Methods to Estimate the Rock Strength and Tooth Wear While Drilling With Roller-Bits—Part 1: Milled-Tooth Bits

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This paper proposes new methods to estimate both the rock strength and tooth wear while drilling with roller-bits. Laboratory drilling tests were conducted to obtain the penetration rate, bit weight and torque using milled-tooth bits with different tooth wear (T0, T4, T7). Drilling media used for the tests were soft to medium-hard rocks whose uniaxial compressive strength ranged from 14 to 118 MPa. Based on the test results, a parameter, which presents the rock strength independent of the tooth wear, was first investigated. The investigation revealed that a parameter related to the axial energy and the rotary energy required to drill rock is effective to estimate the rock strength independent of the tooth wear. Second, methods to estimate the tooth wear were studied based on the same parameter that represents the rock strength. From the results of this study, methods to measure the tooth wear are proposed. [DOI: 10.1115/1.1482405]

Introduction

To control drilling operations effectively, the information concerning the in-situ rock strength and the degree of tooth wear of a drill bit is essential. If the information can be obtained in real time while drilling, we would be able to improve the decision of when to exchange a worn bit for a new one and to set drilling conditions suitable for different rock types. These could contribute to a reduction of problems, such as bit failure problems, while drilling and to improve drilling efficiency. Of course, such controlled drilling operations could reduce total drilling costs.

Several investigators have proposed techniques to evaluate the in-situ rock strength while drilling with roller-cone bits. Bingham [1] reported a method to determine the in-situ shear strength of rock, based on the relationship between the bit weight per unit length of bit diameter and the penetration per revolution. Wolcott and Bordelon [2] proposed a technique to measure the in-situ rock strength based on MWD (measurement while drilling) torque and bit weight data. A new approach for determining the compressive strength of rock in situ, which employs the drill-off test, was presented by Hoberock and Bratcher [3]. These techniques use different methods to measure the in-situ rock strength. Burgess and Lesso Jr. [4] proposed a technique to measure both the in-situ shear strength of rock and tooth wear in soft formation drilling. Pessier and Fear [5] also reported methods to estimate the in-situ compressive strength and tooth wear for roller-bits and PDC bits. Drilling models for roller-cone bits and PDC bits have also been presented (e.g., Warren [6]; Detournay and Defourny [7]). The previous research efforts of the development for determining rock strength and/or tooth wear have mainly concentrated on soft sedimentary rocks such as shale encountered in oil and gas drilling [4]. However, we have often encountered hard igneous rocks in geothermal and mining drilling. Therefore, it is desirable that methods for measuring the rock strength and tooth dullness can be applied more widely, independent of rock types, and that are readily implemented in the field. From the viewpoint of the two aforementioned factors, it might be concluded that the status of the art to measure both the in-situ rock strength and tooth dullness is still in a development stage.

To find new methods for the estimation of rock strength and tooth wear while drilling with roller-bits, drilling tests for several types of rock were conducted in the laboratory using milled-tooth and insert-type roller-cone bits with different amounts of tooth wear (Karasawa et al. [8]; Karasawa et al. [9]). The main objective of these two reports (Parts 1 and 2) is to propose new methods to estimate both the rock strength and tooth wear while drilling with roller-bits. In this paper, the test results and the new methods proposed for milled-tooth bits are described.

Rock Drilling and Operating Conditions

Figure 1 shows the three types of milled-tooth three-cone bits of 98.43 mm (3-7/8 in.) in diameter used for in our drilling tests. They are usually selected for drilling in medium-hard rock formations (IADC 221S). The degree of tooth wear of each bit was set at new (T0), 4/8 worn (T4), and 7/8 worn (T7). Two worn bits were fabricated by grinding the teeth of new bits. The types of rock used for the tests are Ooya tuff, Kimachi sandstone, Sanjome andesite, and Shinkomatsu andesite. Mechanical properties of each rock type were measured from the core samples recovered from the same rock blocks that had been drilled (Table 1).

The drilling machine used for the tests is illustrated in Fig. 2. The transducers shown in the figure measured the bit weight, torque, rotary speed, and displacement to calculate the penetration rate during the tests. The torque measured in the tests contained friction at the helical gear. Therefore, the friction torque was determined and eliminated from the measured torque. Thus, the torque presented is the net torque on the bit. Each rock type was drilled using the test bits at a constant rotary speed of 50 rpm. The bit weight was changed from about 8 to 40 kN for drilling tuff and sandstone and from about 8 to 60 kN for drilling the two types of andesite. Water was used as a drilling fluid at a constant flow rate of 0.11 m^3/min. Drilling tests at the speed of 100 rpm were also conducted using three types of rock (omitting Ooya tuff) at the same drilling conditions as those at 50 rpm. We checked the conditions of the bearing and teeth of each bit after each rock drilling run, and confirmed that the bearing was normal and that tooth wear was very small.

