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Optimum EPB TBM operation considering different foam injection conditions

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ABSTRACT

During EPB TBM tunneling, the adequate usage of additives is an essential factor for successful TBM projects. In recent years, in spite of a number of experimental studies for clarifying the behavior of conditioned soils, such efforts have not been fully successful yet. In this paper, the laboratory-scaled EPB TBM excavation apparatus was devised in order to evaluate the effect of foam injection on EPB TBM operation. A series of experiments utilizing the apparatus were performed by adjusting representative foam injection parameters such as FIR (Foam Injection Ratio), FER (Foam Expansion Ratio) and C_f (Surfactant Concentration). Experimental results show that the considerable amount of foam injection does not always guarantee high performance of EPB TBMs, and there is the optimum foam injection condition for the specific ground conditions.

1. INTRODUCTION

Earth Pressure Balance (EPB) shields are the most commonly adopted type of the tunnel boring machine (TBM) to cope with tunnelling in a variety of geological conditions, especially soft grounds. During excavation, the chamber of EPB TBM is filled with excavated soil in order to support the earth and water pressure in front of the tunnel face. However, when the TBM chamber is filled with muck in a state of insufficient consistency or permeability, many adverse effects to the TBM advance

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could occur. For example, inadequate face pressure can be generated by nonhomogeneous muck in the chamber, which obstructs maintaining the stability of tunnel face. Also, the excessive load and abrasion to the machine could be provoked, and it extends a construction period with the frequent occurrence of TBM downtime. Hence, in order to prevent the aforementioned construction risks, additives such as foam, polymer and bentonite are injected during TBM advance for improving mechanical and hydrological muck behavior. For these reasons, EPB TBM tunnelling with the appropriate soil conditioning is essential for pursuing successful TBM projects.

Accordingly, a number of studies have been carried out to determine the effect of injecting additives in TBMs from the '90s. Especially, in case of the foam, which is cheap and most widely used compared to other additives, there has been many attempts to examine the behavior of foamed soil through typical laboratory tests such as slump, compressibility and permeability test (Budach, 2012; Budach and Thewes, 2015; Maidl, 1995; Peila et al., 2009). In addition, numerous experimental studies were conducted to investigate the effect of foam injection using lab-scaled equipment that reproduces a part of TBM such as the chamber and screw conveyor (Jakobsen et al., 2013a; Jakobsen et al., 2013b; Salazar et al., 2018; Vinai et al., 2008).

Despite these achievements, the concept of soil conditioning in TBM has been established relatively in recent years. Moreover, the previous studies have not been scientifically performed, and thus the accurate behavior of conditioned soil is not fully identified at this point. Therefore, in this paper as a part of succeeding effort, a lab-scaled excavation apparatus was devised, and a series of excavation tests were carried out with varying soil conditioning parameters for examining the effect of injection conditions on the TBM performance when the foam is injected as additives.

In general, the representative soil conditioning terminologies adopted for controlling foam injection according to the monitored machine data such as the torque, thrust force and advance rate during EPB TBM excavation can be summarized as follows (EFNARC, 2005).

$$FIR\ (Foam\ Injection\ Ratio) = \frac{V_f}{V_{es}} \times 100\% = \frac{V_l + V_a}{V_{es}} \times 100\% \quad (1)$$

$$FER\ (Foam\ Expansion\ Ratio) = \frac{V_f}{V_l} = \frac{V_l + V_a}{V_l} \quad (2)$$

$$C_f\ (Surfactant\ Concentration) = \frac{V_{sf}}{V_{sf} + V_w} \times 100\% = \frac{V_{sf}}{V_l} \times 100\% \quad (3)$$

where, V_f = volume of foam; V_l = volume of the surfactant liquid; V_a = volume of air; V_{es} = in-situ volume of soil to be excavated; V_{sf} = volume of surfactant; and V_w = volume of water in the surfactant liquid.

FIR represents the foam injection ratio that refers to the ratio of volume of injected foam to the volume of soil to be excavated. FER is the foam expansion ratio that indicates the ratio of foam volume to the surfactant liquid volume. Finally, C_f (surfactant concentration) refers to the concentration of diluted surfactant in the surfactant liquid, which is a mixture of the surfactant and water.

As mentioned above, the primary purpose of this paper is to investigate the effect of foam injection parameters (FIR, FER, C_f) on TBM performance, by adjusting foam injection parameters during performing a series of lab-scaled excavation tests. Subsequently, the mechanical resistance and wearing on TBMs, and the workability of conditioned soil were evaluated by analyzing the monitored torque data, the weight loss of aluminum cutter bits and the slump value of discharged muck.

