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Paper

# ENERGY LOSS FROM AN ABRASIVE WATERJET FOR ROCK CUTTING

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## ABSTRACT

The abrasive waterjet is an innovative technology for cutting brittle materials. The abrasive waterjet has many advantages in civil engineering for structure demolition or underground excavation due to its low vibration and noise. Waterjet cutting efficiency is important because it determines the construction cost and time of practical applications. To improve cutting efficiency, it is necessary to understand how energy loss is generated during rock cutting. In this study, granite cutting using an abrasive waterjet is performed with the energy parameters of water pressure, traverse speed, and abrasive feed rate. The energy parameters are converted to the kinetic energy dimension, *Joule*. From the theoretical point of view, the same amount of kinetic energy should provide the same amount of work. However, experimental test results show that cutting efficiency can be different at the same kinetic energy. Cutting with a higher water pressure results in better efficiency. A lower traverse speed produces a greater energy loss due to a decreasing deformation zone. An abrasive feed rate that exceeds the optimum values generates energy loss due to particle collision and insufficient transform moment.

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## 1. INTRODUCTION

Abrasive waterjet technology can be very useful in civil engineering to demolish or excavate brittle materials such as concrete or rock. Cutting depth is a very basic index to estimate waterjet efficiency. Cutting depth is strongly related to the following energy parameters: water pressure, traverse speed of nozzle, and abrasive feed rate. Water pressure is the foundation for generating the energy of the jet. A high water pressure has immense energy; it can make a deep cut in brittle materials (Summers, 1995). Traverse speed decides energy exposure time on a target material surface. The lower the traverse speed is, the deeper the cutting depth obtained for concrete (Momber and Kovacevic, 1997) and rocks (Agus et al., 1993; Lauand et al., 2001). A waterjet with increasing abrasive feed rate has great power to wear a brittle material because the material surface is attacked by solid particles entrained in the fluid stream (Finnie 1960; Wang and Guo, 2002). Previous studies (e.g., Summers, 1995; Momber and Kovacevic, 1997) typically expressed and plotted as cutting depth with an energy parameter. The concept of specific energy (i.e., water power available/removed volume) is broadly used to estimate waterjet efficiency (Teale, 1965; Summers, 1995). However, this concept can not consider the impact energy of the accelerated abrasive particles due to high speed jetting. In this study, kinetic energy for abrasive in waterjet is expressed as a function of energy parameters. In addition, energy loss is analyzed by using well controlled experimental data.

## 2. KINETIC ENERGY FOR ABRASIVE WATERJET

An amount of wear energy for a brittle material can be mainly generated by abrasives' kinetic energy when abrasives (i.e. solid particles) are accelerated through contact with high speed water. The magnitude of abrasives' kinetic energy ($E$) is decided by the fed abrasive weight per unit time ($\dot{m}_a$), the velocity ($v_s$) of the jet slurry that is a mixture of water and abrasives, and the jet exposure time ($t$). The kinetic energy of abrasives can be expressed as follows:

$$E = \frac{1}{2}\dot{m}_a\, v_s^2 t \qquad (1)$$

where the jet exposure time is estimated from the focusing nozzle diameter ($d_n$) and the traverse speed of the nozzle ($v_n$):

$$t = \frac{d_n}{v_n} \qquad (2)$$

Jet slurry velocity is obtained by inelastic collision theory using a simple momentum transfer between the high speed water flow rate ($\dot{m}_w$) and the incoming solid particles. Jet slurry velocity can be calculated by:

$$v_s = c_e\, \frac{v_w}{1 + (\dot{m}_a\,/\,\dot{m}_w)} \qquad (3)$$

where $c_e$ is a mixing efficiency coefficient that can be estimated by force measurements. This coefficient depends strongly on the geometry of the focusing nozzle (Typical $c_e$ is 0.57 to 0.71; Momber and Kovacevic, 1995). $v_w$ is the water velocity, which is related to water pressure ($p$). $v_w$ can be calculated as follows (Summers, 1995):

$$v_w = \varphi\sqrt{p} \tag{4}$$

where $\varphi$ is a parameter characterizing the energy transfer in the orifice. Substituting Eq. (2) and (3) into Eq. (1), the abrasives' kinetic energy becomes:

$$E = \frac{1}{2}\dot{m}_a \left[c_e \frac{v_w}{1 + (\dot{m}_a \,/\, \dot{m}_w)}\right]^2 \frac{d_n}{v_n} \tag{5}$$

