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DESIGN OF NEW PDC BITS FOR GEOTHERMAL WELL DRILLING AND EVALUATION OF THEIR PERFORMANCE IN A GRANITE QUARRY

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ABSTRACT

The effect of rake angles on the performance of PDC (polycrystalline diamond compact) bits and the performance of a new PDC cutter were investigated by laboratory rock cutting, drilling and durability tests. PDC core bits were designed for field tests based on the result of laboratory tests and their performance was evaluated in a granite quarry. In the field, the PDC core bit with new cutters succeeded in granite drilling of more than 30 m. From the field tests, it became clear that the new PDC core bit can be applied to drilling of abrassive, fractured and hard rock formations economically.

INTRODUCTION

While PDC bits have been applied widely to drilling of homogeneous soft formations in oil/gas fields, they have not been applied to drilling of heterogeneous hard formations in geothermal fields due to spalling and chipping of PDC cutters. It is important to investigate or improve the following items in the development of PDC bits for geothermal well drilling:

- The optimum backrake and siderake angles in hard rock drilling.
- Impact strength, wear resistance and thermal stability of a PDC cutter itself.
- Arrangement of PDC cutters on a bit body including a bit profile.

With respect to rake (backrake) angle, many studies have been conducted through rock cutting tests (e.g., Hibbs and Flom, 1978) and drilling tests (e.g., Hough, 1986) because the rake angle affects the performance of PDC bits significantly. The optimum rake angle obtained from these tests varies from −5-deg to −25-deg (the results are summarized by Hough, 1986), but it is not clear whether its variation depends on rock type or not. In our previous work (Karasawa et al., 1988) using PDC core bits with backrake and siderake angles between −20-deg and −40-deg, it was estimated that the optimum backrake and siderake angles with regard to penetration rate and cutter strength were −20-deg or less. A new PDC cutter designed to improve cutter strength also proved to have better cutter strength than a conventional one in our previous work mentioned above.

Therefore, we conducted rock cutting, drilling and durability tests in a laboratory to investigate the effect of backrake and siderake angles (less than −20-deg) on the performance of PDC bits and to confirm the performance of the new PDC cutter in detail. Furthermore, field tests were carried out in a granite quarry to know the performance of PDC bits in an actural field which contains abrassive, hard rock formations. This paper describes the results of the laboratory and field tests.

METHODOLOGY

PDC Cutter. Two types of PDC cutters, conventional and new ones, were used to make bits for the laboratory and field tests, The conventional one (13.3 mm diameter by 3.5 mm thick), which is selected through rock cutting tests (Karasawa and Misawa, 1987) from three types of PDC cutters available in the market, is the most suitable for hard rock drilling among the three. A diamond layer of the new PDC cutter shown in Fig.1 is protected by a 0.2 to 0.3 mm thick tungsten carbide layer, but the edge of diamond layer (about 0.5 mm width) is exposed to make the cutting edge. The structure of the new PDC cutter is different from that of the conventional one, however, materials of the new one are the same as the conventional one.

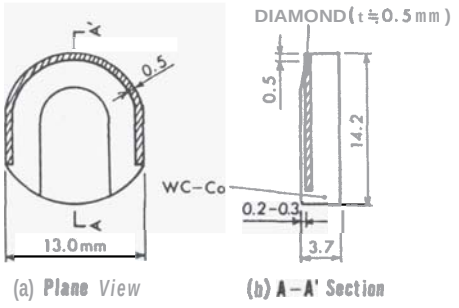


Fig.1 New PDC cutter.

PDC Bits. A PDC bit with a single cutter (only the conventional PDC cutter was used) for the rock cutting tests is shown in Fig.2. Rake angles of the bits were −10, −15, −20, −25, −30 and −40-deg. The bits with −10-deg to −25-deg rake angle had clearance angle of the same value (positive) as rake angle respectively, but clearance angle of −30-deg and −40-deg rake bits was set for 10-deg in order to prevent chipping of diamond layer. The reason for the decrease of clearance angle of the both bits is that a −30-deg rake bit with 30-deg clearance angle and a −40-deg rake bit with 40-deg clearance angle chipped easily in preliminary tests.

