HIGH PRESSURE WATER JET DRILLING IN HOT DRY ROCKS

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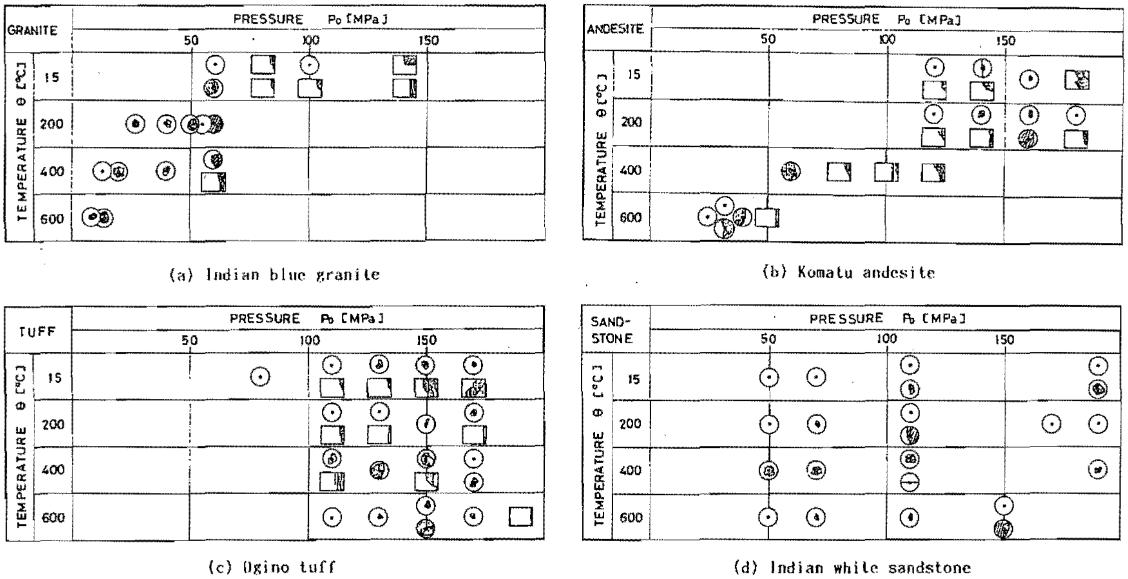
The development of geothermal energy stored in magma or hot dry rocks lacking a hot water circulation system is being considered as one of the new means of supplying energy. To extract heat from such heat source, an artificial circulation system must be devised (Refs. 1 & 2). Thus, it is necessary to develop methods for drilling, slotting and/or cutting these high temperature rocks in order to provide paths of water. High speed water jet drilling and cutting have been thought to be favorable methods for such purpose, because unsteady internal tensile thermal stresses are induced near the rock surface by high cooling power of these impinging jets (Refs. 3 & 4) in addition to the enormous hydraulic erosive power. Some first step experimental studies were previously performed using hot imitation rocks and relatively low speed water jets by the authors (Refs. 5 to 9). For the some data of the them a correlation equation was derived from the dimensional and multivariate analyses (Ref. 10).

Present studies were conducted to verify whether the analyses and the results obtained by the imitation rock experiments are also applied to natural hot dry rocks. This paper deals with experimental studies, which were carried out by using four different type rock specimens, on the effect of speed of the continuous water jet, the temperature and the value of physical properties of the specimens on the breaking pattern and efficiency.

The rock specimens (75 mm in diameter and 150 mm in length) were coring from four kinds of commercial rock blocks, that is, Indian Blue Granite, Indian White Sandstone, Komatsu Andesite and Ogino Tuff. The former two are produced in India and the latter two in Japan.