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Fig. 1 Milled-tooth bits of 98.43-mm (3-7/8-in) diameter (from left: T7, T4, T0)

Derivation of Rock Drillability Parameters

Bingham [10] first employed the u/N-F/d plot systematically to describe the rock drillability, instead of the conventional *u*-*F* plot, where u is the penetration rate, N is the rotary speed, F is the bit weight, and d is the bit diameter. He concluded that this plot provides a means of consistent correlation of data from the mining and petroleum industries. This suggests that the u/N-F/d plot is more general, as compared to the *u*-*F* plot, since we can evaluate drilling data obtained at different rotary speeds and bit diameters if the u/N-F/d plot is used. Hence, we also employ two parameters, the penetration per revolution (u/N) and the bit weight per unit length

Table 1 Mechanical properties of rocks used for drilling tests

Rock	S_c (MPa)	S_t (MPa)	E (GPa)	υ
Ooya Tuff	14.0	1.54	4.25	0.246
Kimachi Sandstone	44.9	4.21	7.07	0.256
Sanjome Andesite	118	9.06	16.6	0.208
Shinkomatsu Andesite	113	7.67	21.6	0.282

S_c: Uniaxial compressive strength, S_t: Tensile strength

E: Young's modulus, υ : Poisson's ratio

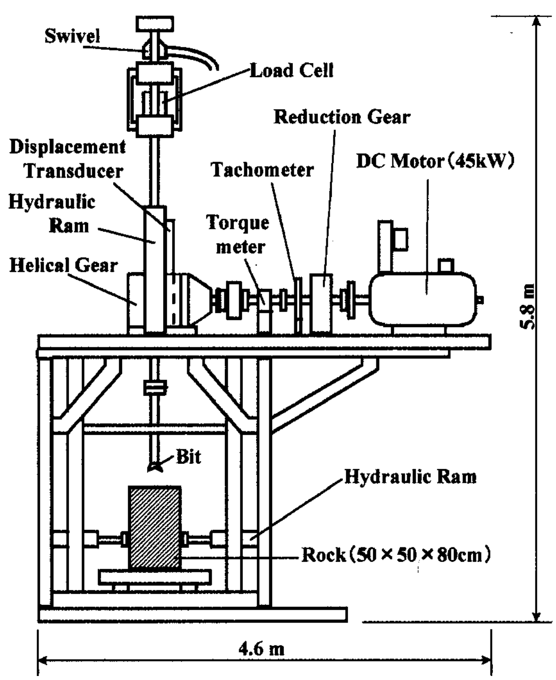


Fig. 2 Drilling machine used for the tests

of bit diameter (F/d), to analyze data obtained from the drilling tests. The effect of bit diameters on the rock drillability will be discussed in Part 2 of this report.

When the torque (T) is used to analyze drilling data in addition to u/N and F/d, it would be necessary to express T so as to include d, similar to the parameter F/d. To do this, we cite the theoretical energy equation presented by Warren [11] as follows:

$$(1/\eta)AE_s'u = Fu + 2\pi NT \tag{1}$$

where η is the efficiency factor to account for nonproductive energy loss, A is the cross-sectional area of a hole, and E_s' is "the specific energy of a rock." The E_s' is defined as the minimum energy required to crush a unit volume of rock. He stated that E_s' is considered a fundamental property of the rock. It is noted that the definition of E_s' differs from the specific energy (e), defined as the energy required to excavate a unit volume of rock, proposed by Teale [12]. In Eq. (1) the axial work done by a bit in a unit time interval (Fu) is generally much less than the rotary work $(2\pi NT)$. Neglecting Fu and arranging Eq. (1) by using $\pi d^2/4$ in place of A, gives

$$\frac{u}{N} = \left(\frac{\eta}{E_s'}\right)\left(\frac{2\pi T}{\pi d^2/4}\right) = \left(\frac{\eta}{E_s'}\right)\left(\frac{8T}{d^2}\right) \tag{2}$$

Because the axial work is neglected, the inverse of (η/E_s') in Eq. (2), namely (E_s'/η), becomes equal to the rotary component of the specific energy, or simply, the specific energy $(2\pi NT/Au$ or $8NT/d^2u)$ derived by Teale, and is readily shown from Eq. (1). Unfortunately, it is very difficult to determine the values of E_s' and η accurately; however, we know the important fact that the minimum value of the specific energy $(2\pi NT/Au)$ is correlated with the uniaxial compressive strength of rock drilled by roller-bits as reported by Teale [12]. Considering Eq. (2) and the aforementioned fact, it is clear that the u/N-$8T/d^2$ plot is more general and useful than the *u*-*T* plot. Thus, we use the rotary energy per revolution divided by the cross-sectional area of the bit $(8T/d^2)$, instead of T to analyze the data.

Results

Figure 3(*a*) shows the relationship between F/d and u/N when Kimachi sandstone was drilled with T0, T4, and T7 bits at 50 rpm. There is evidence that the *u*-*F* or u/N-F/d relationship can be approximated by a straight line within a certain range of F or F/d (Edwards [13]; Bingham [14]). Hence, parts of the data were approximated by the straight line using a least-squares regression method as shown in the figure. Data indicated by the dotted line were influenced by bit-balling, and, therefore, were omitted from the approximation. Bingham [14] called the solid straight line in the figure "the primary performance line," or "the performance line."

