DEVELOPMENT OF PDC BITS FOR DOWNHOLE MOTORS

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SUMMARY - To develop polycrystalline diamond compact (PDC) bits of the full-face type which can be applied to downhole motor drilling, drilling tests for granite and two types of andesite were conducted using bits with 98.43 and 142.88 mm diameters. The bits successfully drilled these types of rock at rotary speeds from 300 to 400 rpm.

1. INTRODUCTION

PDC bits have been widely used for drilling of homogeneous soft to medium-hard rock formations at oil wells because of their better penetration rate and longer bit-life than the roller cone types in such formation drilling. However, it is said that the application of the PDC bits is not appropriate for drilling in hard rock formations such as geothermal wells, since the failure of the PDC cutters often occurs during such drilling.

The authors conducted drilling tests in the laboratory to develop PDC bits for geothermal well drilling (Misawa and Karasawa, 1991; Karasawa and Misawa, 1992). Field tests at actual geothermal wells using PDC core bits with an outer diameter of 215.1 mm (8-15/32 in.) following the laboratory tests, resulted in successful hard granodiorite drilling (Misawa and Karasawa, 1992). However, the development of PDC full-face bits for geothermal well drilling remained as the next challenge, since these tests were mainly conducted to develop core bits.

The objective of this work, succeeding the previous one, is to develop full-face PDC bits with high drilling efficiency which can be applied to geothermal well drilling. One of methods to improve drilling efficiency may be to use PDC bits for downhole motor drilling. These bits might be needed to be redesigned and fabricated so as to rotate at high speeds, since downhole motors usually rotate at about 150 to 400 rpm. Both decreasing of cutter diameter (the standard PDC cutter is 13.3 mm-dia) and increasing of cutter numbers set on a bit body may be one idea for the development of PDC bits for downhole motor drilling. This idea originates from the fact that diamond bits with many diamonds of tiny particles can be used under high rotary speed drilling conditions.

PDC bits with different cutter diameters and with different cutter numbers were fabricated and tested. This paper describes the results of these laboratory tests.

2. METHODOLOGY

2.1 PDC Bits

Figure 1 shows 98.43 mm-dia PDC bits with different cutter diameters and cutter numbers. Shown in Fig.2 is a 142.88 mm-dia PDC bit which was fabricated based on the results obtained from drilling tests with the 98.43 mm-dia bits. Details of these bits are shown in Table 1. There are no criteria for deciding the cutter numbers set on a bit body. Therefore, we first selected a standard bit for deciding the

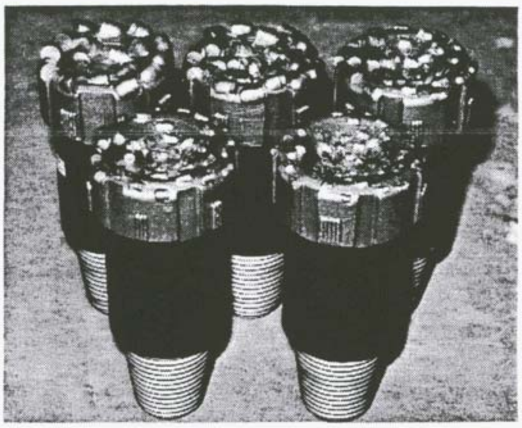


Figure 1- PDC full-face bits with 98.43 mm diameter

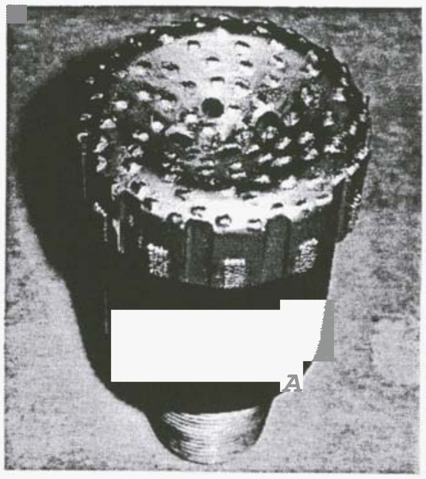


Figure 2- PDC Full-face bit with 142.88 mm diameter

Table 1- Description of PDC bits for drilling tests

Bit No.	Bit Dia.(mm)	Cutter Dia.(mm)	No. of Cutters	Rake* Angles(deg.)
1	98.43	5.0	48	-10
2	98.43	6.6	36	-10
3	98.43	8.2	29	-10
4	98.43	10.8	22	-10
5	98.43	13.3	18	-10
6	142.88	5.0	100	-10

