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Edge excavation performance of a rock material

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This paper aims to investigate experimentally the edge excavation performance of a disc cutter bit on a free edge part of rock material. The tangential, lateral and normal forces acting on the disc cutter bit having three tip angles and the amount of debris in several cutting spaces and penetration depths per round for four kinds of rock samples were measured. As a result, it was observed that the specific cutting energy, i.e. the ratio of the excavation work of the disc cutter bit of a tip angle of $\pi/4$ rad to the amount of debris of an andesite, showed a minimum value 0.036 kNcm/cm^3 at the ratio of cutting space and penetration depth per round of 52.7. The method of the edge excavation for the rock material could achieve the great efficiency of excavation of about 24 times that of plane excavation.

Key words : disc cutter bit, edge excavation, specific energy, cutting space, rock material

1. Introduction

The conventional process of T.B.M. (tunnel boring machine) in tunnel excavation sites has progressed remarkably in many areas. But, there are still urgent needs for the development of new multiple type tunneling machine systems to lower construction costs and to increase the efficiency of excavation by the decrement of excavation forces. The new multiple tunneling machine has the merit of an excavation mechanism which causes shear and tensile failure in rock materials due to the wedge action of a disc cutter bit, while the mechanism of plane excavation of T.B.M. is based on the tensile failure in rock materials due to the penetration of an adjacent disc cutter bit. Furthermore, how to decrease the specific energy for increasing the efficiency of excavation and how to decrease the excavation force for reducing the amount of wear should be considered. The purpose of this paper is to investigate experimentally the characteristics of an edge excavation of rock specimen having two degrees of freedom under a constant penetration depth per round instead of a conventional plane excavation having one degree of freedom.

For the experiments, cement mortar, tuffaceous rock and andesite were prepared as the rock specimens. Three kinds of disc cutter bits having different tip angles were fabricated. The disc cutter bits had a diameter of 15 cm, and the size ratio was designed to be 1/3 in comparison to an actual disc cutter bit. Using a rotary and penetration type excavation test apparatus, the tangential, lateral and normal forces acting on the disc cutter bit and the amount of debris were measured for several combinations of cutting space and penetration depth per round. Afterwards, the specific cutting energy for each cutting space and penetration depth per round could be calculated as the ratio of the rotary excavation power of disc cutter bit to the amount of

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debris. Moreover, it shall be clarified experimentally that the specific cutting energy due to this edge excavation system decreases remarkably and the efficiency of excavation due to the edge excavation increases greatly, in comparison with those due to the conventional plane excavation of T.B.M.

2. Experiment and its method

2.1 Excavation test apparatus

A rotary and penetration type excavation test apparatus [1] consists of a turntable of 40 cm diameter driven by a 1.5 kW motor, a worm gear jack having 35 cm stroke and 50 kN maximum thrust for penetrating a disc cutter bit using a screw rod driven by a 0.2 KW motor with non-step reduction gear ranging from zero to 28.5 r.p.m. and an octagonal ring dynamometer [2] for measuring tangential, lateral and normal force respectively acting on the disc cutter bit during excavation of rock specimen. The disc cutter bit could be rotated at a given circumferential speed of 1.83 cm/s around a circular locus of radius R = 10 cm on the surface of rock specimen and the bit could penetrate into the rock specimen during rotation at the penetration speed of zero to 0.017 cm/s. The rock specimens of 22.0, 24.0 and 26.0 cm diameter and 15.0 cm height were mounted on the turntable. So, the cutting space "S" could be selected as 1.0, 2.0 and 3.0 cm respectively having 1/3 size ratio compared to an actual one. The disc cutter bit could be positioned vertically on the surface of rock specimen via the screw rod by rotating the worm gear installed on the upper frame of the test apparatus. It could horizontally be set at a given cutting space from the edge of the rock specimen to have the same rolling locus of 10 cm radius. For the plane excavation test, the cutting space was always set at 5.0 cm from the edge to avoid the edge failure of the rock specimen.