Figure 3(*b*) shows the relationship between $8T/d^2$ and u/N obtained from the same drilling tests as shown in Fig. 3(*a*). The straight line in this figure was obtained from data, which correspond to the straight line in Fig. 3(*a*). By comparison of Figs. 3(*a*) and (*b*), it is obvious that both figures exhibit nearly the same trends. That is, the slopes of the straight lines, a_F and a_T, do not change very much independent of the tooth wear. The intercepts of the straight lines and the horizontal axes, F_c/d and $8T_c/d^2$, increase with increasing tooth wear. However, the change of F_c/d with the tooth wear is larger than that of $8T_c/d^2$. Ooya tuff also exhibited the same tendencies as those of Kimachi sandstone. For convenience, we express the straight line in the u/N-F/d plot as "the performance line for the bit weight" and that in the u/N-$8T/d^2$ plot as "the performance line for the torque."

The u/N-F/d and u/N-$8T/d^2$ plots for Shinkomatsu andesite at 50 rpm are shown in Figs. 4(*a*) and (*b*), respectively. The slope of the performance line in both figures (a_F, a_T) decreases with increasing tooth wear, but the rate of decrease ratio of a_T is

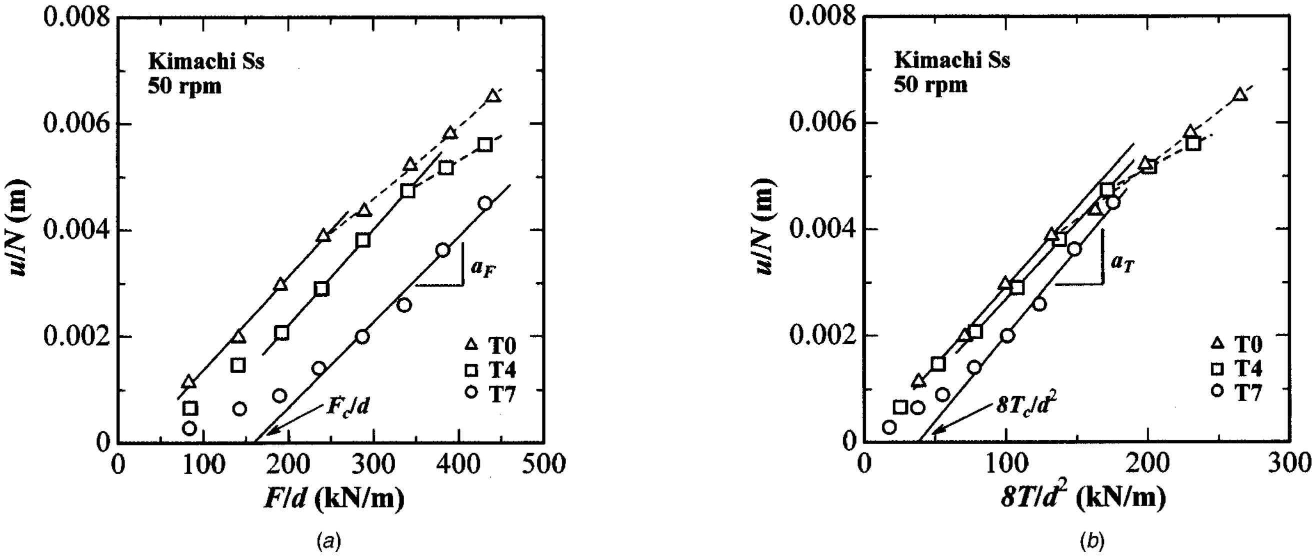


Fig. 3 (*a*) **Relationship between bit weight per unit length of bit diameter (F/d) and penetration per revolution (u/N) for Kimachi sandstone at 50 rpm; (*b*) relationship between rotary energy per revolution divided by cross-sectional area of bit ($8T/d^2$) and u/N for Kimachi sandstone at 50 rpm**

smaller than that of a_F. Moreover, F_c/d and $8T_c/d^2$ do not increase regularly with increasing tooth wear. Sanjome andesite exhibited a similar tendency as that shown by Shinkomatsu andesite. It is obvious that the test results obtained from the two types of andesite drilling exhibit different tendencies from those of tuff and sandstone. At present, it is very difficult to explain the reason why the trends differ, but it may be related to the difference of failure mode (degree of chipping) of rock between soft rocks and harder rocks, with tooth penetration. This difference is often observed in static indentation tests.

