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Slotting of Concrete and Rock Using an Abrasive Suspension Waterjet System

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Abstract

The aim of this study was to determine the optimal traverse speed and rotational speed of a nozzle from an abrasive waterjet system for the dismantling and remodeling of concrete buildings as well as for underground excavations of urban areas. The abrasive suspension waterjet system with a flow rate of 14 l/min was operated at a water pressure of 100 MPa with an abrasive consumption rate of 3 kg/min. Concrete, granite, and obsidian specimens were slotted using the abrasive suspension waterjet and the effect of the traverse and rotational speed of the nozzle on the volume removal rate for each specimen was analyzed. The volume removal rate increased until a certain level of the traverse speed of the nozzle was reached and then it remained the same or declined at higher traverse speeds. The nozzle performed better at a rotational speed of 300 RPM than that of 500 RPM or higher in terms of economics. Higher values of traverse and rotational speeds did not guarantee a higher volume removal rate of materials in abrasive waterjet slotting.

Keywords: *suspension water jet, nozzle head, traverse speed, rotational speed, volume removal rate*

1. Introduction

A waterjet is a tool able to slice materials such as concrete, granite, and obsidian using a jet of water at high velocity. It is used in various industries from mining to aerospace and in diverse operations such as cutting, carving, chipping, and surface cleaning (Gracey and Smith, 1995; Summers, 1995; Momber, 2005; Momber and Kovacevic, 1998; Wu and Kim, 1995; Yeomans and Alba, 1995). The waterjet is a promising tool not only for manufacturing industries but also for the civil engineering field due to its distinctive features of low vibration, little dust, and low impact or disturbance to areas adjacent to the operation. This makes the waterjet an environmentally-friendly technique over conventional cutting and dismantling methods such as the use of drilling and blasting, a hydraulic jackhammer, and a diamond saw cutter. Even though road maintenance is the mainstream use of waterjet in the civil engineering field in Korea, the use of the waterjet is expected to broaden in the near future in the dismantling and remodeling of old buildings especially in urban areas.

Abrasive waterjets use a jet of pressurized water containing abrasives which are mixed with the water right before entering the nozzle (abrasive injection waterjet) or which are mixed with the water in a high-pressure mixer first, before entering the nozzle (abrasive suspension waterjet). Sand, garnet, and silicon carbide are frequently used as the abrasives.

Waterjets had been used to assist drag bits in the drilling of hard rock (Hood, 1976) until Yazici (1989) showed that abrasive waterjets could be used as an independent cutting and drilling tool. Kovacevic *et al*. (1992) suggested that the cutting depth of an abrasive waterjet is a function of the amount of abrasives and nozzle stand-off distance. Momber (1995) introduced the concept of chemical reaction kinetics to explain the cutting mechanism of abrasive waterjets by relating the number of molecules, resultant chemicals, and reaction speed to the number of abrasive particles, volume of rock particles being cut out, and the time of exposure to the waterjet, respectively. Zeng and Kim (1992) suggested the machinability number could be evaluated according to the amount of abrasives and water input, and to the diameter of the abrasives. Momber *et al.* (1999) studied on on-line monitoring of Hydro-Abrasive Erosion (HAE) of pre-cracked multiphase materials with Acoustic Emission (AE) sensing technique. Hu *et al.* (2002) performed the hydro-abrasive erosion tests on Plain Concrete (PC) and on steel-Fibre Reinforced Concrete (FRC) and investigated the erosion behavior of the materials for different erosion conditions (suspension velocity, impact angle and solid content). Kim (2001) used an abrasive injection waterjet for cutting tests and analyzed the effect of rock properties, abrasives,

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and the parameters of the waterjet machine on rock cutting. Han *et al.* (2003) used an abrasive suspension waterjet for disc cutting in granite and concrete and examined the relationship between the volume removal rate and rotational speed of the nozzle. Momber *et al.* (2002) discussed Fast Fourier Transform (FFT) parameters of acoustic emission signals acquired during the Hydro-Abrasive Erosion (HAE) of five different concrete mixtures. The FFT-peak amplitude and frequency showed some pronounced relationships to the depth of penetration and to the fracture behavior of the investigated materials. The FFT-peak amplitude and frequency of the acoustic emission signals can be used for the on-line control of HAE-processes. Momber *et al.* (2011) suggested a model for the cutting of reinforced concrete members with stream-line cutting tools. This model allowed for the stepwise calculation of the energy absorbed during the cutting of the 2 parts of the reinforced concrete members, namely the reinforcing steel bars and the concrete matrix material. The conventional waterjet systems adopted in the study listed above, however, have a practical limitation in cutting depth when they are applied with a nozzle head fixed in the direction of the jet stream. The nozzle head and its shaft should be able to access the inside of the concrete or rock structures for the waterjet to make a deep cut, which means that the cut of the waterjet must be wider than the width of the nozzle head and shaft. For large-scale work and thick materials, slotting should be considered instead of cutting.

