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Experimental study of the drilling process in debris-rich ice

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ABSTRACT

Debris-rich ice is often encountered when drilling into basal ice and rock glaciers. The standard steel bits used for ice core drilling are not suitable because the cutters are very easily broken by rock particles as their hardness and abrasiveness are higher than that of the ice. The tool steel and tungsten carbide inserts are easily damaged in intermixed ice–rock formations. To obtain high-quality core samples in debris-rich ice, it is necessary to find drill bits that can drill ice–rock mixtures with minimal load and acceptable penetration rate and torque. A special testing stand has been designed and constructed to study both standard and custom-made carbide and polycrystalline diamond compact (PDC) drill bits. The results show that both the carbide and the PDC drill bits can drill with high penetration rates in debris-rich ice containing very hard and abrasive granite particles at low drill loads of 500–1200 N. When the rock volume content is 30%, the penetration rates are 4.68 m/h, 5.9 m/h and 11.12 m/h for the standard six-tooth carbide drill bit, a PDC bit with a round compact and a PDC bit with a semi-round compact, respectively, under a drill load of 500 N with a rotation speed of 100 rpm. Within the range of drill loads of 500 to 1200 N and rotation speeds of 50 to 200 rpm, the maximum torque is no more than 45 Nm, and the power consumption is less than 0.8 kW. In addition, the temperature changes of the bit cutters caused by their cutting action were also measured. Results of the preliminary tests show that temperature variations increase from 3.67 to 5.96 °C when the drill load increases from 450 to 1200 N and from 4.17 to 6.21 °C when the rotation speed increases from 50 to 200 rpm.

1. Introduction

Drilling into basal ice, till and bedrock has garnered much scientific interest because it offers unique opportunities to research subglacial environments, basal morphology and tectonics and the subglacial hydraulic system (Hansen et al., 2010). Samples of subglacial material not only contain important records of ice sheet history and climate change but also give significant information about ice-sheet/bedrock interaction and how this zone influences the overlying ice sheet dynamics (Popp et al., 2014). Moreover, there are may be existing biological activity within the ice sheets or in the basal materials. However, the ice located in this zone is extremely difficult to drill because it is often loaded with debris and rock and may have particles of various sizes in it, ranging from clay and silt to pebbles, cobbles and boulders (Talalay, 2013). One of the challenges of drilling in these environments is that the ice can be near the pressure melting point so liquid water may be present already despite additional heat produced by the drilling itself. For example, in 2006–07 drilling season at Dome F, Antarctica in approach to the ice sheet basement extra fine particles of frozen water appeared in the chip chamber, and frozen water chips accumulated on the ice core top (Motoyama, 2007). It was concluded that water beneath the ice sheet had probably leaked into the borehole and had frozen at the bottom. Some parts of the drill were covered with ice and dripping water froze at the open face of the core and drill head. The basal ice core contained small rock particles.

Another challenging scientific problem is related to the study of rock glaciers—ice–rock mixtures moving downslope or true glaciers covered by rock debris in polar and mountain regions (Haeberli et al., 2006). Relatively few boreholes have been drilled into and through rock glaciers to permit investigation of thermal and other characteristics of the deeper subsurface. Although good progress has been made in the development of special drilling equipment for coring in rock glaciers, many problems still need to be solved, especially in the areas of the production of reliable drill bits and the elimination of heat generated in the hole (Green et al., 2007).

The most effective method for penetrating subglacial sediments and bedrock is electromechanical cable-suspended drilling technology. Even the bit load produced by the drill weight is usually within the range 1.5–4 kN, and the rotation speed of the drill is normally in the range of 50 to 120 rpm (Augustin et al., 2007), there have been several successful attempts to drill into debris layers in basal ice. In 1966, in the hole at Camp Century, Greenland, subglacial materials consisting of frozen till and various sizes of rocks were encountered at the depth of 1387.5 m.