* Backrake and Siderake

number of cutters set on each bit. The bit selected is a **98.43** mm-dia bit with eighteen **13.3** mm-dia cutters (bit No.5 in the table), since this bit showed good performance in hard rock drilling in the previous study (Misawa and Karasawa, **1991**). Also, the cutter numbers of each bit with the different cutter diameter were decided according to the next equation.

$$K=18\cdot(13.3/d)\cdot(A/7609) \quad (1)$$

Where. K is the number of cutters, d the diameter of the cutter (mm), A the cross-sectional area of the bit designed (mm^2). The numbers **18, 13.3** and **7609** in the equation are the cutter numbers, the cutter diameter and the cross-sectional area of the standard bit, respectively.

2.2 Test Procedures

Drilling tests with PDC bits were carried out for Sanjome andesite, Shinkomatsu andesite and Sori granite, using the drilling machine shown in Fig. **3**. The tests were conducted in the order of soft to hard rocks. Several blocks were used in the same rock drilling; therefore, the mechanical properties of each block were measured as shown in Table **2.** In each rock drilling with each bit, the rotary speed was increased in the order of 50,100,200,300 and **400** rpm.

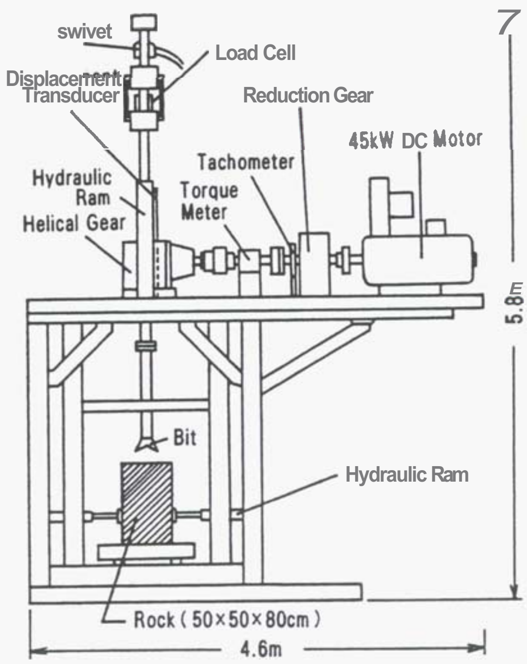


Figure 3- Drilling machine used for tests

Water was used as the drilling fluid at constant flow rates of **90** L/min (the **98.43** mm-dia bits) and 110 L/min (the **142.88** mm-dia bit).

Table 2- Mechanical properties of rocks

Rock	sc (MPa)	ss (MPa)	E (GPa)	ν
Sanjome	85.7-116	7.85-9.63	10.4-17.8	.193-.262
Shinkomatsu	137-168	8.53-9.71	17.7-23.6	.242-.319
sori	158-209	7.68-9.64	43.2-55.0	.320-.377

Sc: Uniaxial Compressive Strength, Ss: Tensile Strength, E: Young's Modulus, ν: Poisson's Ratio

3. RESULTS AND DISCUSSION

Results of the drilling tests with the **98.43** mm-dia bits and with the **142.88** mm-dia bit, are discussed separately in this chapter.

3.1 98.43 mm-dia Bits

Effect of rotary speed on penetration rate- As an example of test results, the relation between the bit weight and penetration rate as Sanjome andesite was drilled with bit **N0.2** is shown in Fig.4(a). It is obvious that the penetration rate at a given bit weight increases as a rotary speed increases. For Sanjome andesite, the penetration rate of all other bits also increased with the rotary speed. Similar tendencies as Sanjome andesite were also seen for **Shinkomatsu** andesite. On the other hand, in Sori granite shown in **Fig.4(b)** the penetration rate of bit No.2 increases with a speed up to 200 rpm, but it decreases at speeds of **300** and **400** rpm as compared to that of 200 rpm. The penetration rate of other bits also decreased at speeds of 300 and **400** rprn as well as for bit No.2. Such decrease in the penetration rate may be caused by the bit vibration due to an eccentric bit rotation, since the bit vibration at speeds of **300** and **400** rpm in granite drilling was larger than that in andesite drilling.