In this study, concrete, granite, and obsidian were kerfed and slotted using the abrasive suspension waterjet, and the effect of the traverse speed and rotational speed of the nozzle on the volume removal rate for each specimen was analyzed. The results of this study are expected to provide fundamental information for the design of an abrasive waterjet system for the dismantling and remodeling of concrete buildings as well as for underground excavations of urban areas.

2. Experimental Setup and Procedure

2.1 Equipment and Sample Specimens

The abrasive suspension waterjet system consisted of a high-pressure pump, a high-pressure mixer, a nozzle guide system, and a nozzle head (Fig. 1). The high-pressure pump creates the cutting power, and the high-pressure mixer blends the high-pressure water with the abrasives and sends it to the nozzle head through a high-pressure hose. A triplex plunger pump with a flow rate of 14 l/min operated at a water pressure of 100 MPa with an abrasive consumption rate of 3 kg/min was used in this study. The nozzle guide system moves the nozzle shaft in a horizontal or vertical direction (Fig. 2) and the nozzle head forces out the water with the abrasives through an orifice. The rotation of the nozzle shaft also takes place at the nozzle guide system by inserting a swivel joint (Fig. 3). The flow passing inside the nozzle head changes its direction by as much as 8^o to make the kerfing into slotting as the nozzle shaft rotates (Fig. 4). The nozzle head consisted of a nozzle body, a spacer, an orifice, and a plug. The orifice was made of hard metal and firmly fastened to the plug to endure the impact of the abrasives. The diameters of the orifice and the nozzle head were 0.7 mm and 14.6 mm, respectively.

The mechanical properties of the specimens are summarized in Table 1. The test procedure for each property followed the standards suggested by the International Society for Rock Mechanics (http://www.isrm.net). Specimens with an NX core size were used. The Uniaxial Compressive Strength (UCS) of obsidian was shown to be about 3 times higher than the UCS of Geochang granite, which is about 4 times higher than the UCS of concrete. The dimensions for each specimen were 15 cm × 15 cm × 100 cm. The grain sizes of obsidian couldn't be measured because it was glassy texture. Geochang granite contained biotite, opaque mineral, plagioclase and quarts. The sizes of each grain are 0.3~0.5 mm, 0.2~0.3 mm, 0.6~0.8 mm and 0.2~7 mm, respectively. The maximum aggregate diameter of concrete is 25 mm (Table 1). The abrasives used for the test were garnet made in Australia. The particle size of the garnet corresponding to an 80 mesh was 150 to 300 microns (150 microns (19%), 180 microns (32%), 212 microns (32%), 250 microns (12%), 300 microns (5%), and the specific gravity was 4.0, and the hardness was 8~9 on the Mohs scale.

2.2 Experimental Procedure

The experiment consisted of 3 tests: the kerfing test, slotting test I, and slotting test II. The kerfing test was done to examine

