is_digilux/). (b) Working face of bionic drill bit D1 type.

diamond drill bits with different matrix hardness and different face contact area; (2) B1 and B2 – surface set diamond bits with standard and improved waterway; (3) C – standard toothed impregnated diamond bit; and (4) D1, D2 and D3 – specially manufactured bionic drill bits. The basic parameters of tested drill bits are given in Table 3. The outer diameter (OD) and inner diameter (ID) of all tested bits are almost the same, in the ranges 59–59.8 and 41–41.5 mm respectively. There are small differences because the drill bits were produced at different factories having different matrix molds.

Drill bits A1, A2 and A3 differ in matrix hardness, which is 40–50, 20–25 and 18–20 HRC, respectively. The waterway area of drill bit A4 is double that of A1, and all other parameters are the same. The surface-set drill bits B1 and B2 differ only in the number of waterways: B1 has six waterways, while B2 has twelve, which means the face working area of bit B2 is ~20% less. Toothed drill bit C has 12 parabolic twin-teeth and extensive waterways in between.

The design of drill bits D1, D2 and D3 is based on the bionic engineering and applied biological methods and systems found in nature to develop drilling tools. The working face of these drill bits has a non-smooth surface like soil flora that have skins with perfect friction and abrasion-resistant properties (Yang and others, 2012). For example, the armor surface of a dung beetle has a great many small cavities (Fig. 3a), which reduce contact area for easy burrowing. In a similar way, soft graphite pellets are added into the matrix of the bionic drill bits, making a non-smooth surface of the working face with the small cavities (Fig. 3b). Drilling fluid easily fills these small caverns which provide better diamond cooling and lubrication of the working face. At the same time, the rock cuttings are removed more quickly from the bit face, avoiding repeated disintegration. All this increases cutting efficiency and reduces bit wearing.

The working face of impregnated drill bits D1 and D2 has a non-smooth 'bionic' surface, and their design is the same except for the crown shape and diamond concentration. Drill bit D1 has a semi-round profile of the crown while the surface of drill bit D2 is flat. The concentration of diamonds in D2 is a little less than in D1. The configuration of waterways in drill bit D3 is oblique, and the working face has small caverns to reduce the working area and to improve circulation of the drilling fluid.

2.4. Operating parameters and testing procedure

Operating parameters of rotary drilling include: (1) bit load (often referred to as 'weight-on-bit' or 'drilling pressure', incorrectly since in fact it is not a 'weight' or 'pressure' but downward 'force' or 'load' exerted on the drill bit), (2) rotational speed and (3) drilling-fluid flow rate. The load applied to the drill bit is one of the most important variables

Table 3. Parameters of tested diamond drill bits

Number	Bit type	OD/ID mm	Diamond concentration ct cm^{-3}	Matrix hardness HRC	Face working area cm^2
A1	Impregnated	59/41	2.2–3.3	40–50	10.9
A2		59/41	2.2–3.3	20–25	10.9
A3		59/41	2.2–3.3	18–20	10.9
A4		59/41	2.2–3.3	40–50	8.7
B1	Surface set	59/41	–	40–50	11.7
B2		59/41	–	40–50	9.3
C	Toothed impregnated	59.8/41.5	4.4	18	≤8
D1	Bionic impregnated	59.5/41.5	3.74	10–20	9.4
D2		59.5/41.5	3.3	10–20	9.4
D3		59.5/41.5	3.74	24	8.8

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Fig. 4. Drill bit above the drilled borehole.

in achieving the desired rate of penetration and optimizing bit life. The recommended uniaxial load for impregnated diamond bits is 10–30 kN and even more, depending on the mechanical properties of the rock to be drilled and the drill bit diameter (Core Drilling Tools, 2011). When the load is insufficient, the diamonds become polished, requiring the matrix to be stripped to expose a new layer of diamonds, and penetration will be very slow. In order to choose reasonable operating parameters for subglacial drilling with electromechanical drills, study of the performance of bits at loads as low as 3–5 kN has been suggested.

The rotation of the drill bit causes the exposed cutting element to cut into the rock mass. Diamond drill bits require higher rotational speeds to achieve an acceptable penetration rate than other types of coring drill bits. The recommended rotational velocity of the OD of diamond bits is 140–240 m min^{-1} (Core Drilling Tools, 2011). In general, the higher the rotational velocity, the faster the rate of penetration. On the other hand, high rotational speed would increase the required torque, run-out of the core barrel and hydraulic resistance due to the rotation of the core barrel in a liquid. Therefore, for experimental study, the rotational velocity was chosen as low as 90–100 m min^{-1} resulting in a rotation speed of ~500 rpm with a 59 mm OD drill bit.

Fluid flow is another critical variable in optimizing drilling efficiency. The fluid must effectively cool the bit, remove the cuttings from the bit face and then transport them to the chip chamber as efficiently as possible. Fluid volume should be increased as penetration rates increase. The velocity of the fluid and ability to carry the cuttings depends on the fluid viscosity. Generally, cuttings should always have an upward velocity of ~0.1 m s^{-1}. The configuration of a 57 mm OD single core barrel supposes a fluid flow rate of ~30 L min^{-1}.