The test results obtained at 100 rpm exhibited almost the same trends as those for 50 rpm. Tables 2 and 3 record a_F, F_c/d, a_T and $8T_c/d^2$ for each bit drilling in each rock type at the rotary speeds of 50 and 100 rpm, respectively. The slope a_T, which corresponds to the value of $8T_c/d^2$ at zero in the tables, was determined so that the performance line intercepts the origin, because $8T_c/d^2$ became a small negative number in the usual approximation. The performance lines for the bit weight and for the torque are expressed as

$$\frac{u}{N}=a_F\,\frac{F-F_c}{d} \tag{3}$$

$$\frac{u}{N}=a_T\,\frac{8(T-T_c)}{d^2} \tag{4}$$

respectively. Because we wish to focus only on the performance line, F_c/d and $8T_c/d^2$ in these equations can be considered threshold values at which tooth penetration commences [13]. Therefore, F_c and T_c represent the threshold weight and the threshold torque, respectively. Replacing (F-F_c) in Eq. (3) with F_e and (T-T_c) in Eq. (4) with T_e, gives

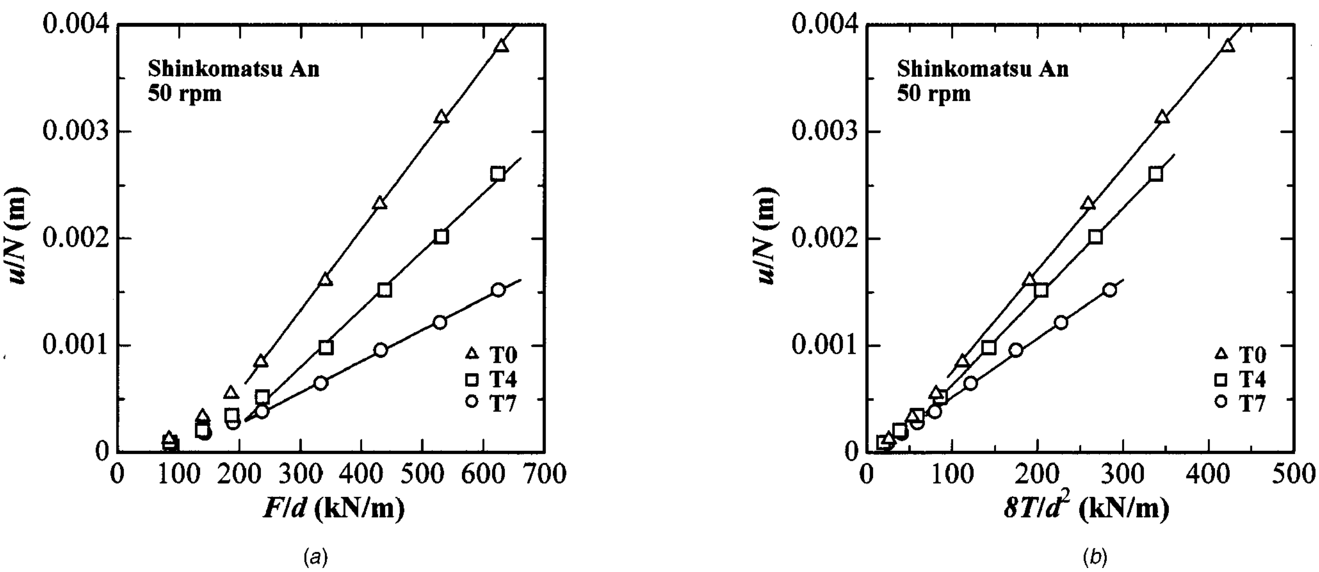


Fig. 4 (*a*) **u/N-F/d plot for Shinkomatsu andesite at 50 rpm; (*b*) u/N-$8T/d^2$ plot for Shinkomatsu andesite at 50 rpm**

Table 2 Values of a_F, F_c/d, a_T, and $8T_c/d^2$ for each bit at 50 rpm

		Bit Weight		Torque	
		a_F (10^{-6}m^2/kN)	F_c/d (kN/m)	a_T (10^{-6}m^2/kN)	$8T_c/d^2$ (kN/m)
Ooya	T0	29.8	4	48.2	0
	T4	27.9	30	45.3	0
	T7	31.6	133	54.8	35.9
Kimachi	T0	17.5	22	29.6	1.2
	T4	18.0	77	28.8	6.4
	T7	16.1	159	32.3	37.7
Sanjome	T0	9.0	97	12.1	15.9
	T4	5.8	108	9.0	8.5
	T7	3.5	102	6.8	3.9
Shinkomatsu	T0	7.6	124	9.6	20.9
	T4	5.4	153	8.3	23.8
	T7	2.9	108	5.5	5.8

$$\frac{u}{N} = a_F \frac{F_e}{d} \tag{5}$$

$$\frac{u}{N} = a_T \frac{8T_e}{d^2} = \left[a_T \frac{2\pi T_e}{(\pi/4)d^2} \right] \tag{6}$$

where F_e is the effective weight and T_e is the effective torque.