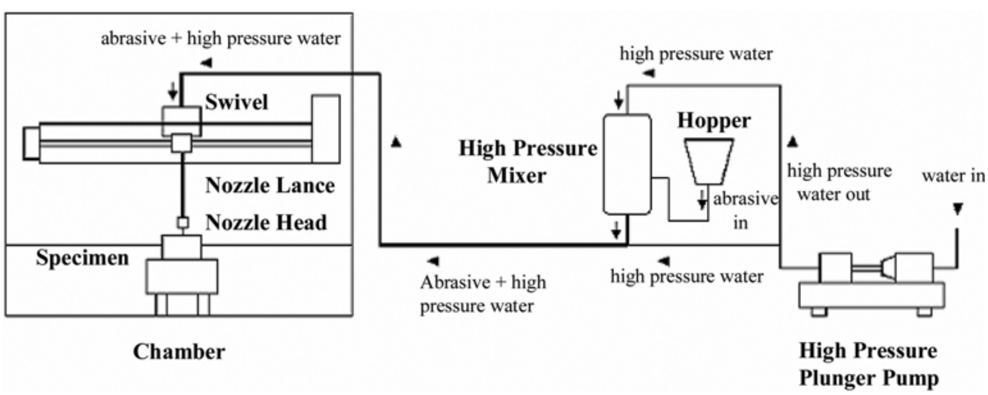


Fig. 1. Schematic Diagram of the Abrasive Suspension Water Jet System

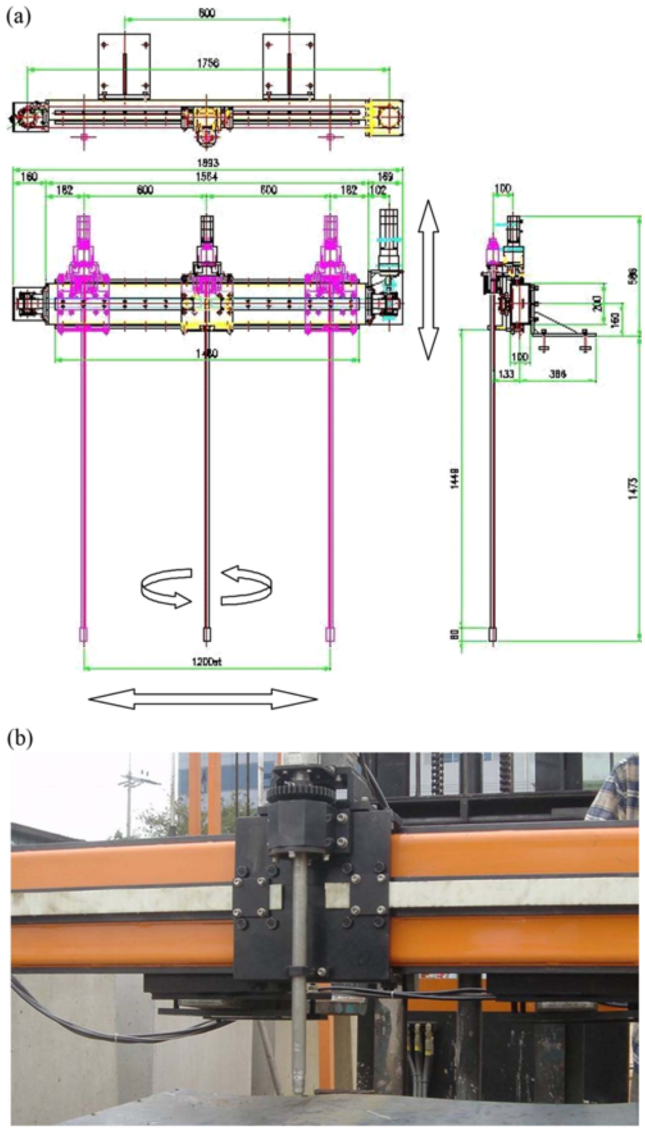


Fig. 2. Nozzle Guide System: (a) Schematic Diagram (unit: mm), (b) Photo of the Guide

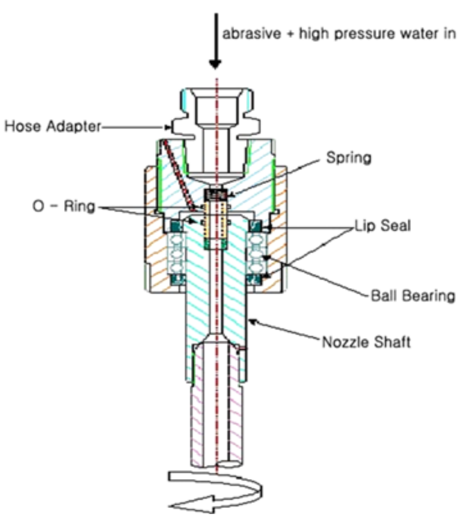


Fig. 3. Schematic Diagram of the Swivel Joint

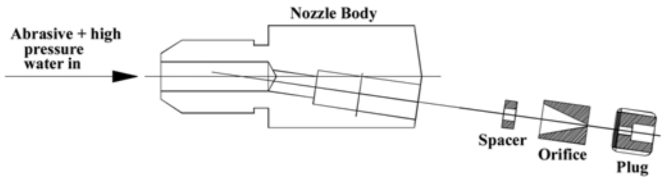


Fig. 4. Schematic Diagram of the Slotting Nozzle Head

Table 1. Mechanical Properties of the Specimens

Properties \ Specimen	Concrete	Geochang Granite	Obsidian
Maximum Aggregate diameter (mm)	25	-	-
Uniaxial Compressive Strength (MPa)	27	120	320
Specific Gravity	2.02	2.45	2.94
Porosity (%)	18.57	0.84	0.26
P-Wave Velocity (m/sec)	3300	3800	5370
S-Wave Velocity (m/sec)	1820	2290	2880
Young's Modulus (GPa)	1.54	3.74	9.95
Poisson's ratio	0.16	0.18	0.23

the kerf width and depth. The difference between the kerfing and slotting tests was in the rotational speed of the nozzle head (Table 2). The kerf width is much smaller than the slot width. The kerf width was used to determine the proper traverse speed of the nozzle during the slotting test. Slotting test I examined the relationship between the stand-off distance and slot width. It was done with a fixed rotational speed of the nozzle head. Slotting test II examined the effect of the traverse speed and rotational speed of the nozzle head on the cutting performance of the abrasive suspension waterjet system. The testing conditions used in all experiments are summarized in Table 2.