## 3. EXPERIMENTAL PROGRAM

### 3.1 Set-up and Procedure

Rock cutting requires a high performance waterjet system. As shown in Table 1, the waterjet system has three main parts to generate high water pressure: a hydraulic oil pump, an intensifier, and a nozzle. The hydraulic oil pump (a 50HP pump is used in this study) initially generates the water pressure, which can be increased 20-fold by the intensifier. The waterjet system used in this study can generate a maximum water pressure of 4200kg/cm$^2$ and a water flow rate of 6liter/min. The generated high pressure water and supplied abrasives at the near end of the nozzle are mixed and fired down on a target material via the focusing nozzle.

Cutting tests for specimens are performed at least three times with an energy variable (i.e., water pressure, traverse speed of nozzle, or abrasive feed rate). The waterjet nozzle is moved in one direction for specimen cutting. The traverse speed of the nozzle is varied from 1.9mm/s to 14.1mm/s to change the exposure time; however, the distances between the surface and the nozzle tip are kept constant at 1cm during the nozzle movement. Water pressure is controlled in a range from 1600kg/cm$^2$ to 3200kg/cm$^2$ in order to supply different magnitudes of waterjet energy. In addition, to generate greater waterjet energy, the abrasive feed rate is changed from 2.2g/s to 24.3g/s. Cutting performance according to waterjet energy level is indicated as a maximum cutting depth.

### 3.2 Rock Specimens and Abrasive

Granite is used as specimen for cutting tests because it is a rock type predominant in the Republic of Korea. The specimens are prepared as cubic shapes with dimensions of 100 x 100 x 200mm. The mechanical properties of the rock specimen are estimated according to the guidelines of the International Society for Rock Mechanics (ISRM; Brown, 1981). The granite specimen properties are summarized in Table 2.

Garnet ($Fe_2O_3Al_2(SiO_4)_3$), which has tiny particles (of less than 0.3 mm, $D_{50}$=0.2mm) and a high degree of hardness (7.5 to 8.5 on the Mohs scale), is used as the abrasive. The particle size distribution of the abrasive is shown in Figure 1.

## 4. RESULTS AND ANALYSES

### 4.1 Simple Cutting Depth Model

The relationship between measured cutting depth and kinetic energy of the jet can indicate the magnitude of energy loss according to the energy parameters: water pressure, traverse speed, and abrasive feed rate. In this study, the kinetic energy is calculated by Eq. (5), where 6.4 and 14.1 are used as $C_e$ and $\varphi$ parameters, respectively, in the calibration tests. For the energy loss analysis from the experimental data, the relationship between cutting depth and kinetic energy is assumed as a power function in which incubative energy, the minimum energy to wear a brittle material surface, is not considered:

$$D = \alpha E^{\beta} \tag{6}$$

where $D$ is the cutting depth, $\alpha$ is the cutting depth when kinetic energy ($E$) is 1J, and $\beta$ is an exponent. Both $\alpha$ and $\beta$ are strongly related to cutting depth efficiency at a certain kinetic energy value. Higher $\alpha$ and $\beta$ indicate higher cutting efficiency (i.e., lower energy loss). Energy loss is estimated by the ratio of attenuated $\alpha_a$ and original $\alpha_o$, when $\beta$ is constant:

$$\text{Energy loss [\%]} = 100\text{- } ((\alpha_a/\alpha_o) \times 100) \tag{7}$$

### 4.2 Cutting Efficiency with Water Pressure

Figure 2 shows the cutting depth as a function of kinetic energy with water pressure. This result indicates that increasing the water pressure induces efficient cutting performance at the same kinetic energy level. In the power function, Eq. (6), the exponent $\beta$ has almost the same value ($\beta \approx 0.78$) regardless of water pressure; on the other hand, $\alpha$ is found to change from 0.29 to 0.52 with an increase in water pressure from 1600 to 3200 kg/cm$^2$. Given these results, 44.2% of energy loss is caused when water pressure in 1600 kg/cm$^2$ compared with when it is 3200 kg/cm$^2$ at the same energy.

Reduction of energy loss with high water pressure might be caused by a geometry space effect. Typically, high water pressure can make a better geometry condition (i.e., larger removal volume) than low water pressure can. At a high water pressure, energy loss may be diminished by decreasing the chance of interference between rebounded abrasives from the bottom of the cutting slot ("outcoming jet") and abrasives fired from the nozzle ("incoming jet").