Experimental variables and conditions were as follows. The temperature of the specimens, θ, was room temperature, 200, 400 and 600℃. Water jet speed at nozzle exit, Um, was varied from about 130 to 400 m/s, which correspond to static pressures of water at nozzle exit, Pw, of 8.83 to 186 MPa, respectively, with consideration of strengths of the specimens to be tested and test intervals and steps (standard variables were set at four steps). Temperature of the water jeted, Tw, was at about 40 . Nozzle diameter, D_O, was fixed at 0.55 mm. Standoff distance, L, was kept constant at 22 mm (L/D_O=40). Impinging time of the jet to the specimens was fixed at 10s. Three pieces of specimens were used for the drilling tests for each conditions. Detailed description of the experimental method and the results has been reported elsewhere (Ref. 11).

Breaking patterns and figures of the specimens drilled by the water jet were so complicated that the breaking efficiency defined by the drilling depth versus static pressure of the jet at the nozzle exit was almost scatterd in all cases as described later. Figures (a), (b), (c) and (d) in Fig. 1 show examples of typical breaking patterns and figures of the drilled specimens observed in the Indian blue granite, Komatu andesite, Ogiono tuff and Indian white sandstone, respectively. As shown in these figures, on the surface of the specimen struck by the water jet, a hole-shaped cavity, a hole surrounded with eroded area-shaped cavity or a crater-shaped cavity was observed. Moreover, crushing of the specimen with vertical fracture surfaces happened violently in the other cases of the granite, the andesite and the tuff. At much higher pressure, P_O, and higher temperature , θ, disking of the samples was appeared much strongly. It seems that the disking phenomenon arised from pressure accumulation of the water jeted in the drilled hole and size effect of the specimens. The depth and volume of the cavity in the specimen drilled by the water jet were measured to evaluate the drilling performance. Figures 2 (a) to (d) show the relationship between the depth of the cavity from the initial surface of the specimen, lp [mm] , and the static pressure of the water jet at the nozzle exit, P_O [MPa] , at every different specimen temperature, θ [℃] , in the case of Indian blue granite. In these figures, open circles designate the experimental points for each case. In general, the experimental points of lp against P_O scattered. So, regression formulas were derived from the least squares, which are applied for the data between the depth, lp and the pressure, P_O, in the case of each temperature, θ. As regression functions, linear, geometric, exponential and algebraic equations, etc. were applied for each