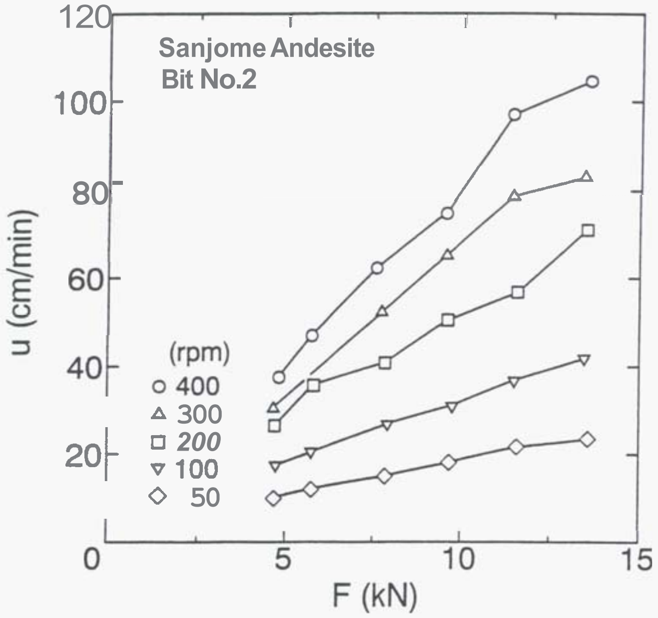
From the results of the tests in the foregoing, it became clear that all bits can drill granite and two types of andesite at speeds up to **400** rpm, and that the effect of the rotary speed regarding the penetration rate depends on the rock type. Namely, granite drilling at the high rotary speeds such as 300 and **400** rprn is rather **difficult** as compared to andesite drilling.

Effect of cutter diameter on bit performance- From the viewpoint of both the specific energy and the penetration rate per revolution, the effect of cutter diameter on the bit performance is investigated in this section. The specific energy was calculated from the next equation (Teale, 1965).

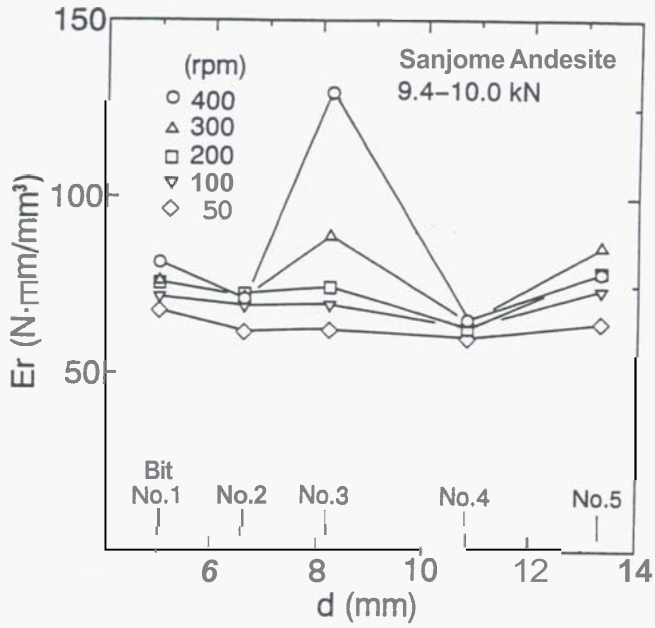
$$Er = (2\pi NT)/(Au') \quad (2)$$

Where, Er is the specific energy ($N\cdot mm/mm^3$), N the rotary speed (rpm), T the torque ($N\cdot mm$), A the cross-sectional area of a bit, **u'** the penetration rate (mm/min).

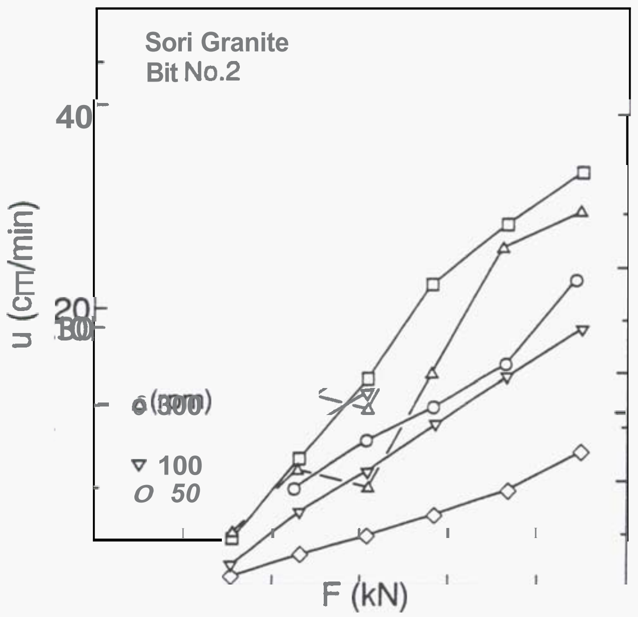
Figures 5(a) and (b) show the relation between the cutter