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The penetration rate decreased to 1.5 m/h–2.2 m/h, the drilling pressure increased to 8 kN, and the power consumption rose to 16 kW when drilling in this stratum (Ueda and Garfield, 1968). From 1989 to 1992, an updated version of the ISTUK drill was used to drill into subglacial bedrock in Dye-3 at Summit, Greenland. Drilling was stopped at a depth of 3028.8 m because the cutting knives of the drill head were damaged by hitting gravel and stones. Subglacial material containing both embedded debris-containing and clear ice layers was obtained. Minor pebbles up to approximately 1 cm in length were present in this material (Talalay, 2013). In 1988, the Russian KEMS-135 electromechanical drill was used for core drilling on Vavilov Glacier. The boundary between glacier and bedrock was at a depth of 459.33 m. The average penetration rate was approximately 1.6 m/h, and the average length of run was 0.37 m when drilling in subglacial material. A 2.28 m subglacial core was retrieved, which was characterized by less than 50% ice content and by structures and textures typical of permafrost. Mineral materials included red-brown siltstones, sandstones and mudstones (Kudryashov et al., 1994). The PICO-5.2″ electromechanical drill was successfully used for core drilling to bedrock at the GISP2 Summit site in central Greenland in 1993 (Gow and Meese, 1996). Debris-rich ice encountered at 3040.34 m depth consisted predominantly of fine-grained amber- to brown-colored sediment, mainly silt with some sand and occasional lithic particles up to 2 cm in diameter. In the 2011 and 2012 seasons, the Hans Tausen drill with a concrete diamond core bit was used to penetrate subglacial coarse material in the NEEM deep drilling project. Several meters of core containing subglacial sediments, rocks and rock fragments were collected, as well as embedded stones up to 2 cm in diameter (Popp et al., 2014).

The subglacial drilling practice has demonstrated that the standard steel bit used for ice core drilling is not suitable for basal debris-rich ice drilling; the cutters are very easily broken by rock particles because their hardness and abrasiveness are higher than that of the ice. Several studies have been conducted to investigate diamond bits for subglacial bedrock drilling. Wang and others tested different diamond bits in rock samples with medium to high drillability at most VIII–IX grades (Wang et al., 1994). To drill hard rocks, Cao and others tested both standard diamond bits and bionic bits in granite rock samples with drillabilities in the range of grades X–XI (Cao et al., 2014). However, these drill bits cannot be used to drill ice–rock mixtures. Sellmann et al. designed and tested many types of auger bits to drill fine-grained soils such as frozen silt and sand (Sellmann and Brockett, 1988; Sellmann and Mellor, 1986). They concluded that the drill bits needed to stay sharp as long as possible in order to obtain the acceptable penetration rate. Saito and Yoshikawa (2008) researched the portable drilling technology used to drill frozen coarse-grained material, such as frozen gravel. More than 20 different auger/core bits were designed and tested in their study, including several different shapes of core bits with carbide and diamond chips, but these auger bits cannot be used in electromechanical drilling technology. Green and others (2007) designed special cutters with tool steel and tungsten carbide inserts for drilling in ice with small rocks. The tool steel inserts did not perform as well as expected; they were easily damaged and wore out quickly. The tungsten carbide inserts also often became chipped and dull. Similarly, carbide inserts on steel cutters were also experimented with in the subglacial environment at NEEM, with similar poor performance characterized by chipping and dulling when encountering rock fragments (Popp et al., 2014). Together with the experience of Green and others (2007), such an approach can be safely discarded.

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, and the rotation speed of the drill is normally in the range of 50 to 120 rpm (Augustin et al., 2007). Taking into consideration the limitations of the bit load and rotation speed available in most electromechanical drills, in this study, standard and custom-made carbide and PDC drill bits for drilling ice–rock mixing material with minimal load and rotation speed are tested.

2. Testing equipment

2.1. Testing stand

The testing stand consists of an OB-330 motor fixed on a frame, an oil cylinder, a steel box, a circulation pump, a mud tank and a control system with various sensors, as shown in Fig. 1. The samples of ice–rock mixtures being tested, with sizes of approximately 300 × 300 × 250 mm, are fixed in the steel box using two strong screw-bolts. An oil cylinder with a maximum stroke of 450 mm is used to drive the steel box up and down. The pressure of the oil being pumped from the hydraulic system to the oil cylinder is adjusted by the proportional relief valve on the control panel of the hydraulic system within the range of 0 to 16 MPa. This means that the maximum axial force can reach 50 kN. The low temperature drilling fluid is circulated by the SUROM centrifugal pump with a maximum flow rate of 40 L/min.

Several parameters, including the drill bit load, the rotation speed, the torque, the penetration depth, the rate and the power consumption are continuously measured and recorded at one second intervals during drilling runs. Two SSI-P50-type pressure sensors installed in the upper and lower chambers of the oil cylinder are used to measure the oil pressure. Then, the axial force is estimated by dividing the pressure difference between the upper and lower oil chambers by the cross-sectional area of the piston rod. Taking into account the weight of the ice–rock mixture samples and the steel box, the load on the drill bit can be calculated.

An LKN-200-type torque sensor, installed between the motor axis and the swivel, is used to measure the torque, the power consumption and the rotation speed of the drill bit. The measuring limit for the torque and the rotation speed is approximately 200 Nm and 1000 rpm, respectively.