Water was used as drilling fluid during all the tests. Six to eight holes were drilled in each rock block. As the core barrel has no core lifter, cores typically remained in the hole after each drill run (Fig. 4). The depth of each hole was 200–300 mm, and triplicate tests were performed to reduce possible experimental errors.

3. TEST RESULTS

3.1. Penetration rate

The penetration rate is estimated as a mean value during the coring run. At any given bit load, the penetration rate of the standard impregnated drill bits A1–A4 is very low, <0.3 m h^{-1}, even with reduced face contact area (Fig. 5). Insufficient bit load blunted the diamonds on the bit face as they are unable to microfracture and expose new cutting edges. As a result, the bit does not perform effectively due to a diminished load. It is notable that the penetration rates of drill bits A1 and A4 initially increase with the load rise from 3 kN to 4 kN, but then decrease when the load increases further to 5 kN. This indicates that the penetration rate of the impregnated diamond bits is not stable under the low-load conditions.

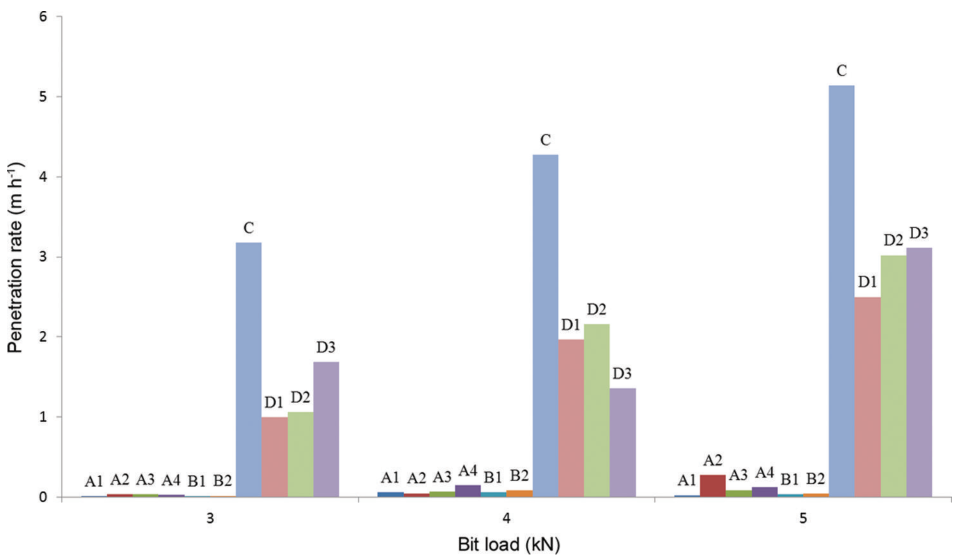

Fig. 5. Penetration rate vs bit load.

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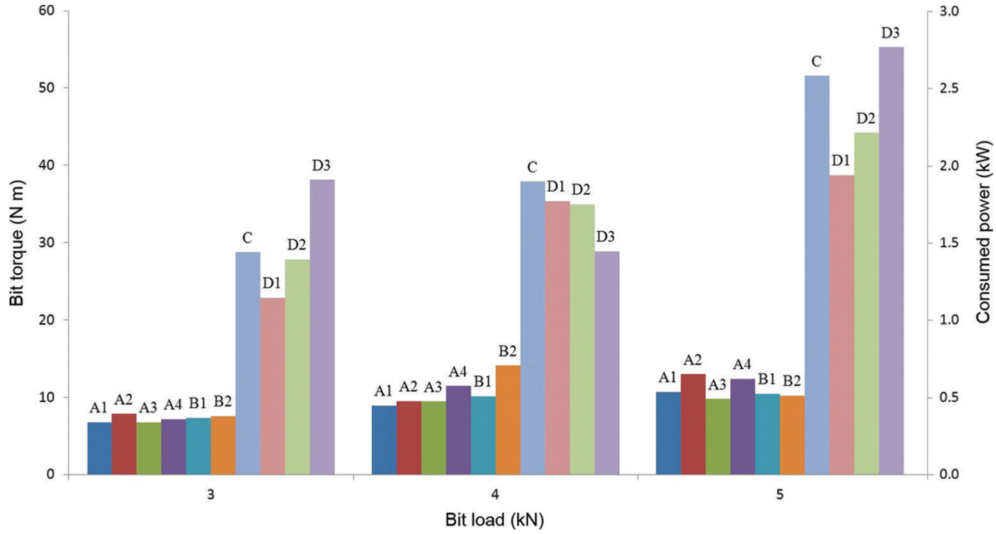

Fig. 6. Torque and consumed power vs bit load.

Although surface-set bits have much larger diamond sizes and have higher diamond exposure than impregnated bits, at low loads the diamond grain cannot effectively pierce the borehole bottom and can only grind rock. Therefore, the advantages of the surface set bits are not fully developed in this case. In addition, the matrix hardness (40–50 HRC) of the chosen surface-set bits is too high to abrade in a timely manner, so the self-sharpening ability of these bits is poor. The penetration rate of the surface-set drill bits B1 and B2 is very low, not exceeding 0.1 m h^{-1}. These results are contradicted by those of Wang and others (1994), who obtained penetration rates of 2.2–2.4 m h^{-1} in granite for surface-set diamond bits of AQ type with a 2.4 kN load. This difference may be explained by different drillability of drilled rocks and/or by the drill bit design.