(a) Sanjome andesite

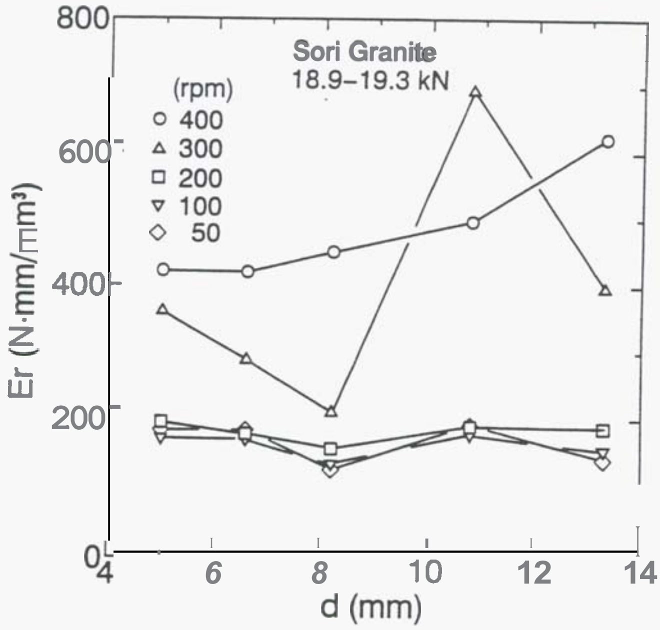


(a) Sanjome andesite



(b) Sori granite

Figure 4- Relation between bit weight (F) and penetration rate (u)

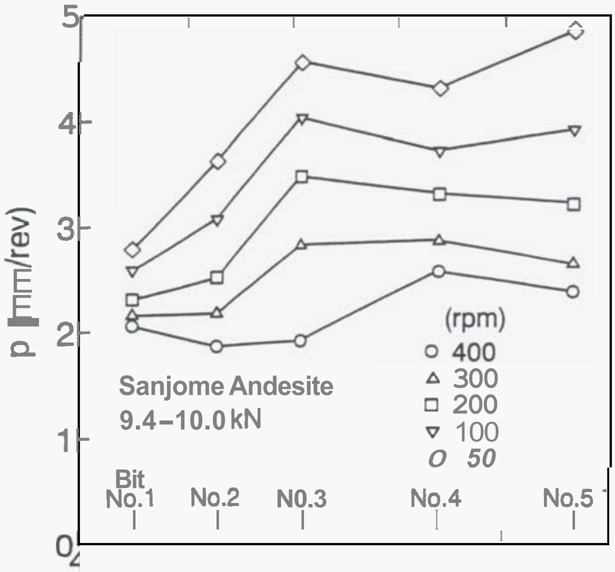


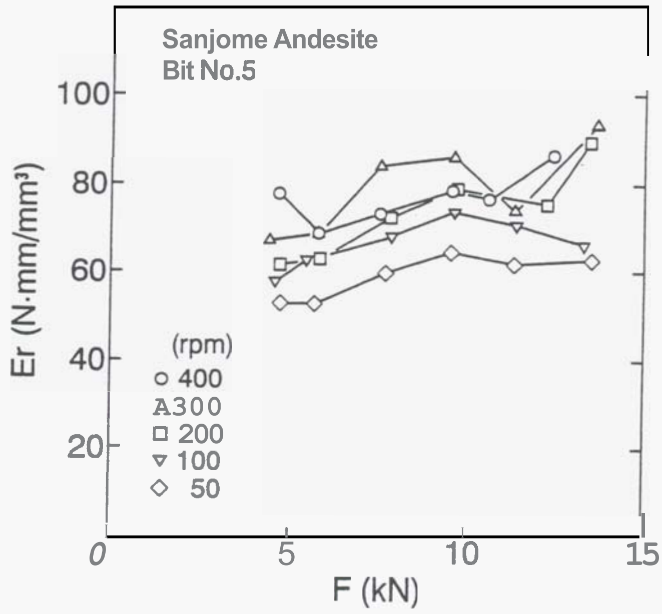
(b) Sori granite

Figure 5- Relation between cutter diameter (d) and specific energy (Er)