A WEP-50 drawstring displacement sensor is installed on the shell of the oil cylinder, and the end of the drawstring is fixed on the body of the steel box. The sensor measures the length of the drill run, and the relative displacement is converted into the penetration rate.

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

Fig. 1. Drill bit test stand.

2.2. Drilling bits

Three standard and custom-made drill bits (Fig. 2) are used to core the ice–rock mixing material, including:

A. A standard carbide bit with six octagonal cutters, which is used to drill hard rocks with drillability of grades IV–VIII in geological drilling (Wang and He, 2014);
B. A standard PDC bit with four round PDC cutters with a diameter of 12.5 mm;
C. A custom-made PDC bit with four semi-round PDC cutters with a width of 9.5 mm.

The carbide cutters are inserted on the body of the drill bit with a rake angle of 0° and a relief angle of 25°. The rake angle (−15°) and the relief angle (15°) are the same for both PDC drill bits. The basic parameters of the tested drill bits are given in Table 1. For these three drill bits, the clearance between the drill bit body and the borehole wall are 1 mm, 2.5 mm and 1 mm, respectively. Core catchers were not used in the drill head because the purpose of the testing is to study the cutting process only.

2.3. Specimen preparation

There are two types of ice–rock mixture specimens used in the tests, as shown in Fig. 3. The rock volume content of the first one is ~10%, and there is no contact between the rock particles. The second specimen contains ~30% rock volume, and the particles are settled together. The tested samples with dimensions of ~250 × 150 × 350 mm are frozen layer by layer in a special freezing chamber at a temperature of −20 °C. The thickness of each layer is ~15 mm, and the rock particles are evenly distributed in it.

Granite with high quartz content was selected as the debris in this study. The rock drillability is in the range of grades X–XI. A stone crusher was used to crush the large rocks into granules, and particles with sizes of 5 to 10 mm were selected to make the frozen ice–rock mixture specimens.

2.4. Operating parameters and testing procedure

Depending on the mechanical properties of the rock to be drilled, the recommended drill load for the carbide drill bit with six octagonal cutters is in the range of 5 to 10 kN, and it is approximately 3 to 5 kN for PDC drill bits with four compacts (Wang and He, 2014). Considering that the load on the bit is produced by the drill weight of the cable-suspended drill, the tests are conducted with loads as low as 0.5–1.25 kN.

Table 1
Parameters of tested drill bits.

Index	Bits type	Cutter shape	Outer/inner diameter of the cutters, mm	Thickness of work layer, mm	Rake angle, deg.	Relief angle, deg.
A	Carbide	Octagonal	60/41	Not applicable	0	25
B	PDC	Round	63.5/37.5	2	−15	15
C	PDC	Semi-round	60/41	2	−15	15

The fundamental mechanism of rock fragmentation induced by both the carbide drill bit and the PDC bits is shear failure, which is very similar to the shearing mechanism in the metal-cutting process. Therefore, the rotation speed applied to the drill bit is one of the most important variables to increase the penetration rate for both carbide and PDC bits. The rotation speed for these drill bits is recommended to be in the range of 150 to 600 rpm. Here, the rotation speed was chosen to be as low as 50 to 200 rpm.

The circulation of low temperature drilling fluid with an adequate rate of flow is extremely important when drilling frozen ice and rock mixtures. If cuttings are produced more rapidly than they are removed, they will be reground by the drill bit. This process not only slows the penetration rate but also raises the temperature of the drill bit cutters, both of which further deteriorate the drilling conditions. Kerosene was used as the drilling fluid in all of the tests, and the flow rate was ~40 L/min.

All experiments were conducted in a cold room at a temperature of −5 °C. The depth of each hole was 250 to 300 mm, and each test was performed twice to reduce possible experimental errors.

3. Results and discussion

3.1. Penetration rate

Due to the difference in hardness and strength between ice and rock, the penetration rate is very fast in pure ice, and it is slowed when the drill bits meet rock pieces under the same conditions. Therefore, the instantaneous penetration rate and torque fluctuate greatly when drilling in such inhomogeneous ice–rock mixtures. Fig. 4 shows the instantaneous penetration rate and cutting torque variations of the carbide drill bit with a rotation speed of 100 rpm and four different drill loads from 580 to 1155 N in the course of drilling samples with a rock volume content of 10%. As an example, at a load of 580 N the penetration rate varies in the range of 0.95 to 2.38 mm/s and the torque jumps from 1.5 to 23 Nm.