Method to Estimate the Rock Strength

Based on Eqs. (5) and (6), we investigated a relationship which would represent the rock strength. For this investigation, we considered the energy required to drill rock and found the relationship by trial and error. Figures 5(*a*) and (*b*) show the relationship between the effective axial energy per revolution divided by bit diameter $(F_e u/Nd)$, and the effective rotary energy per revolution divided by the cross-sectional area of the bit squared $((8T_e/d^2)^2)$, at 50 and 100 rpm. The quantity $(8T_e/d^2)^2$, at a given value of $F_e u/Nd$, tends to increase with increasing rock strength (for example, the uniaxial compressive strength of rock) and the effect of tooth wear on the relationship for each rock is small. Also, it is noted in both figures that the influence of rotary speed on it is small. From Eqs. (5) and (6), the $(8T_e/d^2)^2$-$(F_e u/Nd)$ relationship is given by

$$\left(\frac{8T_e}{d^2}\right)^2 = \left(\frac{a_F}{a_T^2}\right)\left(\frac{F_e u}{Nd}\right) \tag{7}$$

Because Eq. (5) can be transformed into $(u/N)^2 = (u/N)a_F(F_e/d) = a_F(F_e u/Nd)$. The slopes, a_F and a_T, in Eq. (7) are constants, which depend on the rock strength and tooth wear, as is evident from Tables 2 and 3. Therefore, it is obvious that $(8T_e/d^2)^2$ is proportional to $F_e u/Nd$. From the linear correlation and the aforementioned test results, it is clear that either $(a_F/a_T{}^2)$ in Eq. (7) or $(8T_e/d^2)^2/(F_e u/Nd)$ becomes an indicator which can express the rock strength. It is further noted that both parameters have dimensions of stress. This is readily confirmed using the units listed in the Nomenclature. We next convert the units of both parameters (kN/m^2) into (MPa), because the rock strength, such as the compressive strength, is usually expressed as (MPa). For convenience, we represent both parameters converted into (MPa) by "the drillability strength of rock" (D_s) according to Maurer [15]; that is

$$D_s = \frac{a_F}{1000a_T^2} \tag{8}$$

Or, substituting from Eq. (7) yields

$$D_s = \frac{64NT_e^2}{1000F_e ud^3} \tag{9}$$

The drillability strength of rock (D_s) proposed here is a new parameter having the dimensional unit of stress. However, it is noted that D_s is affected by the rock property, the details of a bit (such as the configuration of teeth and skewness of the cones), and mud pressure, etc. According to Bingham [16], more than 26 variables are said to influence drilling. To a greater or lesser extent, these variables might affect D_s; therefore, we should consider that D_s represents the degree of difficulty in roller-bit drilling of rock. This is the reason why D_s is called "the drillability strength of rock." Although D_s contains the influence of the bit configuration and other factors listed in the foregoing, it is a useful parameter to determine rock properties, since there exits a relatively good correlation between D_s and the uniaxial compressive strength of rock (S_c), which is determined by the standard compression test (Fig. 6).

From the results in the forgoing test program, it became clear that the drillability strength of rock (D_s) correlates with the uniaxial compressive strength of rock (S_c), and that the effect of tooth wear on D_s is small. Hoberock and Bratcher [3] suggested that the minimum value of the specific energy, which is correlated to S_c, could provide an approximation of the compressive strength of rock in situ. Hence, it is projected that D_s also might be a useful parameter to estimate the compressive strength of rock in situ, when the relationship between D_s and S_c is obtained with respect to various types of roller-cone bits.

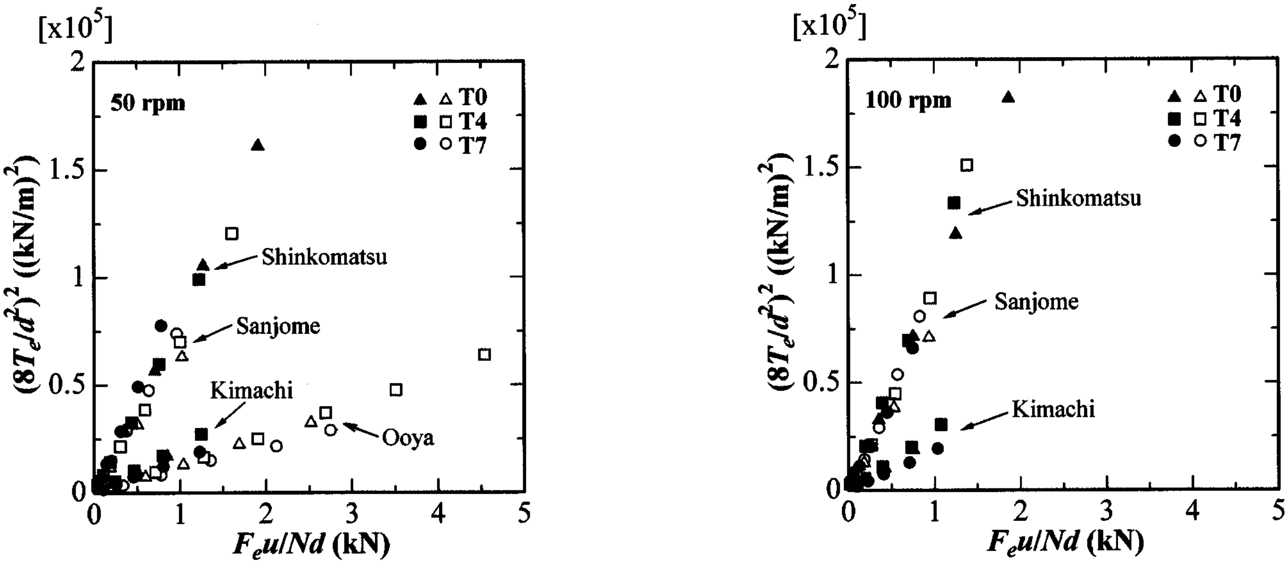
In order to estimate the rock strength, the specific energy is generally used ([3], [4], [5], [12]), while we have proposed a new parameter (D_s).