Figures 1 (a) and (b) show the plan and side views of the disc cutter bit excavating the rock specimen and the forces acting on it respectively. The tangential force F_X , the lateral force F_Y and the normal force F_Z could be measured using the two coupled octagonal ring dynamometers having a maximum capacity of 15, 15 and 50 kN respectively. The horizontal force F_H could be calculated as the resultant force of F_X and F_Y and the horizontal angle θ between them could be given from F_X and F_Y. The values are positive when the direction of each applying force agrees with the designated one in this figure. The side view shows the applying forces in the case of edge

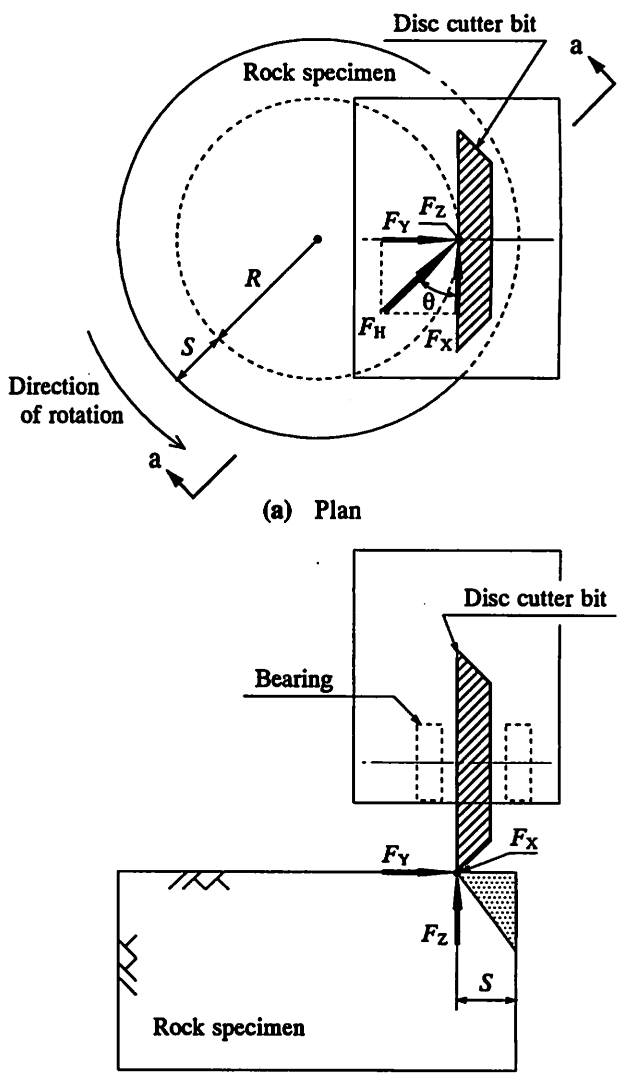

Fig.1 General view of steady state edge excavation

Table 1 Physical properties of rock specimen

Name of rock			Cement mortar A	Cement mortar B	Tuffaceous Rock	Andesite
Apparent specific gravity	G		2.065 ± 0.028	2.136 ± 0.030	1.635 ± 0.017	2.455 ± 0.002
Specific gravity	G_S		2.471 ± 0.040	2.719 ± 0.071	1.707 ± 0.042	2.565 ± 0.020
Natural water content	W	(%)	13.38 ± 0.69	12.08 ± 0.64	3.70 ± 0.15	0.86 ± 0.02
Absorption	W	(%)	12.65 ± 0.28	13.13 ± 1.00	17.52 ± 0.31	1.85 ± 0.09
Unconfined compressive strength	S_c	(MPa)	10.66 ± 1.15	39.42 ± 4.97	10.35 ± 1.72	96.99 ± 13.15
Radial compressive strength	S_t	(MPa)	1.42 ± 0.24	4.59 ± 0.53	1.46 ± 0.22	7.54 ± 1.15
Shore hardness	H_S		10.11 ± 2.37	22.60 ± 2.61	14.18 ± 7.79	43.40 ± 12.80
Elastic wave velocity	V_P	(m/s)	2590 ± 39	2837 ± 31	1916 ± 50	3365 ± 23
Fracture toughness	K_{CB}	(MN/m$^{3/2}$)	0.133 ± 0.020	0.562 ± 0.104	0.166 ± 0.030	0.676 ± 0.131

excavation at the cutting space "*S*" from the edge of the rock specimen.