The relationship between the average penetration rate and the drill load was studied at a fixed rotation speed of the drill bit (100 rpm) (Fig. 5a). Here, the penetration rate is estimated as the mean value

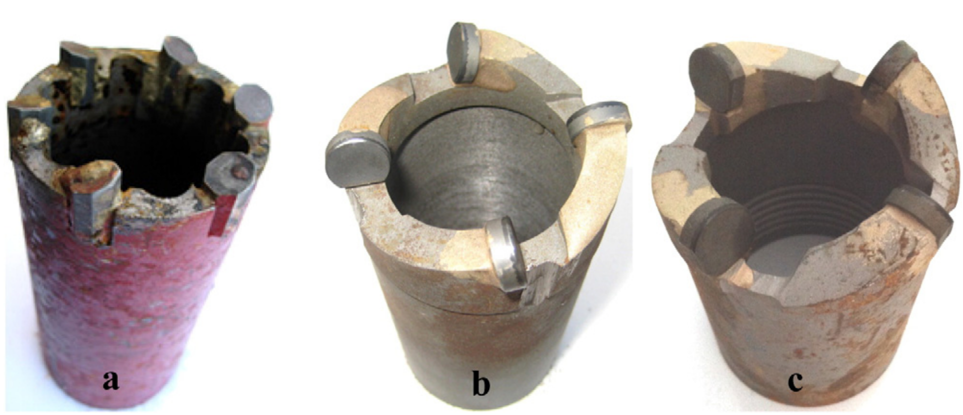

Fig. 2. Tested drill bits: (a) Carbide drill bit; (b) PDC drill bit with round compact; (c) PDC drill bit with square compact.

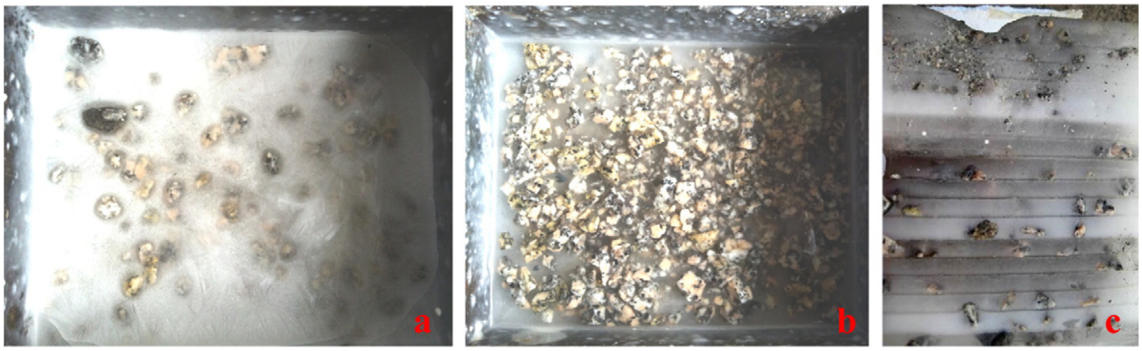

Fig. 3. Samples with different rock contents: (a) ~10% rock particles; (b) ~30% rock particles; (c) profile section of the sample with 10% rock content.

during the coring run. The depth to which the cutter pierced into the ice–rock mixture increases with increases of the drill load, so the drilling speed increases greatly for all three drill bit types. The cutters of drill bit A are sharper than those of the other bits, and the bit has a greater number of cutters. Therefore, the axial force applied to each cutter of drill bit A is lower than that for drill bits B and C at the same drill load conditions. Thus, the penetration rate of drill bit A is far slower than that of the others. When the rock content is 10%, the penetration rate for drill bit A increases from 1.38 to 3.07 mm/s with the increase of the drill load, while for drill bits B and C it increases from 4.83 to 15.17 mm/s and from 3.97 to 13.42 mm/s, respectively. In addition, the penetration rates of the drill bits decrease considerably with increasing rock content in the ice–rock mixture. It is notable that the penetration rate of drill bit C is higher than that of drill bit B when the rock content is 30% at any given drill load, whereas the results are opposite when the rock content is 10% and the drill load is more than 800 N. These results may be attributed to the difference between the compact shapes and sizes of drill bits B and C. The other reason may be that the mechanical properties of the samples are slightly different, as the rock size and its distribution in the samples are not exactly the same.