Core bits with a 98.43 mm O.D. and a 66 mm I.D. for the drilling and durability tests in the laboratory are shown in Fig.3, and all of these ten bits are described in detail in Table 1. Backrake and siderake angles of each bit were set the same value based on the results obtained from the previous work. PDC bits for the field tests in the granite quarry are all core types, and their shape is the same as the core bit used

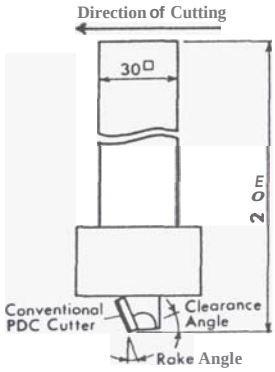


Fig.2 Bit for rock cutting tests.

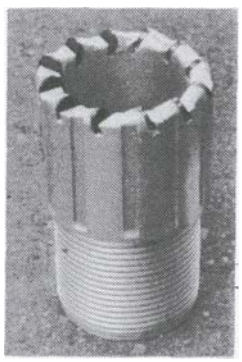


Fig.3 Core bit for drilling and durability tests.

for the drilling and durability tests except that they can hold a core catcher. Table 2 shows detail descriptions of three core bits for the field tests. The surface-set diamond core bit with the same O.D. and I.D. was used to compare the durability to that of the PDC core bits.

Table 1 Description of PDC core bits for drilling and durability tests

Bit No.	Backrake Angle(°)	Sideroke Angle(°)	Type of Cutter	No. of Cutters	Type of Test
1	−20	−20	conventional	12	drilling
2	−20	−20	new	12	
3	−15	−15	conventional	12	
4	−15	−15	new	12	
5	−10	−10	convuntionol	12	
6	−10	−10	new	12	
7	−15	−15	new	12	durability
8	−10	−10	new	12	
9	−5	−5	new	12	
10	−10	−10	new	8	

Table 2 Core bits for field tests

Bit No.	Bit Type	Backrake Angle(°)	Sideroke Angle(°)	Remorks
1	Conventional PDC Core Bit	−10	−10	12 Cutters
2	New PDC Core Bit	−10	−10	12 Cutters
3	Surface-ret Diamond Core Bit	—	—	40 carats, Step Type

Test Equipments. Fig.4 shows a machine used for the rock cutting tests. The rock cutting test by this machine is conducted according to the following procedures: (1) a rock surface is cut by a bit with a straight edge PDC cutter to obtain a flat surface: (2) the test bit is mounted on a piezoelectric dynamometer and is fixed to cut rock at a given depth; and (3) rock is slided by a hydraulic ram at a given cutting speed. Forces loaded on the bit in three components are measured by the piezoelectric dynamometer with transducers manufactured by Kistler Instrumente.

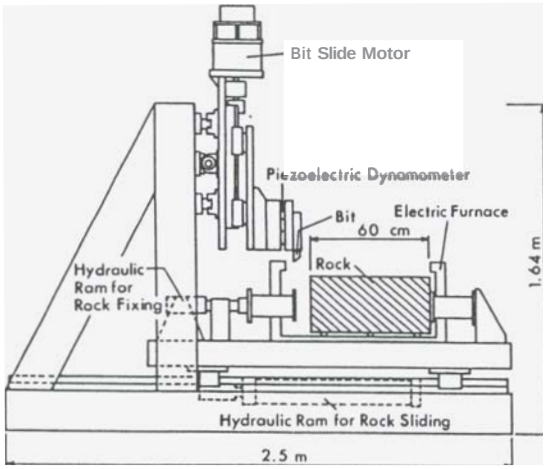


Fig.4 Rock cutting machine.

A drilling machine reported by Misawa et al. (1988) was used for the drilling and durability tests. The maximums of bit weight, torque, rotation speed and flow rate of drilling fluid which can be supplied by this machine, are 294 kN, 2.9 kN-m, 500 rpm and 120 l/min respectively. Size of a rock specimen set on the machine is 50x50x80 cm.