Table 2. Summary of the Testing Conditions used in All Experiments

Parameter \ Test Type	Kerfing	Slotting I	Slotting II
Traverse Speed (mm/sec)	262, 314, 366, 418, 471, 523, 575	10	Calculated by equation (1)
Rotational Speed (RPM)	0	200	250, 300, 350, 400, 450, 500, 550
Stand-off Distance (mm)	60	25~75	60

2.2.1 Kerfing Test

The stand-off distance of the nozzle from the specimen was 60 mm based on the experimental results of Kim (1999) that the cutting depth was hardly affected by the stand-off distance unless the stand-off distance was greater than 110 times the orifice diameter. The traverse speed for the kerfing was set at 262, 314, 366, 418, 471, 523, and 575 mm/sec corresponding to the linear speeds of the nozzle in slotting test II. The kerf width and depth were measured with a dial indicator and dial caliper gage in which the error ranges were within ± 0.01 mm and ± 0.025 mm, respectively. The waterjet flow rate, pressure, and abrasive input rate were set at 14 l/min, 100 MPa, and 3 kg/min, respectively.

2.2.2 Slotting Test

The relationship between the stand-off distance and slotting width was investigated in slotting test I with a constant nozzle rotational speed of 200 RPM and traverse speed of 10 mm/sec with the same waterjet flow rate, pressure, and abrasive input rate as those in the kerfing test. Continuously varying the stand-off distance was achieved by tilting the specimen from the horizontal position. The slotting width depends on the mechanical properties of the specimen, waterjet power, and geometrical relationship of the waterjet and the specimen. Fig. 5 shows the geometrical relationship of the slotting width with the stand-off distance and injection angle of the rotating jet.

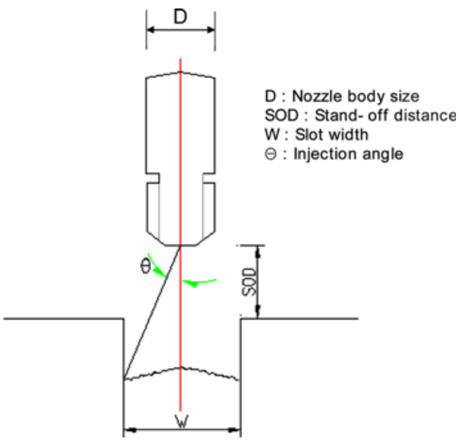


Fig. 5. Concept for Slotting Width with a Single Rotating Jet

The rotational speed and traverse speed of the nozzle in slotting test II was determined by taking into consideration how much of the cutting overlaps. The amount of overlap was evaluated by using the kerfing width. The aim of this study was to obtain the proper traverse speed of the nozzle by comparing the amount of waterjet cutting according to the degree of overlapped cutting. Fig. 6 shows the nozzle path according to the various traverse speeds with a constant rotational speed. The maximum traverse speed at which cutting was not overlapped was calculated as follows:

$$\text{Traverse speed (mm/sec)} = \frac{\text{RPM}}{60} \times W(\text{mm}) \quad (1)$$

The kerfing width (W) according to RPMs of 250, 300, 350, 400, 450, 500, and 550 was 10.2, 10.1, 9.6, 9.3, 9.2, 8.5, and 8.3 mm, respectively. Table 3 shows the traverse speed calculated for each RPM and the Degree of Non-overlapped Cutting (DNC).

The cut volume of each specimen was measured from the volume of the 120 mesh-abrasives filling the slot.