The effect of rotation speed on penetration rate was studied by maintaining a constant load on the bit of 1000 N. The results are presented in Fig. 5b. The penetration rate increases with an increase of the rotation speed and decreases with a reduction of the rock content in the ice–rock mixing materials for all three drill bit types. Moreover, when the rock content is 10%, the penetration rates of the drill bits B

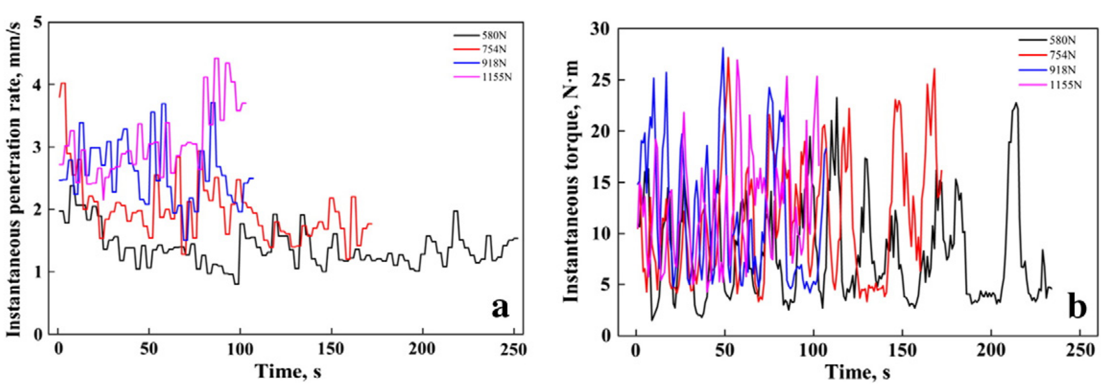

Fig. 4. Drilling parameters with carbide drilling bit: (a) instantaneous penetration rate; (b) instantaneous torque moment.

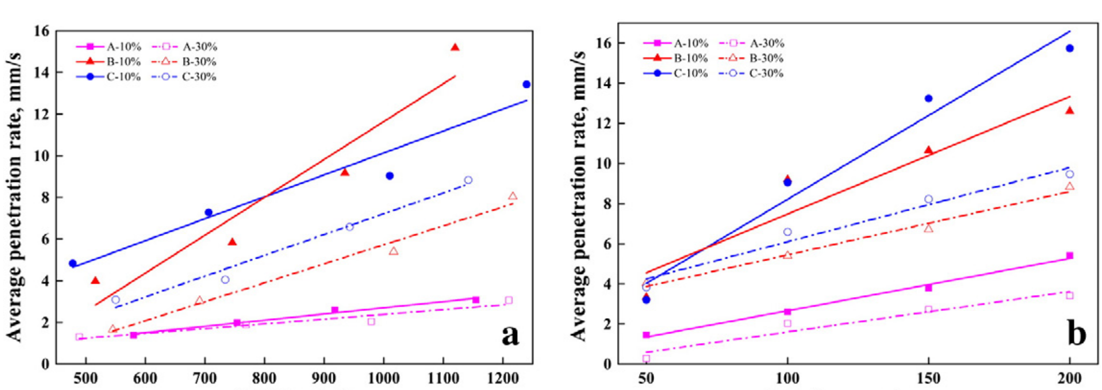

Fig. 5. (a) Penetration rate vs drill load; (b) Penetration rate vs rotation speed.

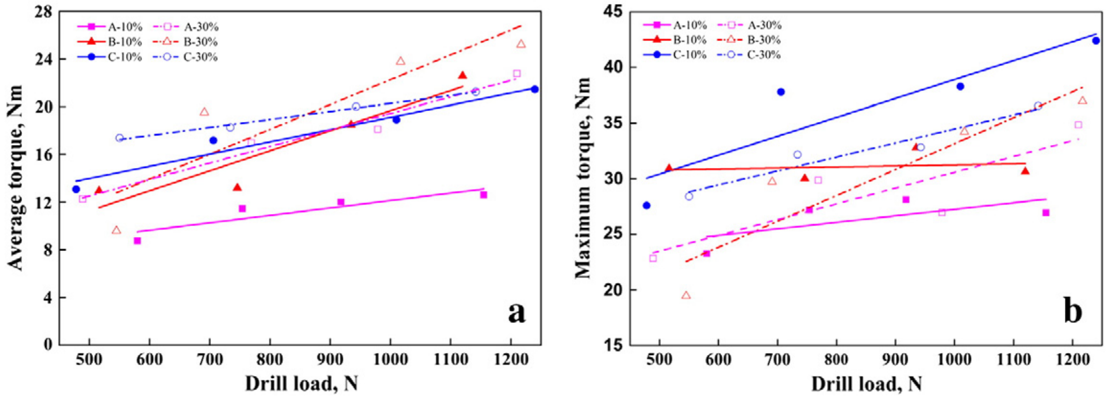

Fig. 6. (a) Average torque vs drill load; (b) Maximum torque vs drill load.

and C are almost the same at lower rotation speed. When the rotation speed exceeds 100 rpm, the penetration rate of the drill bit C is higher than that of the drill bit B.