2.2 Disc cutter bit and rock specimen

As test specimens of an actual disc cutter bit, three kinds of model bit made of S45C metal having 15.0 cm diameter, 1.5 cm thick and tip angle α of $\pi/6$, $\pi/4$ and $\pi/3$ rad were manufactured for the excavation tests.

As rock specimens, two kinds of artificial rock specimens of cement mortar A and B, a tuffaceous rock and an andesite were prepared. For the cement mortar A, the mix design for the fresh high-early-strength portland cement mortar was developed to have a unit weight of fine aggregate of 10.8 kN/m^3, a unit cement content of 6.4 kN/m^3, and a unit weight of water of 3.4 kN/m^3. The mix design of cement mortar B was a unit weight of fine aggregate of 9.15 kN/m^3, a unit cement content of 9.19 kN/m^3, and a unit weight of water of 3.68 kN/m^3. After mixing these materials using a forced batch mixer, the fresh cement mortar were placed into given cylindrical steel containers having the height of 9.5 cm and the diameter of 22, 23, 24, 25 and 26 cm. After wet curing for 3 days (72 hours) at a temperature of 18 °C, the excavation test was executed within one hour to avoid the strength variation of the mortar specimen. The tuffaceos rock is a kind of greentuff, which consists of brown, green and white colored, porous, light and weak rock. The mineral composition is 54 % detritus of pumice stone including rhyolite, 7 % quartz, 5 % plagioclase and 34 % matrix of fine volcanic ash. The mineral composition of the andesite is 21 % plagioclase, 10 % black mica and 68 % matrix.

The physical properties of the four kinds of rock specimen are shown in **Table 1** respectively.

3. Experimental test result

3.1 Excavation force and cutting space

In the excavation test, the skew angle and the clearance angle of the disc cutter bit were always set to be zero.

For the plane excavation test against the cement mortar A and B, the tuffaceous rock and the andesite, three series of tests were executed for the tip angles $\alpha = \pi/6$, $\pi/4$ and $\pi/3$ rad in the penetration depth per round "*p*" of 0.1 cm/round, respectively.

For the edge excavation test against the cement mortar, a total of 90 series of tests were executed for the combinations of three sets of penetration depth per round p = 0.1, 0.2 and 0.3 cm/round, five sets of cutting

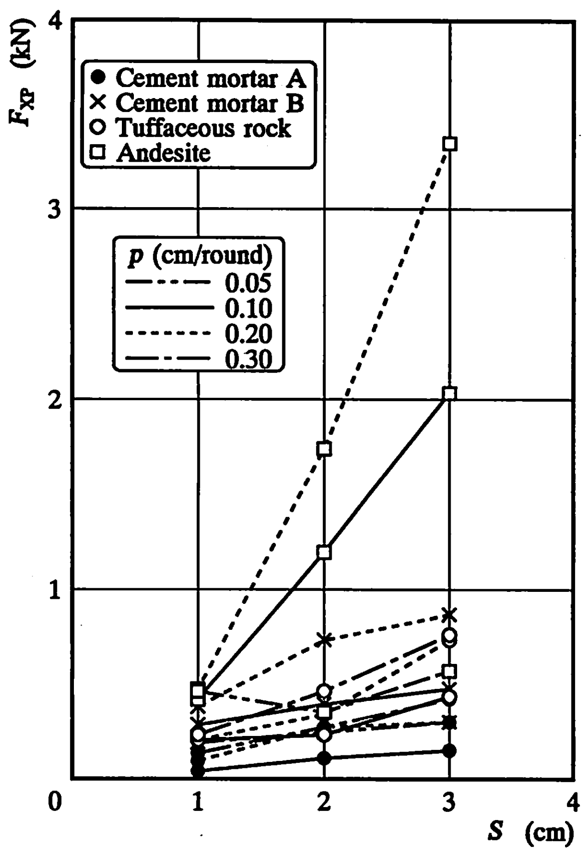

Fig.2 Relationship between peak tangential force F_{XP} and cutting space S ($\alpha = \pi/4$ rad)