Table 3 Values of a_F, F_c/d, a_T, and $8T_c/d^2$ for each bit at 100 rpm

		Bit Weight		Torque	
		a_F (10^{-6}m^2/kN)	F_c/d (kN/m)	a_T (10^{-6}m^2/kN)	$8T_c/d^2$ (kN/m)
Kimachi	T0	16.2	28	25.5	1.7
	T4	15.6	78	23.7	6.5
	T7	12.9	156	26.5	39.1
Sanjome	T0	8.0	89	10.4	7.2
	T4	5.1	102	7.2	0
	T7	2.7	72	5.5	0
Shinkomatsu	T0	6.9	105	8.5	18.6
	T4	4.6	124	6.6	24.9
	T7	2.8	121	5.7	23.8

Method to Estimate the Tooth Wear

We investigated methods to estimate the tooth wear based on the relationships between D_s and the parameters: a_F, a_T, F_c/d and $8T_c/d^2$. However, the inverses of a_F and a_T, namely $1/a_F$ and $1/a_T$, have the dimensions of stress, similar to D_s. Therefore, we also convert the unit of $1/a_F$ and $1/a_T$ (kN/m^2) into (MPa) and represent both parameters converted into (MPa) by "the penetration strength of rock" (I_s), and "the specific energy calculated from the effective rotary energy" (S_e), respectively. From Eqs. (5) and (6), I_s and S_e are given by



(*a*) (*b*)

Fig. 5 (*a*) Relationship between effective axial energy per revolution divided by bit diameter ($F_e u/Nd$) and effective rotary energy per revolution divided by cross-sectional area of bit squared ($(8T_e/d^2)^2$) at 50 rpm; (*b*) $(8T_e/d^2)^2$-$F_e u/Nd$ plot at 100 rpm

$$I_s = \frac{1}{1000a_F} = \frac{NF_e}{1000du} \tag{10}$$

$$S_e = \frac{1}{1000a_T} = \frac{8NT_e}{1000d^2u} = \left[\left(\frac{1}{1000}\right)\left(\frac{2\pi NT_e}{(\pi/4)d^2u}\right)\right] \tag{11}$$

respectively. It is noted that S_e is nearly equal to the minimum value of specific energy ($2\pi NT/Au$) proposed by Teale [12], because T_e does not contain a part of the nonproductive energy loss. He suggested that this loss is dissipated in friction at zero thrust. The penetration strength of rock (I_s) is not a new parameter and it has been applied to measure the rock strength while drilling (e.g., Wolcott and Bordelon [2]). From Eqs. (8) to (11), the relationship among D_s, I_s, and S_e is expressed as

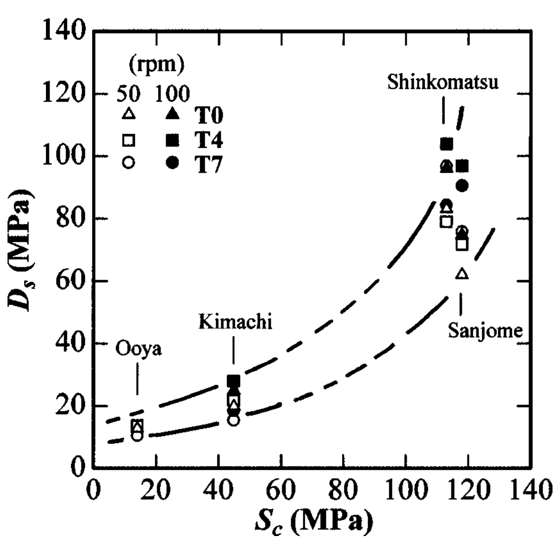


Fig. 6 Relationship between uniaxial compressive strength of rock (S_c) and drillability strength of rock (D_s)