3.2. Torque moment

The drill load has a strong influence on the cutting torque, as presented in Fig. 6. It was found that the cutting torque increases with increasing drill load and decreases with a decrease of the rock content in the ice–rock mixture. Both the maximum and average torque on drill bit A are lower than those on the other two drill bits.

With the drill load increasing from 500 to 1200 N, the average torque increases from 12.25, 9.57 and 17.38 Nm to 22.78, 25.2 and 21.24 Nm for drill bit A, B and C, respectively, in the course of drilling samples with 30% rock content. In the same circumstances, the maximum torque increases correspondingly from 22.82, 19.42, 28.4 Nm to 34.84, 36.94, 42.39 Nm for drill bit A, B and C, respectively. Surprisingly, the maximum torque of drill bit C decreases with increasing rock volume content. Most likely, this effect is connected with inhomogeneity of the sample materials.

With increases of the rotation speed, the cutting torque of drill bit C remains almost the same, while it decreases slightly for drill bit B for all samples (Fig. 7). Even though high rotation speed can cause drilling instability, increasing rotation speed should take priority from the torque point of view over increasing drill load when the penetration rate needs to be improved because this can reduce the anti-torque system burden of the electromechanical drills.

3.3. Consumed power

The relationship between power consumption and drill load with a constant rotation speed of 100 rpm is shown in Fig. 8. It can be seen that the power consumed during cutting increases gradually with an increase of the drill load. Meanwhile, the more rock particles there are in the ice–rock mixture, the more power that is consumed. Within the range of the tested loads, the average power consumption values for the three types of drill bits are no more than 0.25 kW, and the maximum values are less than 0.45 kW.

The power consumption of all three drill bits increases rapidly with an increase of rotation speed (Fig. 9). Although the penetration rate of the carbide drill bit A is far lower than that of the PDC bit B, the consumed power is almost the same. If the rotation speed is 200 rpm, the maximum power consumption is approximately 0.61, 0.72 and 0.79 kW for drill bits A, B and C, respectively, in the case of drilling samples with 30% rock content. The output power of the driven motors of existing electromechanical drills is typically up to 2.2 kW (Talalay, 2003). Therefore, the power consumed drilling in the ice–rock mixture is acceptable.

3.4. Cutting temperature

A major part of the total energy spent during rotation drilling is lost as frictional heat (Loui and Karanam, 2005). The temperature rise caused by this frictional heat has a significant effect on the drilling process. While drilling ice and frozen ground, drill bit heating can result in ice chips melting, causing the chips to get stuck (Azuma et al., 2007). This ice buildup prevents further penetration, reduces core quality and greatly increases the likelihood of the drill becoming stuck (Gundestrup et al., 2002). The temperature rise generated by drilling in ice–rock mixtures would be higher than that generated by drilling in pure ice, due to present of the rocks in the materials and the larger amount of frictional heat. Drilling in rock glaciers showed that the friction on the drill bit produced enough heat to prevent the water from freezing as long as drilling continued (Green et al., 2007). Therefore,

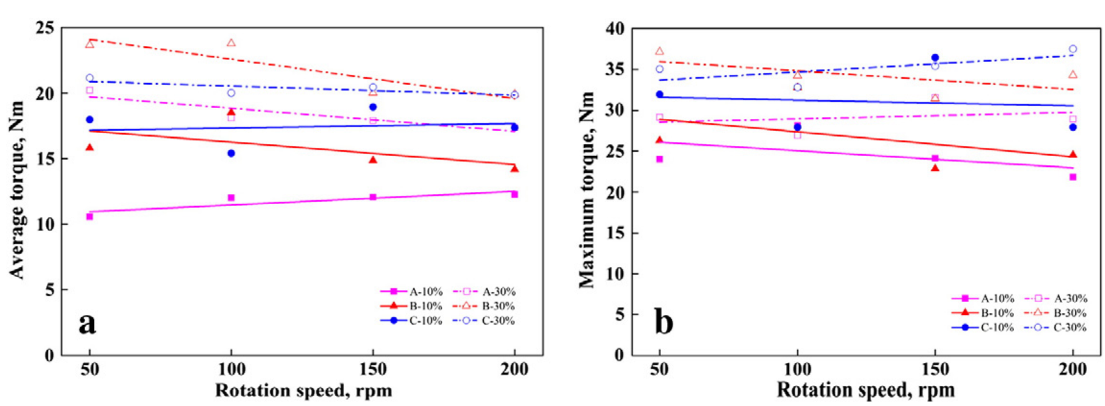

Fig. 7. (a) Average torque vs rotation speed; (b) Maximum torque vs rotation speed.