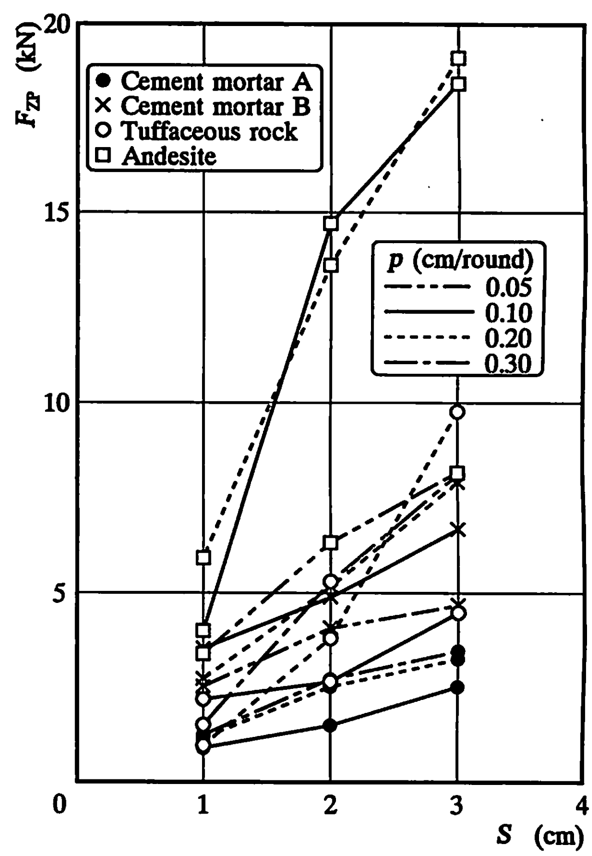

Fig.3 Relationship between peak normal force F_{ZP} and cutting space S ($\alpha = \pi/4$ rad)

space S = 1.0, 1.5, 2.0, 2.5 and 3.0 cm and three sets of tip angle $\alpha = \pi/6$, $\pi/4$ and $\pi/3$ rad. For the edge excavation test against the tuffaceous rock and andesite, a total of 27 series of tests were executed for the combinations of three sets of cutting space S = 1.0, 2.0 and 3.0 cm and the same three sets of penetration depth per round and tip angle as mentioned before were executed respectively.

The peak values of F_X, F_Y, and F_Z had almost simultaneously occurred and they were synchronized with each other. Here, the average value of the first ten peak points of the tangential, lateral and normal forces during excavation was designated as the edge excavation force F_{XP}, F_{YP} and F_{ZP} respectively. The measurements of the peak tangential force F_{XP} and the peak normal force F_{ZP} were very important to calculate the rotational power P_R and thrust power P_T, respectively.

The relationship between the peak tangential force F_{XP} and the cutting space "S" in three sets of penetration depths per round p = 0.1, 0.2, and 0.3 cm/round could be summarized in **Fig.2**, as an example of tip angle of $\alpha = \pi/4$ rad for the cement mortar A and B, tuffaceous rock and andesite respectively. In general, F_{XP} (kN) tends to increase with the increment of p (cm/round) due to the increasing cross section of the part of penetration of the disc cutter bit, and with the increment of S (cm) due to the enlargement of ruptured edge zone of the rock specimen, and with the increment of an unconfined compressive strength S_C (kN/cm^2). But there is little significant affect of the tip angle α (rad) on F_{XP}. From the regression analytical results, the following experimental equation was derived:

$$F_{XP} = 0.253\, p^{0.767}\, S^{1.335}\, \alpha^{0.332}\, S_C^{0.987} \qquad (R=0.942) \qquad (1)$$

where R is the multiple correlation coefficient.

The relationship between the peak normal force F_{ZP} and the cutting space "S" could be also expressed in

Fig.3, as an example of $\alpha = \pi/4$ rad. In general, the peak normal force F_{ZP} (kN) increases almost linearly with the increment of the unconfined compressive strength S_C (kN/cm^2), and of the cutting space S (cm) due to the enlargement of the ruptured edge zone of the rock specimen. F_{ZP} tends to increase slightly with the increment of p (cm/round) due to the increasing cross section of the part of penetration of the bit, and with the increment of the tip angle α. From the regression analytical results, the following experimental equation was derived:

$$F_{ZP} = 1.863\, p^{0.261} S^{1.035} \alpha^{0.435} S_C^{0.730} \qquad (R=0.937) \tag{2}$$