A spindle type boring machine mounted on a test field in the granite quarry is shown in Fig.5. The boring machine is equipped with a 18.5 kW DC motor. Two hydraulic rams can supply a load up to 98 kN and six rotation speeds between 50 rpm to 535 rpm are supplied by the spindle. We paid attention to the method of fixing of the boring machine and to size of a rod in order to prevent vibration of drill string. The boring machine was mounted on the H-beams which were fixed firmly in the concrete base. Fig.6 shows a single tube

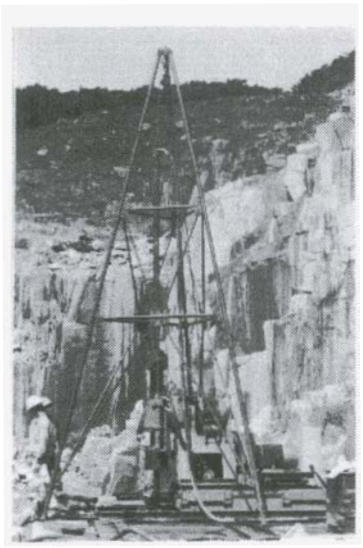


Fig.5 Boring machine and test field in a granite quarry.

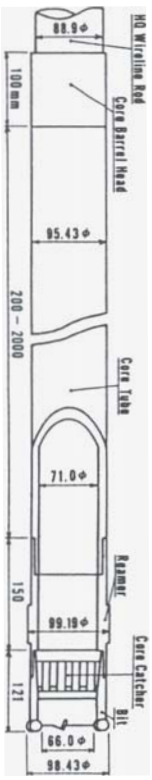


Fig.6 Single tube core barrel and rod.

core barrel and a rod used in the field tests. The HQ wireline rod whose diameter is close to that of the core bit was connected to the core barrel with a reamer.

Test Mediums and Test Procedures. Rock cutting tests for Akiyoshi mahle, Sanjnmr andesite, Shinkomatsu andesite and Sori granite were carried out at a constant cutting speed of 5 m/min and a constant cutting depth of 0.5 mm. The uniaxial compressive strength of each rock is about 59, 86, 82 and 161 MPa respectively. Horizontal and vertical forces loaded on the bit during rock cutting were recorded on magnetic tapes and analyzed.

Rocks used for the drilling tests are Sanjome andesite, Shinkomatsu'andesite and Sori granite. The tests were conducted in the order of soft to hard rocks using No.1 to No.6 bits 'shown in Table 1. The penetration rate and the torque were measured at a constant rotary speed and variable bit weight between 4 kN and 16 kN. The rotary speed was kept at 50, 80 and 110 rpm for each rock sample, and water was used as drilling fluid at a constant flow rate of 90 l/min.

From the drilling tests, it became clear that the new PDC core bit had better performance in general than the conventional one, and that -10-deg or -15-deg both backrake- and siderake angles were better than -20-deg both rake angles with regard to the penetration rate and the cutter strength. The durability tests for Sori granite were therefore conducted using No.7 to No.9 new PDC core bits shown in Table 1 to know the effect of the rake angles on the durability. In addition, the durability test by No.10 core bit with eight cutters (Table 1) was also carried out for Sori granite in order to investigate the effect of the number of cutters on the durability. Its durability was compared to that of the No.8 bit with twelve cutters. In the durability tests, the penetration rate was kept constant at about 5 cm/min. The rotary speed is 50 rpm and water flow rate is 90 l/min. The test with each bit was stopped when drilled length reached to 12 m.

Based on the results of the rock cutting, drilling and durability tests in the laboratory, we decided to conduct the field tests using the -10-deg backrake and siderake core bits with the new PDC cutters and the conventional ones (Table 2). And the granite quarry was selected as a first test field, because granite is one

of rocks which are difficult to drill. Granite mined in the quarry, called Aoba granite, is holocrystalline medium-grained biotite granite. Conditions of the field tests were as follows:

- orotary speed (PDC bit) = 50 rpm
- rotary speed (diamond bit) = 200 rpm
- openetration rate = about 5 cm/min
- water flow rate = 90 l/min.