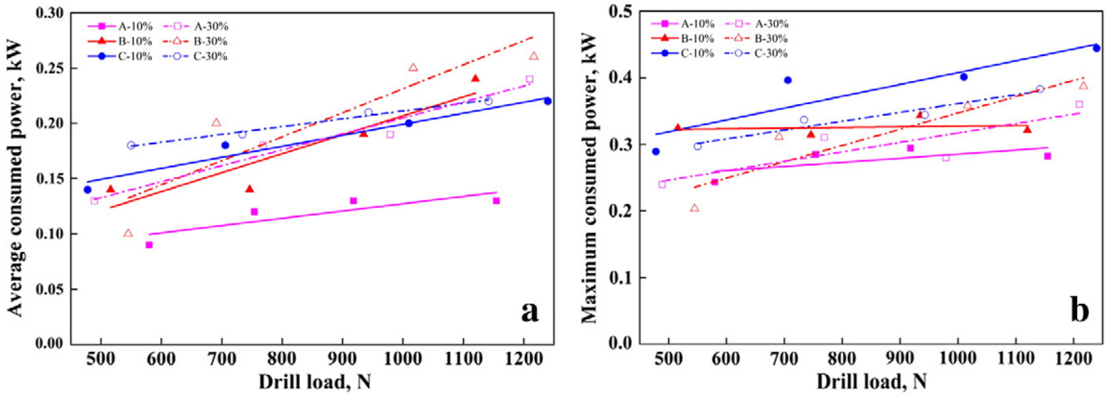

Fig. 8. (a) Average power consumption vs drill load; (b) Maximum power consumption vs drill load.

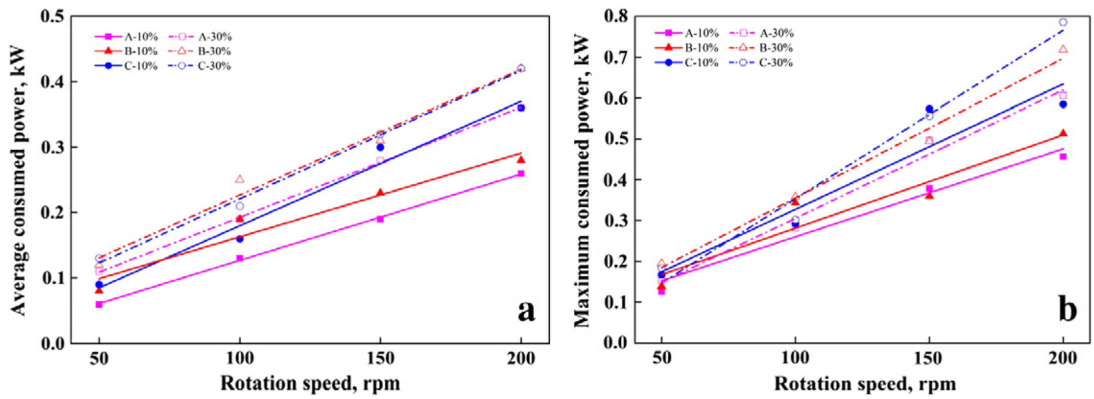

Fig. 9. (a) Average power consumption vs rotation speed; (b) Maximum power consumption vs rotation speed.

care should be taken to minimize the heat generated in the hole because such heat can cause the drill to freeze in the hole. If the drill starts to freeze, the drill motor requires more power. If the drill stops turning, it will freeze instantly.

There are many factors that can affect the temperature rise, including drill bit type, cutter shape and size, drilling parameters and so on (Che et al, 2012). In the current study, the preliminary tests to measure the cutting temperature were conducted using a PDC drill bit with the same structural parameters as drill bit B except for the wall thickness of the bit crown. To install the thermometer, the thickness of the crown was increased to 6 mm instead of the standard thickness of 3.5–4 mm.

A platinum resistance thermometer with an accuracy of ±0.01 °C was inserted into a 3-mm diameter hole drilled at a distance approximately 4 mm from the cutting edge of the PDC cutter. Silicone grease was used as the heat conducting medium, and glass glue was used to ensure a good seal. The ice–rock mixture with a rock volume content of 30% was prepared for this testing. All experiments were performed outdoors. Hence, the initial temperatures of the testing stand, cutters, ice–rock mixture samples and drilling fluid were all at the same temperature as the environment.