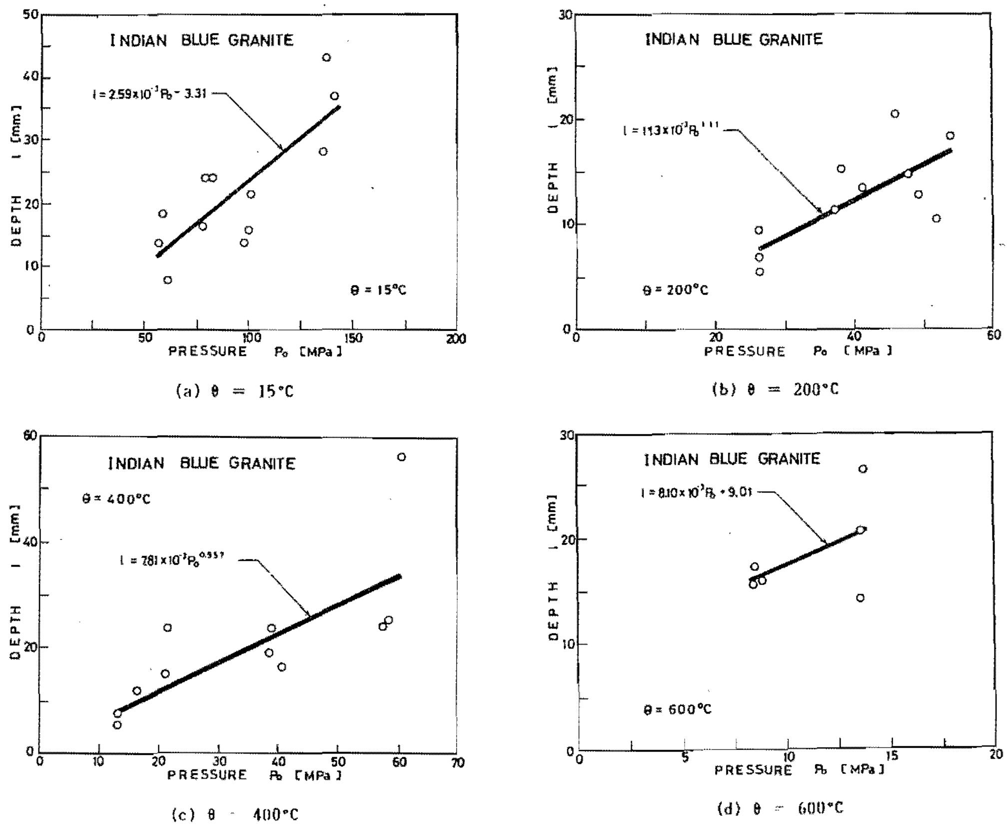
(a) Indian blue granite

(b) Komatu andesite

(c) Ogino tuff

(d) Indian white sandstone

Fig. 1. Examples of typical breaking patterns and figures of the drilled specimens observed in the different rocks.



(a) θ = 15°C

(b) θ = 200°C

(c) θ = 400°C

(d) θ = 600°C

Fig. 2. Relations between the depth of cavity and the jet pressure at the different specimen temperatures in the case of Indian blue granite.

case. Then the best fitted one was decided as the experimental formula for that case. Following four formulas were obtained for the Indian blue granite at every specimen temperature, θ.

$$lp = 2.59 \times 10^{-3} P_o - 3.31 \quad \text{for} \quad \theta = 15 \text{ °C} \tag{1}$$

$$lp = 113 \times 10^{-3} P_o^{1.11} \quad \text{for} \quad \theta = 200 \text{ °C} \tag{2}$$

$$lp = 7.81 \times 10^{-3} P_o^{0.957} \quad \text{for} \quad \theta = 400 \text{ °C} \tag{3}$$

$$lp = 8.10 \times 10^{-3} P_o + 9.01 \quad \text{for} \quad \theta = 600 \text{ °C} \tag{4}$$

For the Komatu andesite following four equations were derived from the least squares for the data:

$$lp = 2.01 \times 10^{-3} P_o - 12.2 \quad \text{for} \quad \theta = 15 \text{ °C} \tag{5}$$

$$lp = 7.32 \times 10^{-4} P_o + 8.55 \quad \text{for} \quad \theta = 200 \text{ °C} \tag{6}$$

$$lp = 4.15 \times 10^{-4} P_o^{1.22} \quad \text{for} \quad \theta = 400 \text{ °C} \tag{7}$$

$$lp = 7.44 \times 10^{-9} P_o^{2.53} \quad \text{for} \quad \theta = 600 \text{ °C} \tag{8}$$

And for Ogino tuff following experimental formulas were obtained:

$$lp = 7.36 \times 10^{-3} P_o^{0.839} \quad \text{for} \quad \theta = 15 \text{ °C} \tag{9}$$

$$lp = 2.39 \times 10^{-3} P_o^{0.743} \quad \text{for} \quad \theta = 200 \text{ °C} \tag{10}$$

$$lp = 33.9 \times P_o^{-0.0122} \quad \text{for} \quad \theta = 400 \text{ °C} \tag{11}$$

$$lp = 6.47 \times 10^{-4} P_o^{1.12} \quad \text{for} \quad \theta = 600 \text{ °C} \tag{12}$$

For Indian white sandstone following experimental formulas were also derived:

$$lp = 7.71 \times 10^{-3} P_o^{0.804} \quad \text{for} \quad \theta = 15 \text{ °C} \tag{13}$$

$$lp = 2.90 \times 10^{-1} P_o^{0.430} \quad \text{for} \quad \theta = 200 \text{ °C} \tag{14}$$

$$lp = 1.21 \times 10^{-3} P_o + 18.3 \quad \text{for} \quad \theta = 400 \text{ °C} \tag{15}$$

$$lp = 1.10 \times 10^{-2} P_o \quad \text{for} \quad \theta = 600 \text{ °C} \tag{16}$$