The condition of core samples recoverd by the core bits is illustrated in Fig.7. Some natural fractures and weatherd zones were observed in the core samples, but many of them were fresh and homogeneous granite. Mechanical properties of core samples, whose locations are indicated by black circles in the figure, were measured. The uniaxial compressive strength of fresh core samples was around 245 MPa. From the condition of core samples and the mechanical properties, the condition of the granite formation drilled are judged to be almost same regardless of hole and hole depth.

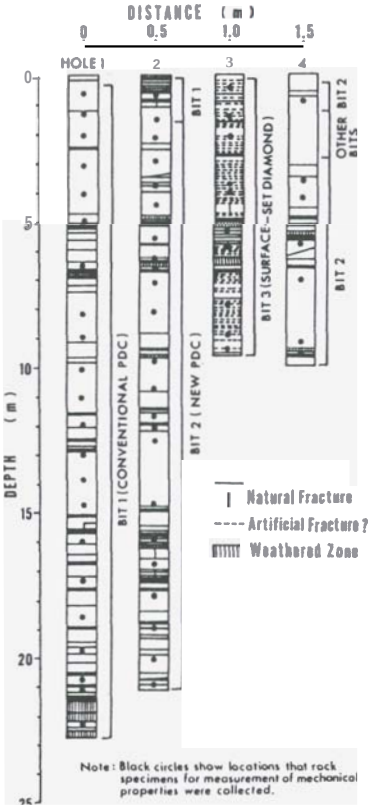


Fig.7 Condition of core samples recoverd.

RESULTS AND DISCUSSION

Rock Cutting Tests. Figs.8(a) and (b) show the effect of rake angle on the horizontal force (Fh) and the vertical force (Fv) respectively. The horizontal and vertical forces have a trend to decrease with the decrease of rake angle (absolute value), and its trend does not depend on rock type. The forces necessary to cut the rock at the given depth are minimized at a -10-deg rake angle in the range of -10-deg to -40-deg, and this result agrees well with that of Hibbs and Flom (1978). It is suspected that the penetration rate, in the case of an actual bit, becomes larger according to the decrease of rake angle between -10-deg and -40-deg when the bit weight is kept constant, since the vertical force corresponds to the bit weight.

Plots of results with the -25-deg rake bit except Akiyoshi marble were eliminated from the figure due to chipping of the diamond layer, however, -30-deg and -40-deg rake bits (10-deg clearance angle) did not chip. As mentioned before, -30-deg and -40-deg rake bits (with 30-deg and 40-deg clearance angles) chipped readily. Hence, it is obvious that the diamond layer of bits with rake angle of above -25-deg chips easily if the clearance angle was not set below 25-deg.

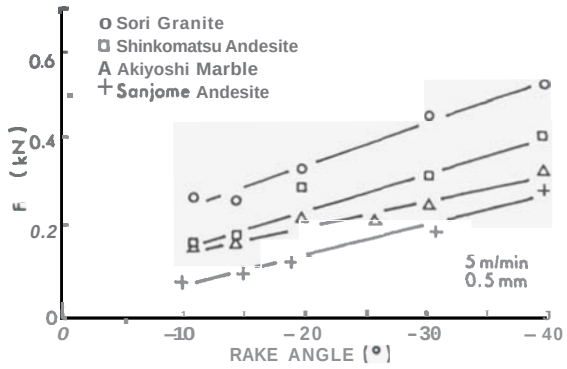


Fig.8(a) Effect of rake angle on horizontal force.

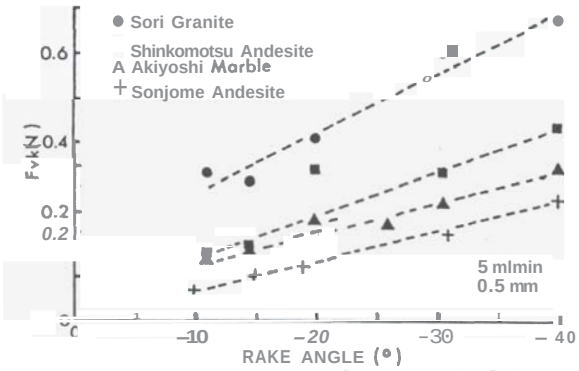


Fig.8(b) Effect of rake angle on vertical force.