The variations of the cutter temperature at a rotation speed of 100 rpm are shown in Fig. 10a. The environmental temperature was

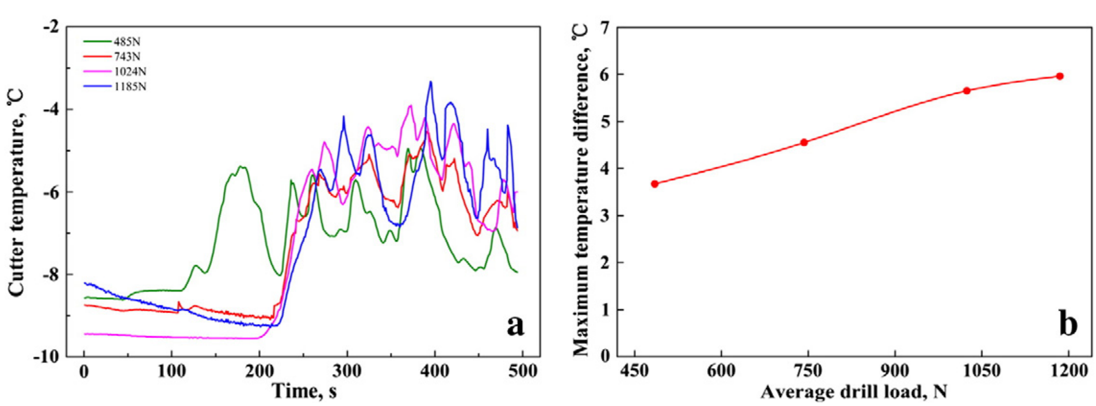

Fig. 10. (a) Cutter temperature vs drill load; (b) Maximum temperature difference vs drill load.

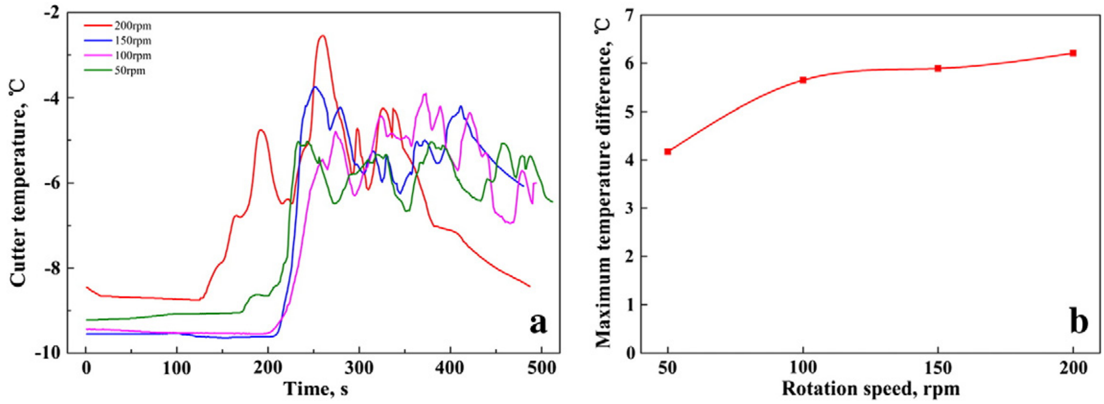

Fig. 11. (a) Cutter temperature vs rotation speed; (b) Maximum temperature difference vs rotation speed.

approximately −9 °C. The temperature increases rapidly when drilling starts and then fluctuates greatly with the alternation of rock particles and ice in the samples. It is found that the temperature increases as the drill load increases (Fig. 10b). As the drill load increases from 450 to 1200 N, the maximum temperature difference increases from 3.67 to 5.96 °C.

The penetration rate increases with an increase in the rotation speed because more cuttings are produced per unit time. The heat generated in drilling correspondingly increases as shown in Fig. 11a. The maximum temperature difference of the cutter increases from 4.17 to 6.21 °C when the rotation speed increases from 50 to 200 rpm (Fig. 11b).

4. Conclusions

(1) The penetration rate fluctuates greatly when drilling in debris-rich ice due to the difference in hardness and strength between ice and rock. Though the penetration rate of the carbide drill bit is far slower than that of the PDC drill bits under the same conditions, both the carbide and PDC drill bits can achieve high penetration rates in debris-rich ice with low drill loads of 500–1200 N and rotation speeds of 50–200 rpm.

(2) For all tested types of drill bits, the maximum torque is no more than 45 Nm, and the power consumption is less than 0.8 kW, which are acceptable for the existing electromechanical drills.

(3) The temperature rise of the cutter caused by frictional heat in debris-rich ice is quite high, and the maximum temperature rise can reach 6.21 °C under the tested conditions. This can result in ice chips melting, which may cause the drill to freeze into the hole. Both reduction of the heat generated during debris-rich ice drilling and effective cooling of the near-bottom area need to be studied further.

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