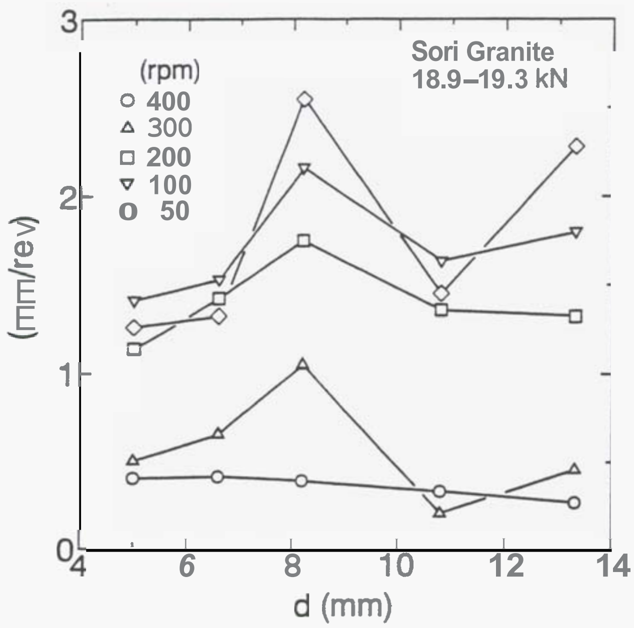
diameter and specific energy for Sanjome andesite and Sori granite, respectively. The bit weight ranged from 9.4 to 10.0 kN for Sanjome andesite and fiom 18.9 to 19.3 kN for Sori granite. For Sanjome andesite (Fig.5(a)), the specific energy at an almost constant bit weight does not change very much with either of the rotary speed or the cutter diameter, except for that of bit No.3 at a speed of 400 rpm. Shinkomatsu andesite exhibited almost the same results as Sanjome andesite. For Sori granite (Fig.5(b)), the specific energy also does not change very much independent of the rotary speed and the cutter diameter up to 200 rpm. but the specific energy of bits Nos.4 and 5 tends to increase compared with the other bits.

A smaller specific energy means better drilling efficiency fiom the point of view of energy. Thus, it is estimated that 5.0 to 8.2 mm-dia cutters are appropriate relative to 10.8 to 13.3 mm-dia ones, when hard and abrasive rock such as Sori granite is drilled at a higher rotary speed above 300 rpm. As can be seen in Fig.5(b), in granite drilling the specific energy at a rotary speed of 300 and 400 rpm increased as compared with that at a rotary speed below 200 rpm. This suggests that granite drilling at a higher rotary speed above 300 rpm becomes difficult when compared with that at lower speeds below 200 rpm. This conclusion agrees well with that obtained fkom the relation between the bit weight and penetration rate in the foregoing.

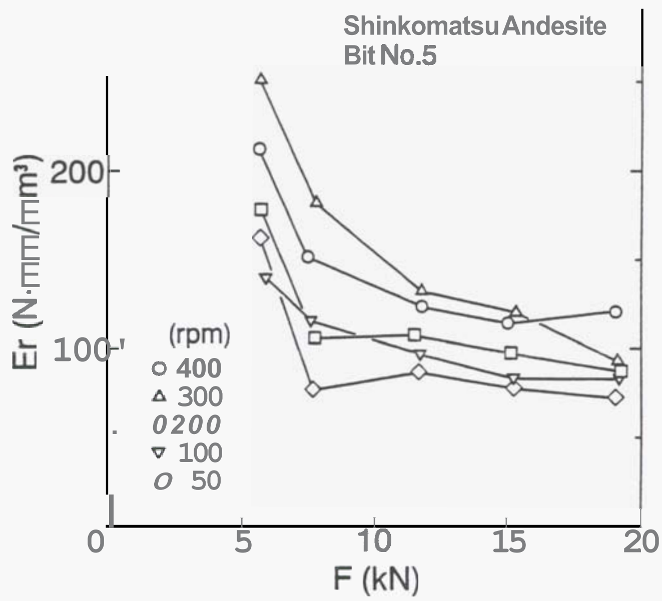




(a) Sanjome andesite



(b) Son granite



(b) Shinkomatsu andesite

Figure 6- Relation between cutter diameter and penetration rate per revolution (p)