$$D_s = \frac{S_e^2}{I_s} \tag{12}$$

Figure 7(*a*) shows the relationship between D_s and I_s. The straight line of each bit in the figure was obtained from the approximate fit of the data at 50 and 100 rpm. Since I_s increases clearly with tooth wear at D_s values greater than the range of about 30 to 40 MPa, and the change of I_s for each bit is small at D_s values less than that range. Similar tendencies as those of I_s are also seen in the case of S_e (Fig. 7(*b*)); however, the rate of increase of I_s with tooth wear, is larger than that for S_e. Figure 8(*a*) is the relationship between D_s and the threshold weight per unit length of bit diameter (F_c/d). F_c/d increases with tooth wear when D_s is smaller than about 40 to 60 MPa, while a clear relationship between F_c/d and the tooth wear is not found when D_s is larger than that range of values. As can be seen in Fig. 8(*b*), the threshold energy per revolution divided by the cross-sectional area of the bit ($8T_c/d^2$) exhibits the same trends as those of F_c/d. From a comparison between Figs. 7 and 8, it is clear that I_s and S_e are more effective in harder rock, and F_c/d and $8T_c/d^2$ are more effective in softer rock for estimating the tooth wear. However, a close examination of all relationships is recommended in order to estimate the tooth wear as precisely as possible, and separate from the rock strength.

In order to determine the tooth wear, Burgess and Lesso Jr. [4] used the model proposed by Warren [11]. Pessier and Fear [5] employed the specific energy, the mechanical efficiency and the bit-specific coefficient of sliding friction (μ). Details of μ will be discussed in Part 2 of this report. On the other hand, we employed the relationships between D_s and the parameters: a_F, a_T, F_c/d and $8T_c/d^2$ in the foregoing derivation for D_s.

Conclusions

Drilling tests for four types of rock, with the uniaxial compressive strength range of 14.0 to 118 MPa, were performed using milled-tooth-type three-cone bits with different tooth wear (T0, T4, and T7), in order to find new methods to estimate both the rock strength and tooth wear while drilling with roller-bits. The main results are summarized as follows:

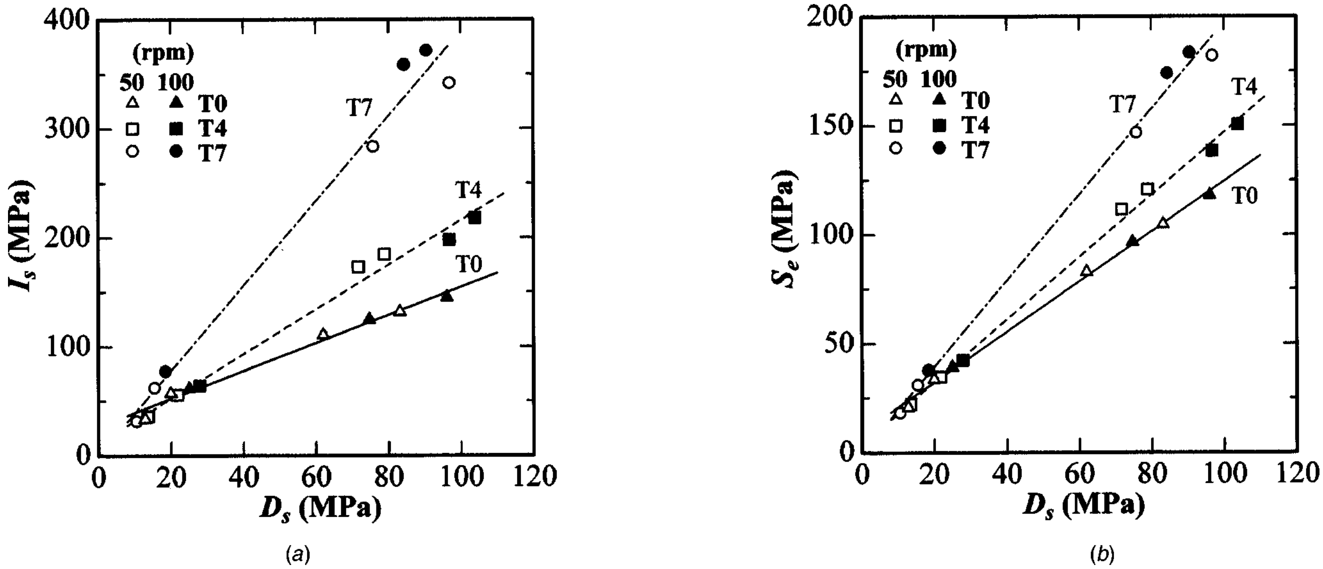


Fig. 7 (*a*) Effect of tooth wear on penetration strength of rock (I_s); (*b*) effect of tooth wear on specific energy calculated from effective rotary energy (S_e)

1 The $(8T_e/d^2)^2$-$F_e u/Nd$ relationship is a useful indicator which represents the rock strength, and the effect of tooth wear on it is small. The parameter $F_e u/Nd$ is the effective axial energy per revolution divided by bit diameter, and $(8T_e/d^2)^2$ is the effective rotary energy per revolution divided by the cross-sectional area of the bit squared. On the basis of this result, this indicator that expresses the rock strength was defined as the drillability strength of rock (D_s).