Drilling Tests. The effect of backrake and siderake angles on the penetration rate showed almost same tendency regardless of the rotation speed, therefore, relationship between the bit weight and the penetration rate of each bit at the rotation speed of 50 rpm is shown in Figs.9 and 10. Figs.9(a), (b) and (c) show the results of the drilling tests with the conventional PDC core bits for Sanjome andesite, Shinkomatsu andsite and Sori granite respectively. The results of the drilling tests with the new PDC core bits for the same rock samples are shown in Figs.10(a), (b) and (c). In these figure 10, 15 and 20 represent the core bits with both backrake and siderake angles of -10, -15 and -20-deg respectively.

Clear relationship between the both rake angles and the penetration rate is not found in the both figures. However, in the case of the conventional PDC core bits (Fig.9), the bit with backrake and siderake angles of -10-deg shows higher penetration rate than that with both rake angles of -15-deg or -20-deg. In the case of the new PDC core bits (Fig.10), the bit with backrake and siderake angles of -10-deg or -15-deg shows higher penetration rate than that with both rake angles of -20-deg in two types of andesite, but the maxinum penetration rate is obtained at -15-deg both backrake and siderake angles in granite. The results of the drilling tests do not necessarily agree with that of the rock cutting tests. The penetration rate may be alsb influenced by the degree of chipping, wear flat, and sharpness of diamond particles which contact with the rock surface in addition to backrake and siderake angles. As shown in Figs.9 and 10, the penetration rate of the new PDC bits is generally higher than that of the conventional ones in harder rock such as Shinkomatsu andesite and Sori granite.

Figs.11 and 12 are photographs of the conventional and new PDC cutters after the drilling tests for three types of rock (the total drilled length was about 5 m). A, B and C in the figures are one of outside cutters on the bits with backrake and siderake angles of -10, -15 and -20-deg respectively. Chipping of the diamond layer is observed in all conventional PDC cutters, but the degree of chipping decreases with the decrease of both rake angles. On the other hand, chipping of the diamond layer is hardly found in the new PDC cutters with -10-deg and -15-deg both rake angles. However, small chipping or wear of cutters with -15-deg both rake angles is somewhat larger than that of cutters with

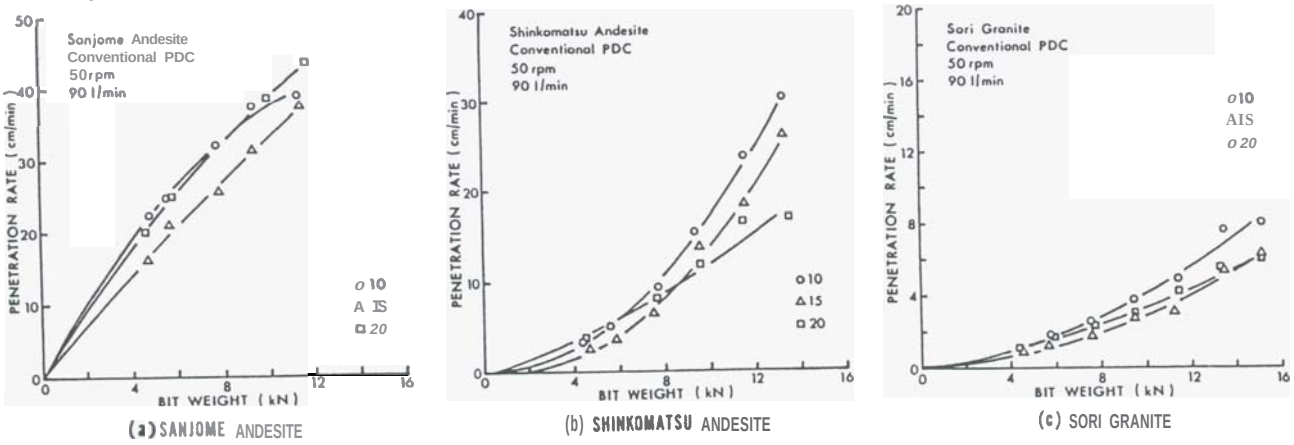


Fig.9 Results of drilling tests by conventional. PDC core bits.