### 4.3 Cutting Efficiency with Traverse Speed

A faster traverse speed of the nozzle generates a better cutting efficiency. Figure 3 shows that the inclination of the curve at 14.1mm/s traverse speed is steeper than that of 1.9mm/s. This phenomenon is verified by comparing $\alpha$ or $\beta$ values. The value of $\alpha$ changes from 0.064 at 14.1mm of traverse speed to 0.021 at 1.9mm of traverse speed, as shown in Figure 3. By looking at the drop in the value of $\alpha$, the generated amount of energy loss at the 1.9mm/s speed is found to be 67.2%. Meanwhile, $\beta$ is 1.32 regardless of traverse speed.

Change of traverse speed is an important parameter because traverse speed is directly proportional to the magnitude of energy exposure time. For cutting depth analysis with traverse speed, the step formation and cutting zones of the cutting material should be considered (Hashish, 1984; Momber and Kovacevic, 1998). In the step formation mechanism, increasing the traverse speed induces an increased impact angle of the jet. The impact angle change with traverse speed generates additional removal effects for a brittle material. Thus, a slow traverse speed can improve cutting performance.

### 4.4 Cutting Efficiency with Abrasive Feed Rate

The theoretical relationship (refer to Eq. (1)) infers that the increasing abrasive feed rate induces increased cutting energy, which can make a deep cutting depth. However, compared with the theoretical model, experimental cutting data might indicate different behavior. The relationship between cutting depth and abrasive feed rate tends to show a quadratic curve, which has a maximum point (refer to Figure 4). The maximum point denotes the optimized abrasive feed rate ($R$:10.9g/s obtained in this study). Figure 5 shows that at the same kinetic energy ($R$:10.3g/s) an over-optimized feed rate ($R$:19.3g/s) has a lower cutting depth than a near-optimized feed rate does; however, the over-optimized feed rate theoretically has greater kinetic energy than the near-optimized feed rate. This reverse phenomenon can be explained by the fact that the likelihood of particle collision increases when the feed rate of the abrasive material is higher than the optimal rate. Energy loss of 36.9% during cutting is generated when the abrasive feed rate exceeds the optimized rate by 8.4g/s.

## 5. CONCLUSIONS

A better understanding of energy loss for cutting rock is very important. In this study, experimental cutting tests were performed with the following energy parameters: water pressure, traverse speed of nozzle, and abrasive feed rate. The energy loss is estimated with a simple cutting depth model expressed by the energy term. The main findings are as follows:

- Low water pressure generates greater energy loss than does high water pressure during rock cutting.
- Energy loss is reduced with fast traverse speed due to increased impact angle for a brittle material.
- Exceeding the optimal abrasive feed rate causes energy loss due to abrasive collisions during jetting in spite of yielding a higher jet energy than possible when jetting with the optimal feed rate.

## 6. ACKNOWLEDGEMENTS

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## 8. NOMENCLATURE

$E$ - abrasive kinetic energy
$D$ - cutting depth
$R$ – abrasive feed rate
$\dot{m}_a$ - fed abrasive weight per unit time
$\dot{m}_w$ - water flow rate
$v_s$ - jet slurry velocity
$v_w$ - water velocity
$t$ - jet exposure time
$d_n$ - focusing nozzle diameter
$v_n$ - traverse speed of the nozzle
$c_e$ - mixing efficiency coefficient
$\varphi$ - energy transfer parameter
$p$ - water pressure
$\alpha, \beta$ - cutting efficiency factors
$\alpha_a$ - attenuated $\alpha$ factor
$\alpha_o$ - original $\alpha$ factor

## 9. TABLES

**Table 1.** Generation of high water pressure in a waterjet system

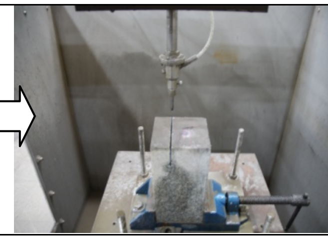
| **Waterjet system** | **Hydraulic oil pump** | **Intensifier** | **Nozzle** |
|---|---|---|---|
| |  |  |  |

**Table 2.** Specimen properties

| **Rock type** | **Density [kN/m$^3$]** | **Specific gravity** | **Porosity [%]** | **Uniaxial compressive strength [MPa]** | **Tensile strength [MPa]** | **Dynamic Young's modulus [MPa]** | **P-wave velocity [m/s]** |
|---|---|---|---|---|---|---|---|
| Granite | 25.7 | 2.64 | 1.04 | 100 | 10.2 | 30.2 | 3394 |