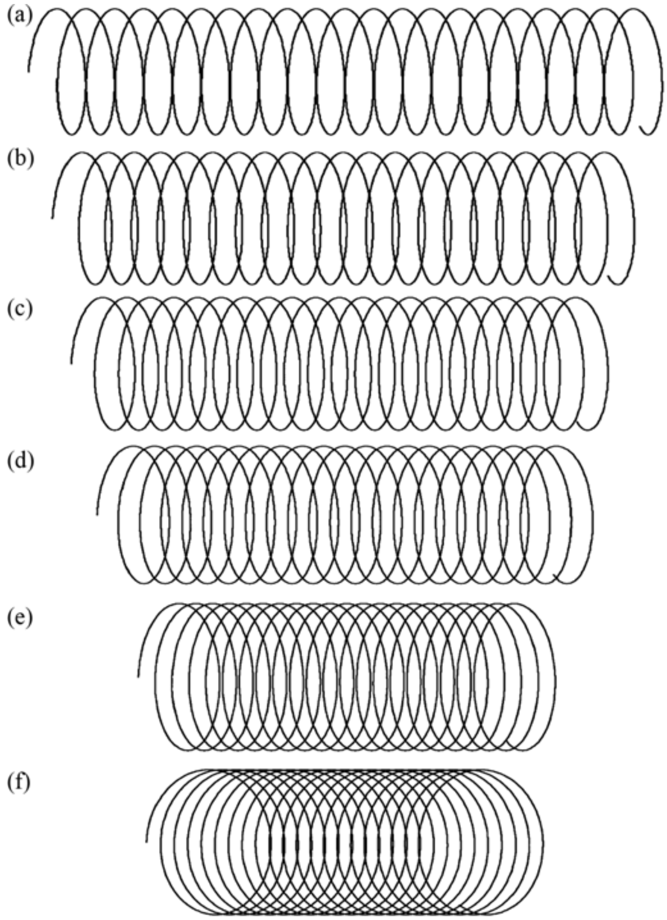


Fig. 6. Nozzle Path According to the Traverse Speed (W = kerf width): (a) Traverse Speed = RPM/60×(6/6)W (mm/sec), (b) Traverse Speed = RPM/60×(5/6)W (mm/sec), (c) Traverse Speed = RPM/60×(4/6)W (mm/sec), (d) Traverse Speed = RPM/60×(3/6)W (mm/sec), (e) Traverse Speed = RPM/60×(2/6)W (mm/sec), (f) Traverse Speed = RPM/60×(1/6)W (mm/sec)

Table 3. Traverse Speed (mm/sec) for RPM and the Degree of Non-overlapped Cutting (DNC)

RPM / DUC	250 (W=10.2 mm)	300 (W=10.1 mm)	350 (W=9.6 mm)	400 (W=9.3 mm)	450 (W=9.2 mm)	500 (W=8.5 mm)	550 (W=8.3 mm)
(6/6)W	42.5	50.5	56.0	62.0	69.0	70.8	76.1
(5/6)W	35.4	42.1	46.7	51.7	57.5	59.0	63.4
(4/6)W	28.3	33.7	37.3	41.3	46.0	47.2	50.7
(3/6)W	21.3	25.3	28.0	31.0	34.5	35.4	38.0
(2/6)W	14.2	16.8	18.7	20.7	23.0	23.6	25.4
(1/6)W	7.1	8.4	9.3	10.3	11.5	11.8	12.7

3. Results and Discussion

3.1 Kerfing Test

A series of kerfing tests showed that a decrease in kerf depth and width coincided simply with a decrease in the traverse speed of the nozzle head as shown in Fig. 7 for granite. This seems to be because the specimen was exposed to the waterjet for a relatively short time for complete cutting to be made at a given condition: even the lowest traverse speed of 262 mm/sec was too high for the given power of the waterjet to be able to show its full ability to make a kerf.

The volume removal rate defined by the traverse speed multiplied by the cross-sectional area of kerf, however, simply increased as the traverse speed increased up to 366 mm/sec and then it declined as shown in Fig. 8. An increase in the traverse speed means an increase in the cutting (kerfing) length per unit time in the axial direction of the kerf. Even though the increased kerf length contributed to the enhancement of the volume removal rate, the increased traverse speed caused the decrease in the kerf cross section at the same time as inferred from Fig. 7. Therefore, it can be seen from Fig. 8 that the decrease in the volume removal rate due to the reduction in the kerf cross section exceeded the increase in the volume removal rate due to the enhancement of the kerf length per unit time when the traverse speed increased beyond a certain level, which was approximately 400 mm/sec in this study.