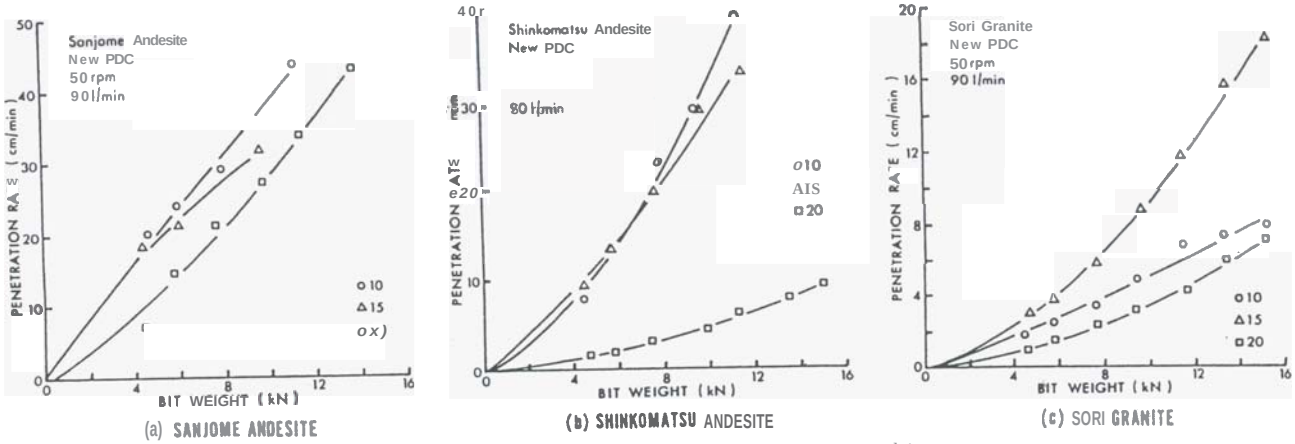
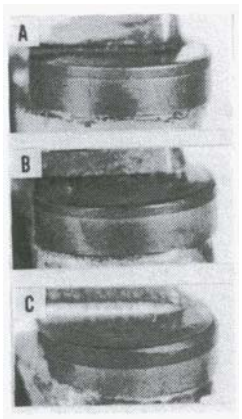
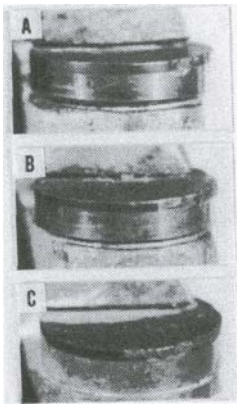


Fig.10 Results of drilling tests by new PDC core bits.



A:−10−deg Backrake & Siderake Angles
B:−15−deg Backrake & Siderake Angles
C:−20−deg Backrake & Siderake Angles

Fig.11 Condition of conventional PDC cutters after drilling tests.



A:−10−deg Backrake & Siderake Angles
B:−15−deg Backrake & Siderake Angles
C:−20−deg Backrake & Siderake Angles

Fig.12 Condition of new PDC cutters after drilling tests.

−10−deg both rake angles. Strength of the new PDC cutter also increases with the decrease of backrake and siderake angles as well as the conventional one. The higher penetration rate of the new PDC core bits when compared to the conventional one in harder rock as mentioned above, is probably caused by less chipping of the diamond layer in the new PDC core bits.

From the results of the drilling tests, it became clear that −10−deg both backrake and siderake angles, in the range of −10−deg to −20−deg, are preferable in the case of the conventional PDC cutter with regard to the penetration rate and the cutter strength. In the case of the new PDC cutter, both rake angles of −10−deg or −15−deg are preferable than that of −20−deg. The new PDC cutter protected by the tungsten carbide layer, had better cutter strength when compared to the conventional one. The cutter strength is very important for extended bit−life, because the chipping of the diamond layer reduces it significantly. Hence, it is suspected that the new PDC core bit has longer bit−life than that of the conventional one.