3.2 Amount of debris and cutting space

When the disc cutter bit rotated on the edge of the rock specimen mounted on the turntable, the debris excavated under a constant penetration depth per round was gathered using a brush. Then the weight W (gf) at the end of the excavation was measured by use of an electric balance. The amount of the volume of debris could be calculated as the weight of debris divided by the unit weight of the rock specimen ρ (gf/cm^3). The time of rotation of the disc cutter bit until the initial edge failure has completed at the nth rotation around the running circle of radius R could be calculated as the circumferential length $L = 2\pi n R$ (cm) divided by the rotating speed V (cm/s). Therefore, the amount of excavation per second V_E (cm^3/s) can be given in the following equation as the amount of debris divided by the time:

$$V_E = \frac{W V}{\rho L} \tag{3}$$

In general, the amount of excavation V_E tends to increase with the increment of "p" and α, and to increase parabolically with the increment of the cutting space "S", but it decreases slightly with the increment of the unconfined compressive strength S_C (kN/cm^2).

From the regression analysis, the following experimental equation was derived:

$$V_E = 7.467\, p^{0.715} S^{1.470} \alpha^{0.642} S_C^{-0.019} \qquad (R=0.894) \tag{4}$$

From the above experimental test results, it was observed that the effect of the cutting space "S" on the amount of excavation V_E was greater than that of the penetration depth per round "p".

4. Considerations

4.1 Specific cutting energy and cutting space

The specific cutting energy was defined by Snowdon *et al.*[3] to be the energy, i.e., mean rolling force times length of cut, consumed in excavating unit volume of rock for comparing the relative efficiency of rock excavation using disc cutter bits. Here, the specific cutting energy E_S (kNcm/cm^3) could be calculated as the excavation power P (kNcm/s) divided by the amount of excavation per second V_E (cm^3/s) as follows:

$$E_S = \frac{P}{V_E} \tag{5}$$

The relationship between the specific cutting energy E_S and the cutting space "S" in three sets of penetration depth per round "p" of 0.1, 0.2 and 0.3 cm/round is shown in **Fig.4**, for an example of tip angle α of $\pi/4$ rad. In general, the specific cutting energy E_S (kNcm/cm^3) decreases hyperbolically with the increment of the cutting space S (cm) and it increases gradually with the increment of the penetration depth per round p (cm/round). E_S also increases with the increment of the unconfined compressive strength S_C (kN/cm^2). But there is hardly any significant effect of the tip angle α (rad) on E_S. From the regression

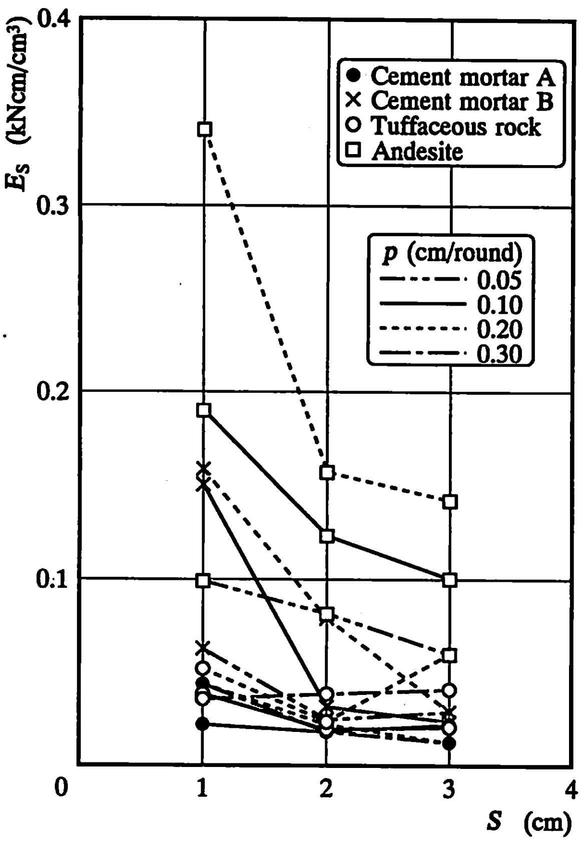

Fig.4 Relationship between specific cutting energy E_S and cutting space S ($\alpha = \pi/4$ rad)