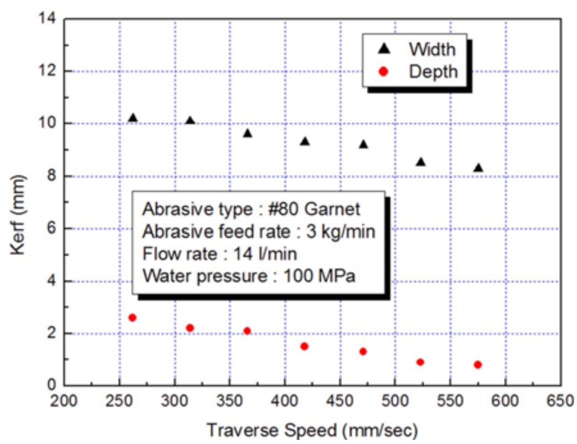


Fig. 7. Kerf Width and Depth vs Traverse Speed of the Nozzle Head for Granite

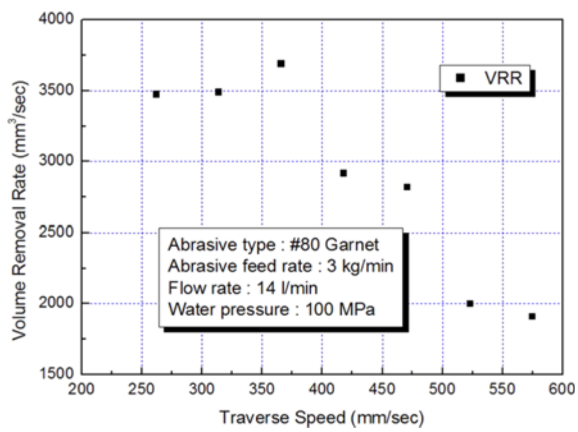


Fig. 8. Volume Removal Rate vs Traverse Speed of the Nozzle Head for Granite

3.2 Slotting Test

When the stand-off distance was increased from 25 mm to 75 mm, the width of the slot increased in slotting test I where the nozzle rotational speed and traverse speed were 200 RMP and 10 mm/sec, respectively (Fig. 9). Since the slot width has to be large enough for a nozzle head to access the inside of the specimens, the stand-off distance had to be greater than 45 mm considering the nozzle head had a diameter of 14.6 mm. The stand-off distance was fixed as 60 mm for slotting test II.

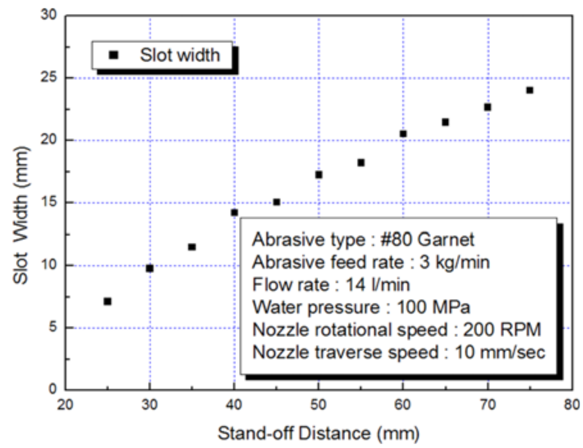


Fig. 9. Slot Width vs Stand-off Distance for Granite

Figure 10 shows the change in the volume removal rate according to the traverse speed with the rotational speed of the nozzle at 300 RPM and 500 RPM. Throughout the 7 cases for the volume removal rate tests where the RPM ranged from 250

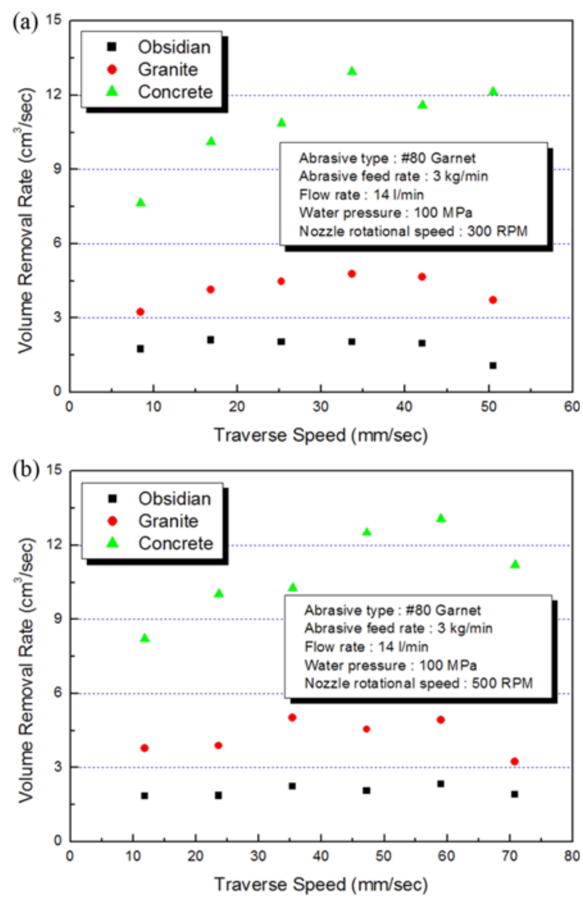


Fig. 10. Volume Removal Rate vs Traverse Speed of the Nozzle Head: (a) 300 RPM, (b) 500 RPM