Durability Tests. The results of durability tests with the new PDC core bits for Sori granite in the laboratory are summarized in Table 3. The bit weight and the torque necessary to maintain a constant penetration rate of about 5 cm/min becomes larger in the order of the bits with −10, −15 and −5−deg both backrake and siderake angles (No.7 to No.9 bits in the table). In particular, the core bit with both rake angles of −5−deg needs fairly larger bit weight when compared to that with both rake angles of −10−deg. −5−deg both backrake and siderake angles is not proper in granite drilling, because the exceeding bit weight causes chipping or spalling of the diamond layer. Although large chipping was recognized in some cutters of these bits after the durability tests, many of cutters showed relatively good condition. However, clear relationship between the rake angle and the cutter strength was not found in the durability tests.

Combination of the results of rock cutting, drilling and durability tests with both the conventional and new PDC cutters shows that −10−deg both backrake and siderake angles is generally better with regard to the penetration rate and/or the cutter

Table 3 Summary of durability tests for Sori granite

Bit No.	Rake * Angle (°)	No. of Cutters	RPM	Bit Weight (kN)	Torque (N−m)	length (m)	Rate (cm/min)
7	−15	12	50	13.4−23.2	255−485	12.3	5.6
8	−10	12	50	11.0−20.8	230−412	12.2	5.6
9	− 5	12	50	18.3−35.5	338−579	12.1	5.9
10	−10	8	50	11.0−15.9	216−363	12.2	5.8

* Backrake & Siderake

strength. However, it is difficult to judge clearly which rake angle is better, −10−deg or −15−deg both backrake and siderake angles, in the new PDC cutter.

The bit weight and the torque of the PDC core bit with eight cutters (No.10 bit in Table 3) to obtain the penetration rate of about 5 cm/min, is small when compared to the bit with twelve cutters (No.8 bit in Table 3). However, clear difference of the cutter strength between the both bits was not recognized. It is obvious. that the PDC core bit with eight cutters also has good performance as well as that with twelve cutters in granite drilling.

Field Tests. Although all of the core bits did not completely reach the limit of bit−life in the field tests, the tests were stopped due to the limit of a test schedule. In order to confirm the bit−life (drilled length) of all bits, we conducted durability tests for Aoba granite in the laboratory after the field tests under the same conditions as the field tests. Summary of the field tests including the laboratory tests is shown in Table 4. The surface−set diamond core bit was judged to reach almost the limit of bit−life, because the penetration rate decreased even in the limit bit weight for this bit. On the other hand, both the new PDC core bit and the conventional one still had considerable bit−life after the laboratory tests. The new PDC core bit possesses bit−life more than three times, at least, when compared to that of the surface−set diamond core bit. Chipping and wear flat of the new PDC cutter were less than that of the conventional one; therefore, the new PDC cutter may be preferable in hard formations. In addition, it was noted that both the new PDC and conventional cutters did not chip or spall even if fractured or weatherd zone was drilled in the field.

Table 4 Summary of field tests

Bit No.	Bit Type	RPM	Bit Weight (kN)	Drilled Length (m)	Rote (cm/min)
1	Conventional PDC	50	1.8−21.8	23.8 (25.2)*	5.9
2	New PDC	50	1.8−29.1	27.4 (32.2)*	4.5
3	Surface-set Diamond	200	4.9−25.5	10.5 (11.6)*	6.3

* The numbers in parentheses include durability tests for Aobo gronite in o laboratory after field tests.

In order to estimate an economical aspect of PDC bits in hard rock drilling, drilling cost per meter of each bit was calculated using the following equation (Moore, 1986).

$$ct = \frac{B\ t\ Cr(t + Tr)}{F}$$

where: Ct = drilling cost, $/m
B = bit cost, $
Cr = rig cost, $/hr
t = drilling time, hr
Tr = round trip time, hr
F = drilled length, m

The calculation of drilling cost per meter was conducted under the following assumptions:

- Rig cost per hour equals to 1.
- Penetration rate is 3 m/hr (5 cm/min).
- String pulling rate is 200 m/hr.
- Bit−life (drilled length) of conventional PDC, new PDC and surface−set diamond core bits is 25.2, 32.2 and 11.6 m respectively.