## 10. GRAPHICS

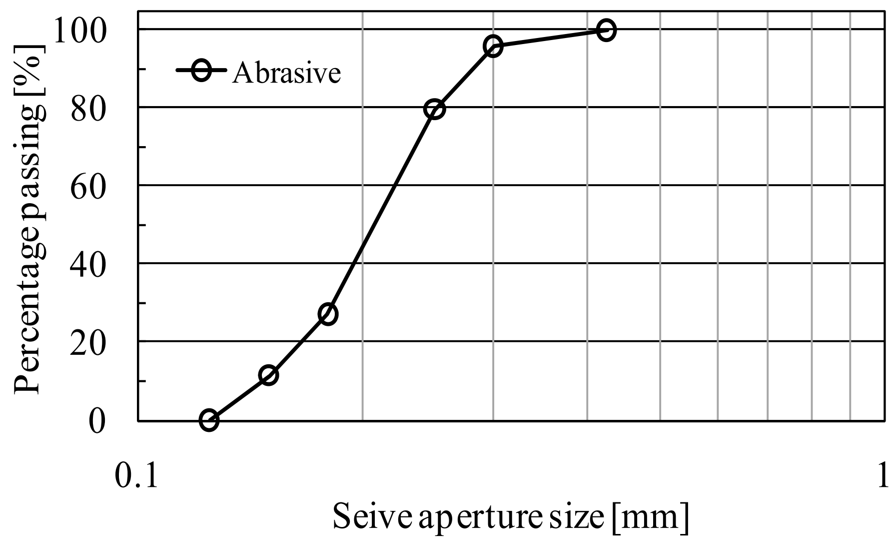



**Figure 1.** Particle size distribution of abrasive

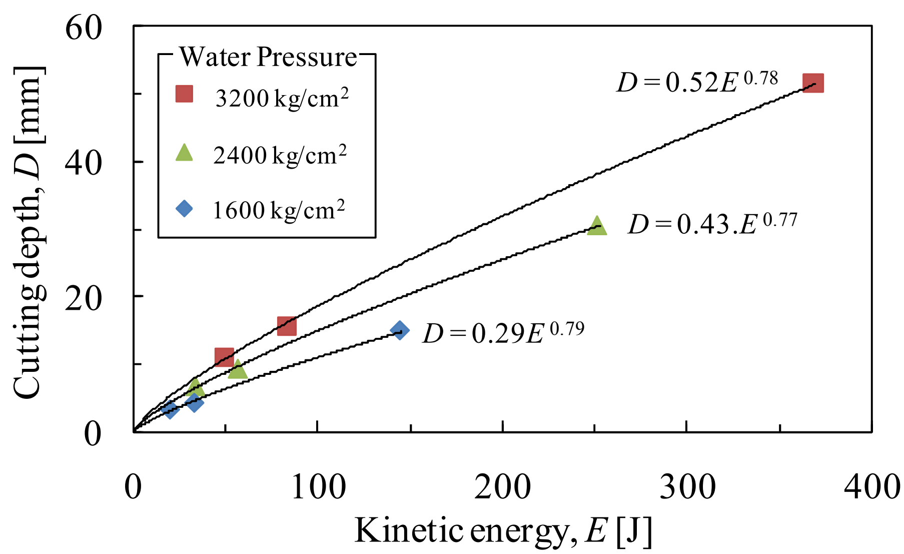



**Figure 2.** Cutting performance with water pressure

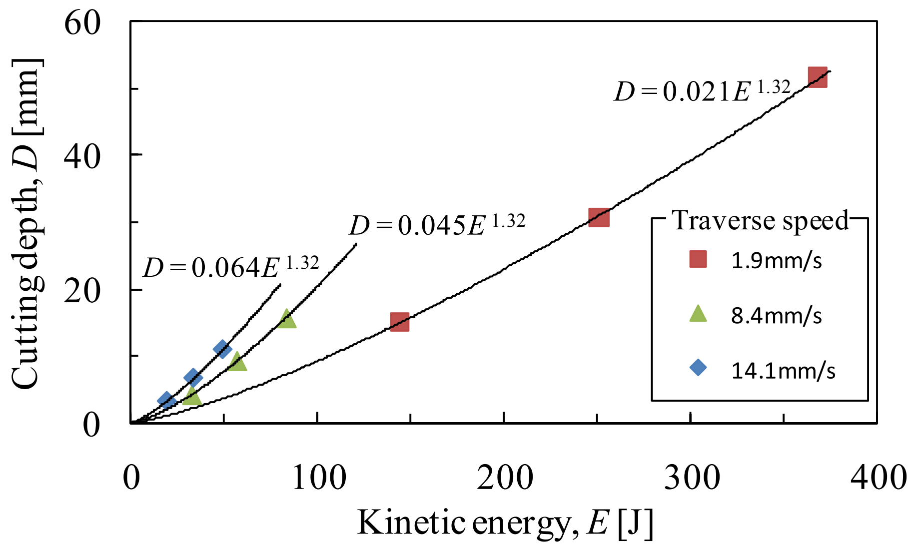