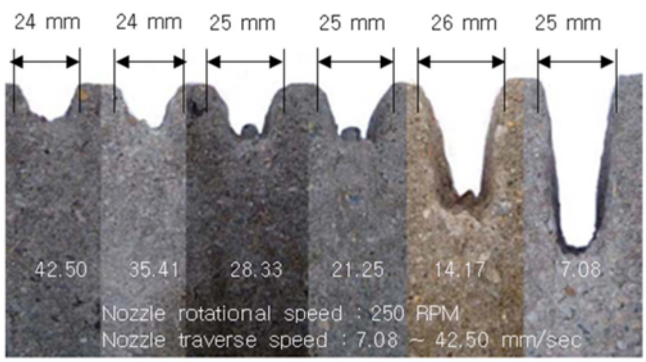
to 550, the volume removal rate increased until a certain level of traverse speed was reached and then it remained the same or declined in the following ranges. The 'certain level' depended on the specimen: the volume removal rate of a stronger specimen started to remain the same or decrease at a relatively lower level of traverse speed. The volume removal rate of concrete started to remain the same or decline at a traverse speed of 40~60 mm/sec while granite and obsidian started at 25~40 mm/sec and 15~35 mm/sec, respectively. These results show that higher values of traverse speed and rotational speed did not guarantee a higher volume removal rate for materials in abrasive waterjet slotting. For the concrete specimen, the maximum value of the volume removal rate (13.89 mm^3/sec) was observed at a traverse speed of 63.4 mm/sec and a rotational speed of 550 RPM. The maximum values of the volume removal rate for granite (5.01 mm^3/sec) and obsidian (2.33 mm^3/sec) were observed at 35.4 mm/sec and 59.0 mm/sec, respectively, with a rotational speed of 550 RPM for both. The second highest value of the volume removal rate for concrete was 12.94 mm^3/sec with a traverse speed and rotational speed of 33.7 mm/sec and 300 RPM, which was 7% less than the highest value. As for the granite and obsidian, a traverse speed and rotational speed of 33.7 mm/sec and 300 RPM (4.76 mm^3/sec) and 16.8 mm/sec and 300 RPM (2.1 mm^3/sec), respectively, reduced the volume removal rate by 5~10% compared to the maximum values. Lower rotational speed means a longer life for the nozzle guide system. Therefore, choosing a rotational speed of 300 RPM instead of 500 RPM or higher could be better in terms of economics. The Volume Removal Rate (VRR) was calculated as follows:

$$VRR\ (\text{cm}^3/\text{sec}) = A\ (\text{cm}^2) \times V_T\ (\text{cm/sec}) \quad (2)$$

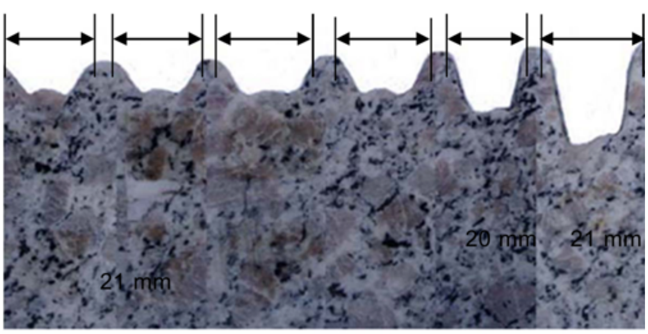
where VRR is the volume removal rate, A is the slot section area, and V_T is the nozzle traverse speed.

Figure 11 shows cross sections of the concrete and granite specimens after slotting at 250 RPM with various traverse speeds: the right most column corresponds to the case for the lowest traverse speed. This figure shows that lower traverse speeds caused deeper slots, especially in weaker materials, but it did not affect the slot width in the same material.

Specific energy is the energy required to remove a unit volume of materials, which is used to indicate the energy efficiency of



(a)



(b)