2 The conditions of tooth wear can be estimated from the relationships between D_s and the parameters: I_s, S_e, F_c/d, and $8T_c/d^2$, where I_s is the penetration strength of rock, S_e the specific energy calculated from the effective rotary energy, F_c/d the threshold weight per unit length of bit diameter, and $8T_c/d^2$ the threshold energy per revolution divided by the cross-sectional area of the bit.

This report deals mainly with the proposal of new methods for the estimation of both rock strength and tooth wear while drilling with roller-bits. It should be emphasized that the drillability strength of rock (D_s) was found from the test results using roller-bits with different tooth wear in soft to medium-hard rocks.

However, several problems remain to be solved in the future. The most important of these research tasks are considered to be:

- The methods developed in this paper must be tested in field drilling trials.
- The present methods need information about the slopes and intercepts derived from the u/N-F/d and u/N-$8T/d^2$ plots. Expanded data sets would be useful in deriving simpler analysis methods and more practical techniques for field applications.
- It is necessary to solve for the details of the mechanisms that effect of tooth wear in order to resolve the question of the reasons for the small influence on D_s.
- It might be valuable to use the present test data to investigate its application to drilling models. Several examples are given in the Introduction. For example, Detournay and Defourny [7] re-

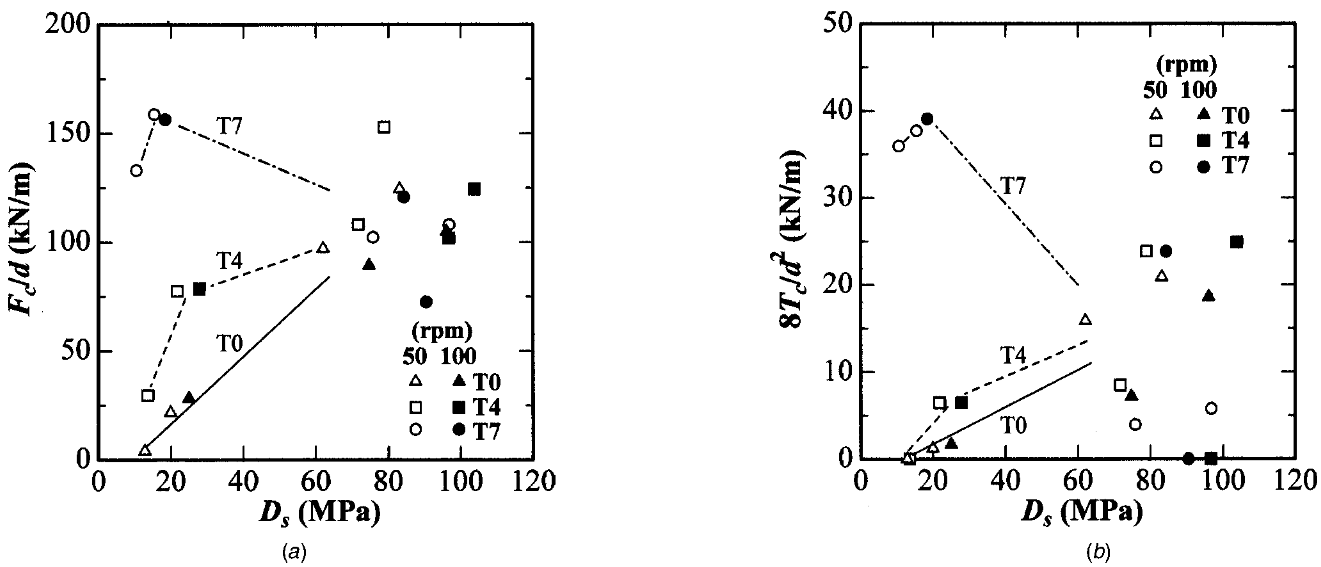


Fig. 8 (*a*) Effect of tooth wear on threshold weight per unit length of bit diameter (F_c/d); (*b*) effect of tooth wear on threshold energy per revolution divided by cross-sectional area of bit ($8T_c/d^2$)

ported results for single points tests with PDC cutters, that gave a straight line between the specific energy (corresponding to S_e) and the drilling strength of rock (corresponding to I_s) independent of wear flat area. These investigations might provide evidence for simpler and more effective applications of the presented methods.

Nomenclature

F = bit weight [kN]
F_c = threshold weight [kN]
F_e = effective weight [kN]
T = torque [kN·m]
T_c = threshold torque [kN·m]
T_e = effective torque [kN·m]
u = penetration rate [m/min]
N = rotary speed [rpm]
d = bit diameter [m]
a_F = slope of performance line for bit weight [m^2/kN]
a_T = slope of performance line for torque [m^2/kN]
S_c = uniaxial compressive strength of rock [MPa]
D_s = drillability strength of rock [MPa]
I_s = penetration strength of rock [MPa]
S_e = specific energy calculated from effective rotary energy [MPa]

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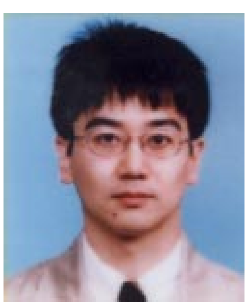

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