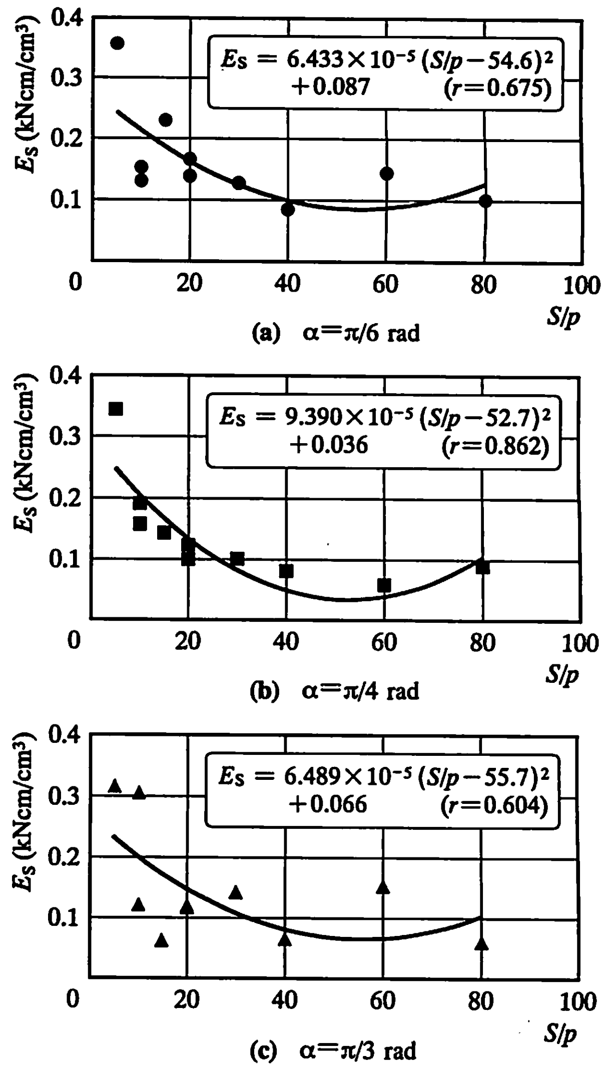

Fig.5 Relationship between specific cutting energy E_S and ratio of cutting space to penetration depth per round S/p for three kind of tip angles α (Andesite)

analytical results, the equation was derived as follows:

$$E_S = 0.105\, p^{0.576}\, S^{-0.869}\, \alpha^{-0.273}\, S_C^{0.880} \quad (R=0.889) \qquad (6)$$

To find the optimal excavation condition, the relationship between the specific cutting energy E_S (kNcm/cm³) and the ratio of the cutting space S (cm) to the penetration depth per round p (cm/round) were determined for an example of andesite, as shown in Figs. 5(a), (b) and (c). From the regression analysis, the equations could be derived as shown in the figures.

From the equations, it was observed that the average ratio of cutting space to penetration depth per round S/p for each tip angle to minimize the specific cutting energy E_S was 54.3 ± 1.2. That is, the most efficient excavation could be achieved at the minimum value of specific cutting energy of 0.036 kNcm/cm³, when the ratio S/p was designed to be 52.7 at $\alpha = \pi/4$ rad.

4.2 Comparison between plane and edge excavation

For the plane excavation using a disc cutter bit on several rock materials, the most efficient spacing/penetration ratio S/d to get a minimum specific cutting energy was proposed by Snowdon *et al.*[3] for different unconfined compressive strength. Therefore, to maximize the efficiency of the plane excavation for the mortar specimen A of the unconfined compressive strength σ_C of 10.7 MPa, the spacing/penetration S/d should be designed to be 3.0 for the plane excavation having one degree of freedom.