The result of calculations is shown in Fig.13. In the figure bit costs are expressed as that the rig cost/hr equals to 1. Though the minimum bit−life of the PDC core bits is assumed, the drilling cost per meter of the bits becomes lower than that of the surface−set diamond core bit when the hole depth exceeds about 400 m. PDC bits may be able to be applied economically to drilling of abrassive hard formations such as granite regardless of hole depth, and it is noted that the saving of drilling cost is remarkable in deeper holes.

Fig.14 shows core samples recovered by the PDC core bit. The surface of the core samples which were

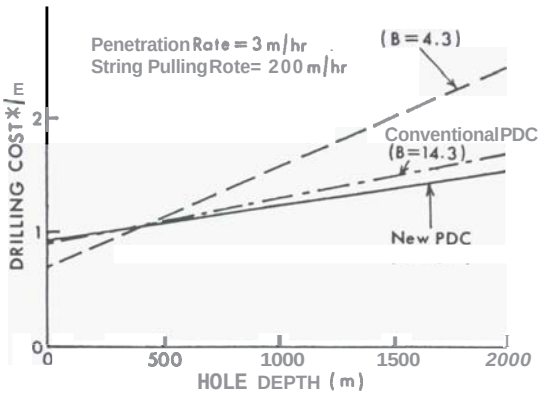


Fig.13 Comparison of drilling cost between surface −set diamond core bit and PDC core bits.

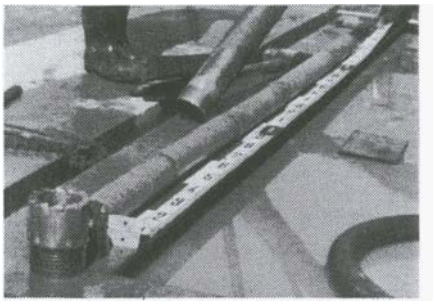


Fig.14 Photograph of core samples recovered by PDC core bit.

recovered by the PDC core bits, was very smooth as well as the case of the surface−set diamond core bit. The smooth surface of core samples is originated in smooth rotation of the bits during drilling. One of reasons for the good performance of the PDC bits in the field is the smooth rotation of the bits. It is caused by the strong fixing of the boring machine, the proper drill string, and the lower rotation speed.

CONCLUSIONS

In order to investigate the effect of rake angles on the performance of PDC bits and to confirm the performance of the new PDC cutter, the laboratory rock cutting, drilling and durability tests for several types of rock were conducted using bits with the conventional and/or new PDC cutters. The results are summarized as follows:

1. The horizontal and vertical forces are minimized at a −10−deg rake angle in the range of −10−deg to −40−deg, and its rake angle does not depend on rock type.
2. Bits with rake angle of more than −25−deg chip readily.
3. The optimum backrake and siderake angles, between −10−deg and −20−deg both rake angles, is −10−deg with regard to the penetration rate and the cutter strength in the case of the conventional PDC cutter. The optimum both rake angles are −10−deg or −15−deg in the new PDC cutter.
4. −5−deg both backrake and siderake angles are not preferable in granite drilling.
5. The new PDC cutter has better cutter strength than the conventional one.
6. Eight cutters is sufficient in granite drilling with a PDC core bit of around 100 mm O.D. and 66 mm I.D.

Based on the results of the laboratory tests, PDC core bits were designed and tested in the granite quarry to know the applicability of PDC bits in an actual field which contains hard rock formations. The results are:

1. The new PDC core bit has bit−life more than three times when compared to the surface−set diamond core bit.
2. The PDC core bit can be economically applied to drilling of abrassive, fractured and hard rock forrnations.

As a small diameter PDC core bit proved to have the good performance in hard rock drilling, a large diameter PDC core bit (8-1/2 in., 216 mm) will be tested in order to know the applicability of it to drilling of actual geothermal wells.

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CONVEKSTON FACTORS FOR CONVENTIONAL UNITS

mm	x	3.973 E-02	=	in.
m	x	3.281 E+00	=	ft
kN	x	2.248 E+02	=	lbf
N-m	x	7.376 E-01	=	lbf-ft
l	x	2.642 E-01	=	gal
MPa	x	1.450 E+02	=	psi