The contact area of toothed drill bit C is much smaller than that of the other tested drill bits, so the pressure acting on the diamond working area is greatly increased such that the diamond grains can easily pierce rocks. In addition, the matrix of drill bit C is soft (18 HRC), so the new diamond layer can be exposed as the matrix wears away, and the working face can re-sharpen or renew the cutting edges while drilling. Toothed drill bit C is far faster than any other drill bits at applied loads. If the bit load increases from 3 kN to 5 kN, the penetration rate of bit C increases from 3.18 m h^{-1} to 5.14 m h^{-1}. During drilling, the contact area between the rock and the face of drill bit C increases with the matrix wearing, so the penetration rate gradually decreases. The penetration rates of bionic drill bits at low loads may also be considered suitable and fall within the range 1.0–1.69 m h^{-1} under the lowest tested load.

3.2. Torque on the drill bit and consumed power

The torque on the impregnated and surface-set bits is quite low, 7–12 Nm, as the diamond grain cannot effectively pierce the rocks to a certain depth (Fig. 6). Thus, consumed power is only 0.35–0.75 kW. Using toothed bit C, the torque rises significantly from 28.8 Nm to 51.6 Nm with an increase in load from 3 kN to 5 kN. At that load, consumed power increases from 1.5 kW to 2.7 kW. Although the penetration rate of bionic drill bits is lower than the toothed bit rate, the torque and consumed power are about the same.

3.3. Bit wear

The lifetime of the drill bits is affected by the hardness and abrasiveness of the rocks being drilled, together with bit load, rotation speed, penetration rate and lubrication properties of the drilling fluid. In the course of experiments, the wear of impregnated and surface-set drill bits is imperceptible except for bit C.

The high hardness and abrasivity of the used granite coupled with the small contact area of drill bit C are responsible for significant matrix wear. The initial matrix height of the new bit C is 14.6 mm, and in the wake of 40 min drilling with cumulative penetration of 2.64 m bit^{-1} under a load of 3 kN, the matrix height is reduced to 4.9 mm (Fig. 7).

The wear of bionic drill bits is far less; the matrix height is down only by 0.1–0.3 mm after cumulative penetration of ~1.2 m bit^{-1}. According to the field tests of Gao and others (2009), the bit life of bionic drill bits is ~2.5 times longer than with conventional diamond bits under the same conditions.

4. CONCLUSIONS

The bit load is an important parameter in all types of diamond drill bits. If the load is too low (3–5 kN), diamond

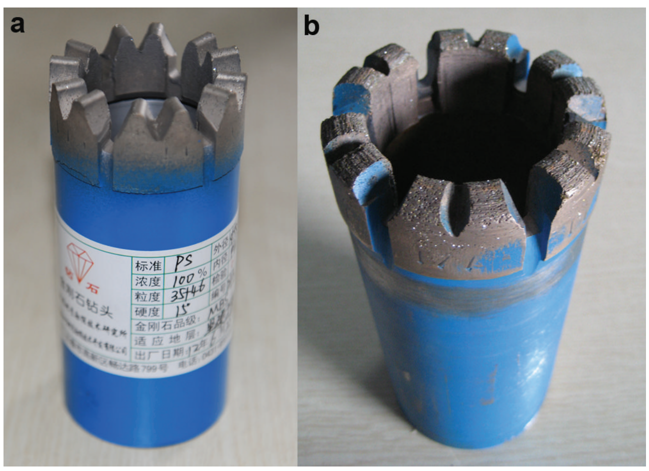

Fig. 7. New (a) and used (b) toothed drill bit C.

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grains of the standard impregnated and surface-set bits cannot pierce the rock and the bit fails to penetrate. High penetration rates with low loads in very hard and abrasive granite are achieved with toothed diamond drilling bits. If the load is 3 kN, the penetration rate with these bits reaches 3.18 m h^{-1}. The high rate of penetration of bit C is most probably due to the minimal initial working area. The penetration rate of bionic drill bits at the same load is lower but also suitable (1.0–1.69 m h^{-1}) in the respect that the expected bedrock interval to be drilled is rather shallow from a few to several tens of meters.

Considering the limitation of anti-torque system parameters, the torque on the toothed drill bit (28.8–51.6 Nm) can be securely held by a skate-type anti-torque system (Talalay and others, 2014). The output power of the driven motors of the existing electromechanical ice-core drills is typically up to 2.2 kW (Talalay, 2003). Hence, the power consumption of toothed drill bits (1.5 kW) at the load of 3 kN is acceptable.

The wear of the toothed bit is significant, and the lifetime in very hard formations is likely less than 4–5 m bit^{-1}. Nevertheless, this type of drill bit can be chosen for subglacial drilling since we can change it when the drill is lifted to the surface to recover the core.

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