**Figure 3.** Cutting performance with traverse speed of nozzle

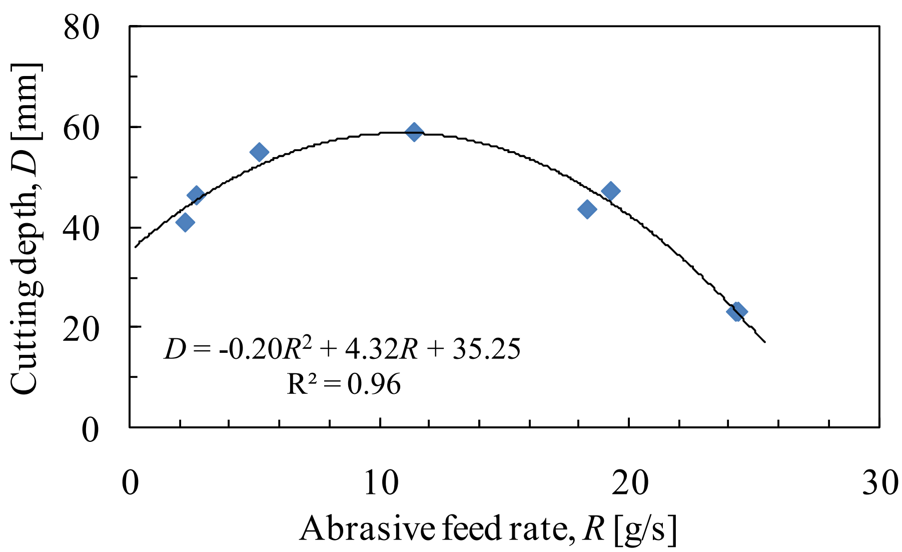



**Figure 4.** Cutting depth with respect to abrasive feed rate

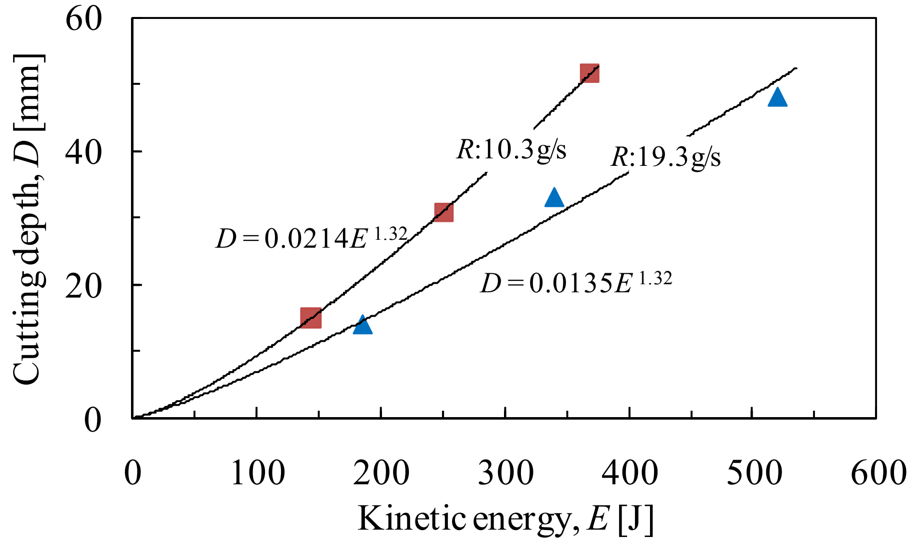



**Figure 5.** Comparison between a near-optimized and an over-optimized feed rate