Table 2 Plane excavation test results for cement mortar A (S = 3.0 cm, p = 0.1 cm/round)

α (rad)	F_{XP} (kN)	F_{YP} (kN)	F_{ZP} (kN)	V_E (cm^3/s)	P (kNcm/s)	E_{SP} (kNcm/cm^3)
π/6	0.321	1.216	4.356	0.292	0.166	0.568
π/4	0.268	0.611	3.539	0.623	0.086	0.139
π/3	0.330	0.981	5.218	0.393	0.140	0.356

On the other hand, Gong *et al.*[4] presented that the optimum spacing/penetration S/d to minimize the specific cutting energy could be calculated using the fracture toughness[5] K_{CB} (MN/m$^{3/2}$) and the unconfined compressive strength σ_C (MPa) of rock sample as follows:

$$\left(\frac{S}{d}\right)_{\text{opt}} = 152\, K_{CB}{}^{0.54}\, \sigma_C{}^{-0.64} \qquad (R{=}0.951) \tag{7}$$

In the case of cement mortar A, the optimum spacing/penetration could be determined to be 11.2 by substituting the value of fracture toughness K_{CB} of 0.133 MN/m$^{3/2}$ and the value of unconfined compressive strength σ_C of 10.7 MPa into the above equation.

Here, several plane excavation tests using the same disc cutter bit were executed on the same mortar specimen A at the optimum spacing/penetration of 11.2 for the penetration depth d of 0.268 cm at the penetration depth per round p of 0.1 cm/round, the cutting space S of 3.0 cm and three sets of the tip angle α = π/6, π/4 and π/3 rad[6]. Table 2 shows the measured values of the peak tangential force F_{XP}, the peak lateral force F_{YP}, the peak normal force F_{ZP}, the amount of excavation V_E, the power of excavation P and the specific cutting energy E_{SP} in the plane excavation test for p = 0.1 cm/round and the tip angle α = π/6, π/4 and π/3 rad respectively. In this case, the specific cutting energy E_{SP} showed the minimum value 0.139 kNcm/cm^3 at α = π/4 rad.

It was observed that the average value of the peak tangential force F_{XP} =0.306 kN for the plane excavation was about 2.62 times that of 0.117 kN for the edge excavation, the average value of the peak lateral force F_{YP} = 0.936 kN for the plane excavation was about 4.65 times that of 0.201 kN for the edge excavation and the peak normal force F_{ZP} =4.371 kN for the plane excavation was about 2.31 times that of 1.891 kN for the edge excavation. The average amount of excavation V_E = 3.319, 2.828 and 4.465 cm^3/s at α = π/6, π/4 and π/3 rad for the edge excavation could be calculated as about 7.61, 6.49 and 10.24 times that of 0.436 cm^3/s for the plane excavation respectively. Therefore, it was clarified that the average specific cutting energy for the edge excavation from E_{SE} = 0.021 kNcm/cm^3 at α = π/4 rad to 0.019 kNcm/cm^3 at α = π/6 rad decreased to the value from 1/17 to 1/19 times the average specific cutting energy E_{SP} = 0.354 kNcm/cm^3 for the plane excavation.

As a result, it could be estimated that the method of the edge excavation for the cement mortar A and B, the tuffaceous rock and the andesite[7] might achieve the greater efficiency of excavation of 18, 41, 9 and 24 times that of the plane excavation, respectively.

5. Conclusion

The edge excavating performance on the free edge part of several rock specimens were investigated under a constant penetration depth per round and cutting space of a disc cutter bit. The measured specific cutting energy, i.e., the ratio of the excavation power to the amount of excavation per second of the edge excavation was compared with that of the conventional plane excavation method. The results obtained can be summarized as follows:

1) The peak tangential and normal forces in the edge excavation tend to increase with the increment of the penetration depth per round due to the increasing cross section of the part of penetration of the disc cutter bit, and with the increment of cutting space due to the enlargement of ruptured edge zone of the rock specimen. They also tend to increase with the increment of the unconfined compressive strength, but there is little significant affect of the tip angle.

2) The amount of excavation per second tends to increase with the increment of penetration depth per round and tip angle and to increase parabolically with the increment of cutting space, but it decreases slightly with the increment of the unconfined compressive strength.

3) The specific cutting energy decreases hyperbolically with the increment of the cutting space and increases gradually with the increment of penetration depth per round and the unconfined compressive strength, but there is no significant affect of the tip angle on it. The average ratio of the cutting space to the penetration depth per round to minimize the specific cutting energy is almost equal 54.3 for each tip angle.

4) The method of the edge excavation for the cement mortar A and B, the tuffaceous rock and the andesite might achieve the greater efficiency of excavation of 18, 41, 9 and 24 times that of the plane excavation, respectively.

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