A general dimensionless correlation equation between drilling depth, lp, and the other parameters concerned in the jet and the specimen was derived from the dimensional and multivariate analyses and the data as follows:

Table 1 shows a part of data used to the analyses. Numbers of sets of sample, N, equal to 42, 49, 48 and 52 for the granite, the andesite, the sandstone and the tuff. The correlation equation for each rock is as follows;

For the granite,

$$lp/D_o = 7.417 \times 10^{-7} (\Delta T/Tw)^{0.1318} (Pew)^{0.2474} (Rew)^{1.672} \left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{-0.2312} (aw/as)^{4.214} (Prw)^{0.003542} \tag{17}$$

For the andesite,

$$lp/D_o = 1.172 \times 10^{-18} (\Delta T/Tw)^{0.1856} (Pew)^{-10.15} (Rew)^{13.58} \left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{0.6577} (aw/as)^{3.419} (Prw)^{13.62} \tag{18}$$

Table 1. Example of data samples used for the analyses

Sam. No.	Kind of Rock	Spec. Temp.	$\frac{\Delta T}{T_w}$	Pe_w $\times 10^5$	Re_w $\times 10^5$	$\frac{\sqrt{(P_t^2+P_w^2)}}{\sigma}$	$\frac{a_w}{a_s}$	Pr_w	l/D_o (exp)	l/D_o (est)
1	Imi. Rock	200	12.74	10.10	1.194	1.453	1.119	8.455	12.43	17.7
2	Imi. Rock	400	38.16	10.03	1.054	1.660	0.9930	9.517	32.04	22.6
3	Imi. Rock	600	45.18	10.08	11.41	1.876	0.9048	8.833	35.04	23.3
4	Granite	200	3.738	8.201	1.947	2.105	0.2184	4.213	12.44	13.1
5	Granite	400	9.752	5.937	1.261	31.58	0.2981	4.708	12.58	19.1
6	Granite	600	18.22	5.039	0.9286	60.12	0.4016	5.427	29.13	19.0
7	Andesite	200	3.050	20.84	5.664	1.174	0.2625	3.678	31.78	40.4
8	Andesite	400	8.787	14.21	3.305	2.908	0.3031	4.301	46.27	33.7

For the sandstone,

$$lp/D_O=1.224\times10^{-12}(\Delta T/Tw)^{0.04924}(Pew)^{0.08646}(Rew)^{1.954}\left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{0.2649}(aw/as)^{1.324}(Prw)^{4.371} \quad (19)$$

For the tuff,

$$lp/D_O=5.392\times10^{-19}(\Delta T/Tw)^{0.1175}(Pew)^{0.9553}(Rew)^{2.196}\left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{-0.6185}(aw/as)^{0.8767}(Prw)^{3.798} \quad (20)$$

For the four rocks (N = 42 + 49 + 48 + 52 = 191),

$$lp/D_O=4.914\times10^{-10}(\Delta T/Tw)^{0.06663}(Pew)^{2.801}(Rew)^{-1.191}\left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{0.3142}(aw/as)^{-0.3623}(Prw)^{-0.3479} \quad (21)$$

For an imitation rock (N = 100) (Ref. 10),

$$lp/D_O=1.823\times10^{-35}(\Delta T/Tw)^{1.708}(Pew)^{5.371}(Rew)^{0.3589}\left[\sqrt{(Pt^2+Pw^2)}/\sigma\right]^{-1.231}(aw/as)^{0.4834}(Prw)^{-0.1690} \quad (22)$$

where, as and aw = thermal diffusivity of specimen and water jet,respectively, Pt = thermal stress, Pw = water jet pressure at nozzle exit, Pew = Peclet number of water jet, Prw = Prandtl number of water jet at nozzle exit conditions, Rew = Reynolds number of water jet at nozzle exit and σ = parameter of specimen strength.

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