Figure 7- Effect of bit weight on specific energy

Figures 6(a) and (b) show the relation between the cutter diameter and penetration rate per revolution (p). Data plotted in the figures were the same drilling conditions as those plotted in Figs.5(a) and (b), respectively. For Sanjome andesite (Fig.6(a)) bits Nos.3 to 5 showed a larger p than bits Nos.1 and 2 at a speed up to 200 rpm, but the difference of p regarding all bits became small at a speed above 300 rpm. In addition, although p for all bits decreased with an increasing the rotary speed, the decreasing ratio of p was smallest for bit No.1. Shinkomatsu andesite exhibited almost the same tendencies as Sanjome andesite. In Son granite drilling (Fig.6(b)), the decreasing ratio of p with an increase in the rotary speed was smaller for bits Nos. 1 and 2 than that of the others. In addition, p of bits Nos.1 and 2 was almost the same or somewhat small compared with that of the other bits at speeds up to 200 rpm, but p of bits Nos.1 to 3 tended to increase compared with that of bits Nos.4 and 5 at 300 and 400 rpm.

Taking all results of the above into consideration, it is speculated that the use of cutters with a diameter below 8.2 mm is effective in increasing the drilling efficiency at a rotary speed above 300 rpm, particularly for granite drilling. However, this is not effective in increasing the drilling efficiency as a speed is set below 200 rpm.

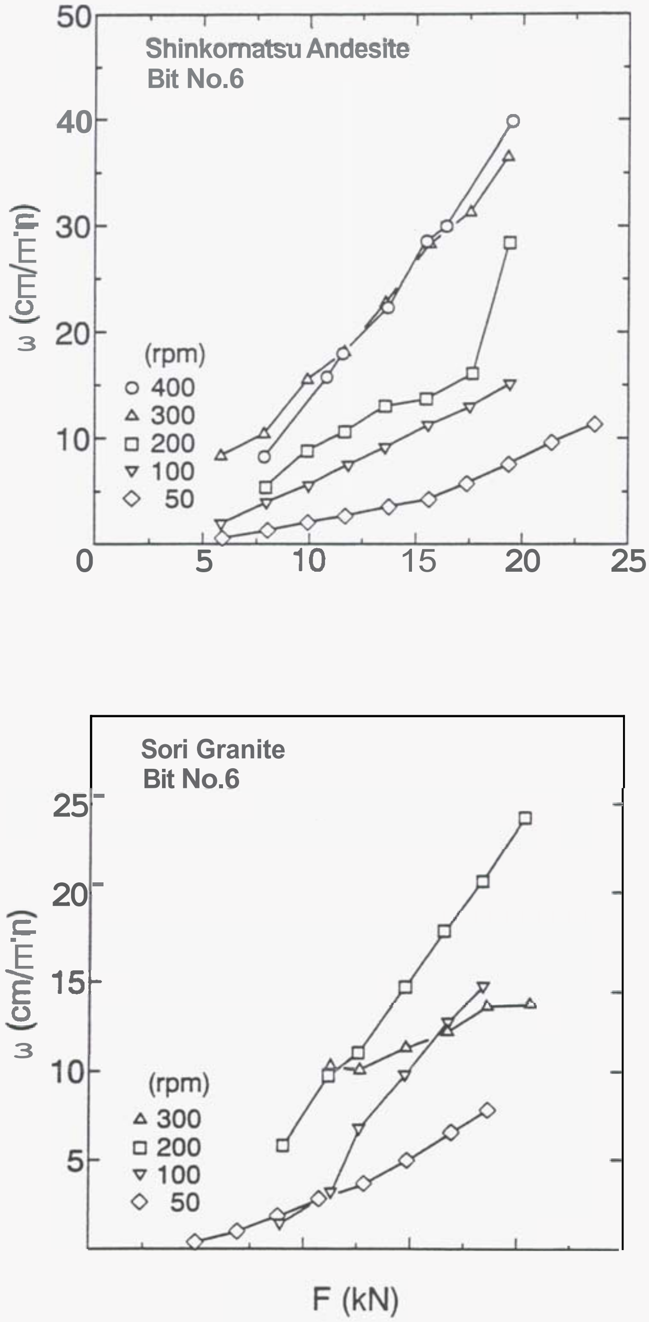
Drilling condition of PDC bits- Shown in Figs.7(a) and (b) is the relation between the bit weight and specific energy. in the case of Sanjome andesite and Shinkomatsu andesite drilled using bit No.5. The specific energy of all bits exhibited almost the same level independent of the bit weight for Sanjome andesite drilling, but it increased generally at a lower bit weight of about 6 to **8 kN** for Shinkomatsu andesite drilling. The specific energy of Sori granite also increased at a lower bit weight (about **8** to **12** kN) as well as Shinkomatsu andesite. The increase in the specific energy in both rock types at a lower bit weight was remarkable at higher rotary speeds. as can be seen in **Fig.7(b)**. Also observed was a relatively large bit vibration at a lower bit weight and at higher speeds. particularly in granite drilling. Therefore. a bit weight more than the above-mentioned values must be loaded on the bits during Shinkomatsu andesite and Son granite drilling.