Fig. 11. Cross Section of Slotted Specimens: (a) Concrete, (b) Granite

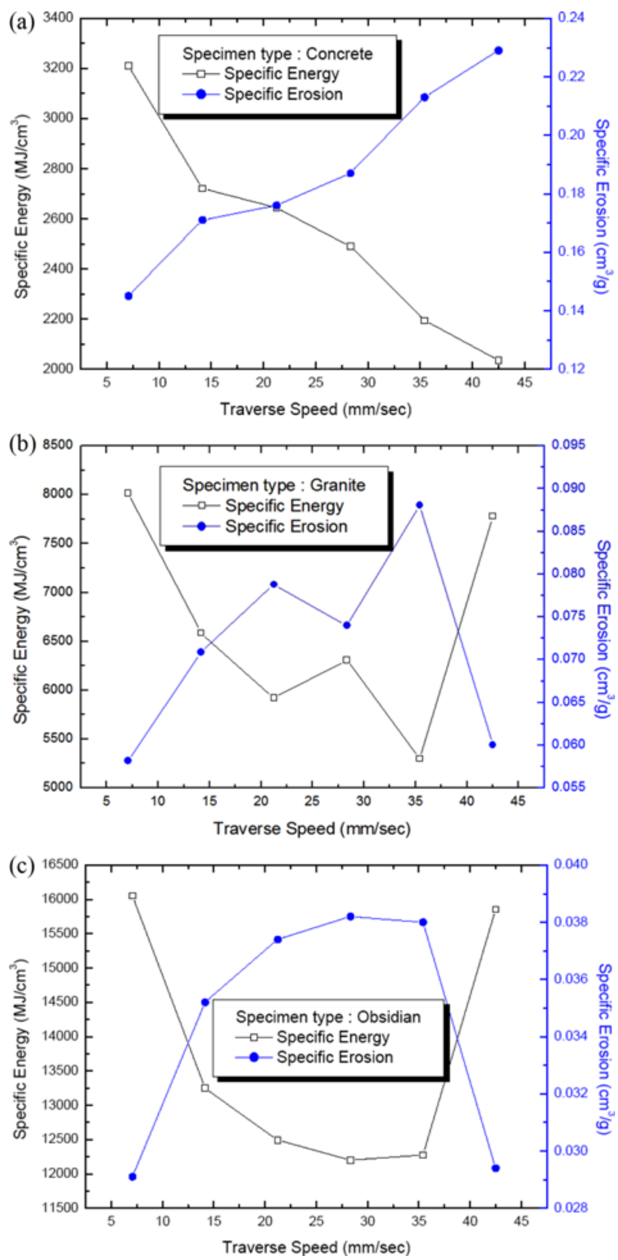


Fig. 12. Specific Energy and Specific Erosion according to the Traverse Speed: (a) Concrete, (b) Granite, (c) Obsidian

(abrasive) an waterjet. Specific erosion is a volume removed by 1 g of abrasives, which is used to express the efficiency of the abrasives. The Specific Energy (SE) and Specific Erosion (ER) can be calculated as follows:

$$SE = \frac{P \times Q}{VRR} \tag{3}$$

where SE is the specific energy (J/m^3); P is the pump pressure (Pa); Q is the flow rate (m^3/sec), and VRR is the volume removal rate (m^3/sec) and:

$$ER = \frac{VRR}{AFR} \tag{4}$$

where ER is the specific erosion (m^3/g), and AFR is the abrasive feed rate (g/sec).

Figure 12 shows the SE and ER of the concrete, granite and obsidian in units of MJ/m^3 and cm^3/g, respectively. This figure shows that the SE decreased as the ER increased, and vice versa. The results from the concrete showed that the ER monotonically increased as the traverse speed increased. The results from the obsidian and granite, however, showed that the ER decreased rather than increased at the highest traverse speed. The VRR simply increases with the increase of the traverse speed for concrete. This means that ER increases as the traverse speed increases because $ER=VRR/AFR$. Granite and obsidian, however, have shown that VRR rather decreases at the highest traverse speed.

The average of the width and depth of each kerf and slot was obtained from measurements except maximum and minimum values. The average values were plotted in the graphs. The standard deviation of the measurements for rocks is approximately 0.6 mm, and that for concrete is around 1.8 mm. The cut volume of each specimen was measured from the volume of the abrasives filling the slot.

4. Conclusions

An abrasive suspension waterjet system with a flow rate of 14 l/min operated at a water pressure of 100 MPa with an abrasive consumption rate of 3 kg/min was used to analyze the effect of the traverse and rotational speeds of the nozzle on the volume removal rate of concrete, granite, and obsidian specimens. Three kinds of tests were done for the analyses: a kerfing test, slotting test I, and slotting test II.

1. A series of kerfing tests showed that a decrease in kerf depth and width coincided simply with a decrease in the traverse speed of the nozzle head. This seems to be because the specimen was exposed to the waterjet for a relatively short time for complete cutting to be made at a given condition. A decrease in the volume removal rate due to a reduction in the kerf cross section is thought to exceed an increase in the volume removal rate due to the enhancement of kerf length when the traverse speed increases beyond a certain level, which was approximately 400 mm/sec in this study.
2. An increase in the stand-off distance caused the slot width to increase in slotting test I in which the nozzle rotational speed and traverse speed were 200 RPM and 10 mm/sec, respectively.
3. The volume removal rate increased until a certain level of the traverse speed was reached and then it remained the same or declined at higher levels of the traverse speed. The 'certain level' depended on the specimen: the volume removal rate of a stronger specimen started to remain the same or decrease at a relatively lower level of traverse speed. It was observed that higher values of traverse and rotational speed did not guarantee a higher volume removal rate of materials in abrasive waterjet slotting.
4. The results from the concrete specimen showed that its specific erosion increased as the traverse speed increased. The results from the obsidian (and granite) specimen, however, showed that its specific erosion decreased rather than increased at the highest traverse speed.

The results of this study are expected to provide fundamental information for the design of an abrasive waterjet system for the dismantling and remodeling of concrete buildings as well as for underground excavations of urban areas.

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