3.2 142.88 mm-dia Bit

We have plan to develop a PDC full-face bit of actual size **(215.9** mm **(8-1/2** in.)) for downhole motor drilling during the last stage of this work. As a course in this development, we have started testing a bit with an intermediate diameter between **98.43** and **215.9** mm. On the basis of the above results in the forgoing, a bit with 5.0 mm-dia cutters (No.6) was first fabricated and tested.

Figure 8(a) shows the test results in the case of Shinkomatsu andesite. The penetration rate increased at rotary speeds up to 300 rpm. For Sanjome andesite, the penetration rate also increased with an increase in the rotary speed. These results agreed well with those of the **98.43** mm-dia bits. The cutting speed of some cutters set on a bit body increased as the bit diameter became larger at a given rotary *speed;* therefore, we presumed that rock drilling with the **142.88** mmdia bit becomes impossible at higher rotary speeds before these tests. However, this presumption was not correct in the two types of andesite drilling. at least for these testing conditions. It seems that the maximum rotary speed which would be able to supply a PDC bit is not inversely proportional to the bit diameter. On the other hand, the penetration rate of Sori granite **(Fig.8(b))** increases up to a *speed* of 200 rpm, but it decreases at **300** rprn compared with that at 200 rpm. In addition, the drilling becomes impossible at 400 rpm due to a fairly large bit vibration. The loss of about ten cutters from around center on the bit body was observed during granite drilling. It is estimated that this phenomenon affected the penetration rate and the stability of bit rotation to a considerable extent.

From the results of these tests, it was obvious that the **142.88** mm-dia bit can also drill granite and the two types of andesite at a higher rotary speed **(300** to 400 rpm). Assuming that the rotary speed which would be able to rotate is inversely proportional to the bit diameter. a rotary speed of 200 to **260** rpm *can* be calculated in the case of the **215.9** mm-dia bit based on the results of bit **No.6**. Therefore, can be concluded that a **215.9** mm-dia bit has potential for being applied to downhole motor drilling.



(b) Sori granite

Figure 8- Relation between bit weight and penetration rate

Of course, further improvements will be necessary with regard to **142.88 mm-dia** bits. In addition, the brazing technique of cutters on a bit body must be improved, since the loss of cutters originates **from** the imperfect brazing between the cutters and the bit body.

4. CONCLUSIONS

To develop PDC full-face bits for downhole motor drilling, the **98.43** mm-dia bits with different cutter diameters and with different cutter numbers have been tested using granite and two types of andesite. The **142.88** mm-dia bit was fabricated and tested based on the results of the **98.43 mm-**dia bits. The test results *can* be summarized as follows:

(1) Both bits with **98.43** mm and **142.88** mm diameters could successfully drill through medium-hard to hard rock at speeds from 300 to 400 rpm.

(2) In hard rock drilling such as granite, the bits with cutters of 5.0 to 8.2 mm-dia performed better than those with cutters of 10.8 to 13.3 mm-dia.

(3) Granite drilling is somewhat more difficult compared with andesite drilling at higher rotary speeds (300 to 400 rpm).

(4) Relative large bit weights must be loaded on a bit for Shinkomatsu andesite and Sori granite drilling, particularly at higher rotary speeds.

We will continue drilling tests of 142.88 mm-dia bits to improve the performance with respect to the drilling efficiency and durability at higher rotary speeds.

5. REFERENCES

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