2. LAB-SCALED EXCAVATION TEST

2.1 Test Apparatus

In this paper, a lab-scaled excavation test apparatus was devised in order to simulate the advance of EPB shield TBM in the laboratory. Fig. 1 shows the overall configuration of the devised lab-scaled excavation test apparatus. The equipment is mainly composed of an excavation chamber, a blade with five cutter bits, a screw conveyor for discharging muck, a three-level stacked mold for compacting a soil specimen and a foam generator. It can simulate the excavation mode of EPB TBM advance: excavation in the vertical direction by rotating the blade, soil conditioning with the foam and extraction of the excavated soil through the screw conveyor. In the excavation stage, the machine penetrates the prepared specimens by rotating the blade. On the blade, five aluminum cutter bits are placed with at different distances from the axis of rotation. Besides, the foam generator system supplies the constant quality of foam by injecting a designated amount to increase soil consistency, and to prevent the apparatus from exceeding its capacity during excavation. In order to achieve this, pipes are embedded inside the rotary shaft of the blade, which conveys the generated foam toward the direction of advance. During excavation, the torque meter installed at the upper part of the excavation chamber records torque data. Finally, aluminum cutter bits mounted on the blade are designed to be detached, and it allows to measure the weight of cutter bits before and after the experiment.

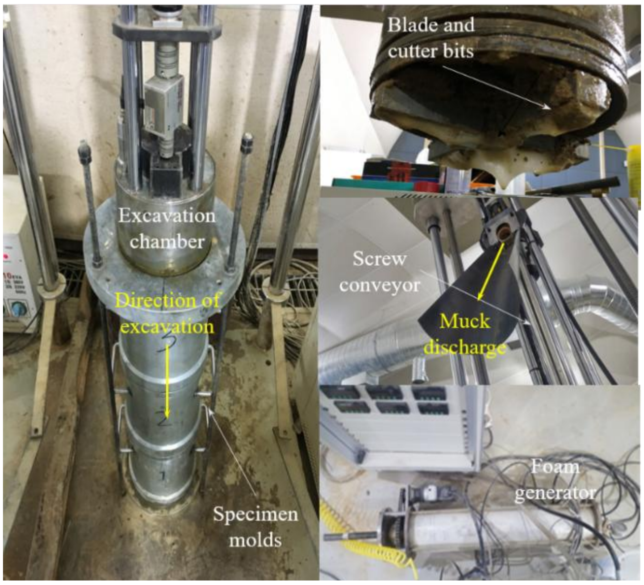

Fig. 1 Lab-scaled excavation test apparatus for evaluating effect of foam injection

2.2 Properties of Specimen and Foam

For the experiment, artificial sandy soil was prepared by the sieve analysis. The sample was composed of artificial silica sand (75%) and fine contents (15%). Illite was selected to satisfy the designed fine particle fraction (d < 0.075 mm). The particle size of artificial silica sand was kept less than 2 mm to compensate the reduced scale of the test apparatus, especially the diameter of screw conveyor (40 mm). The grain-size distribution curve of the specimen adopted in this study is shown in Fig. 2. Before all the experiments, the specimen was uniformly compacted in five equal layers in the three-level stacked mold with 10% of water content and 1.92 to 1.93 t/m^3 of dry unit weight in order to maintain identical sample preparation.

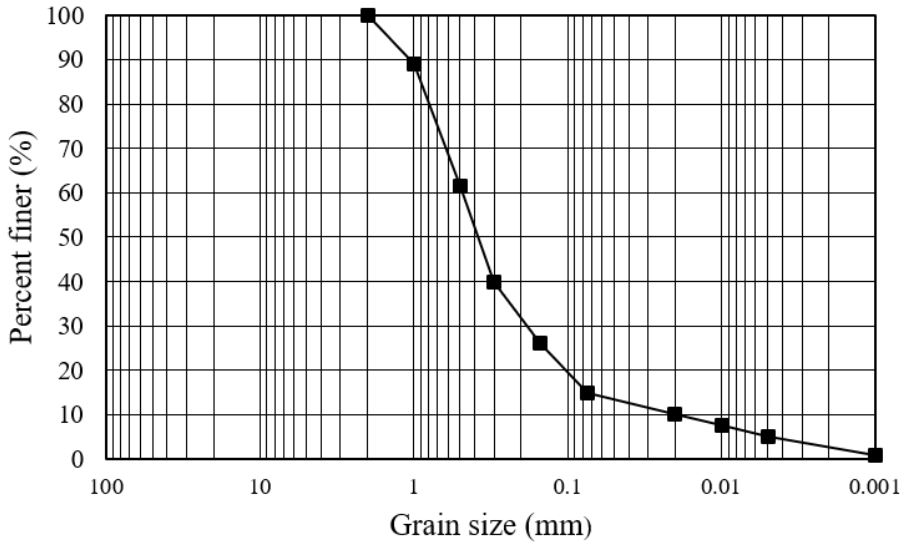

Fig. 2 Particle size distribution of artificial silica sand specimen

For the foam surfactant, MAK foam, produced by MAK Tech, which is commonly applied in EPB TBM tunnelling projects in South Korea, was adopted as a foaming agent. Fundamental properties of the foam surfactant are summarized in Table 1.

Table 1. Property of foam surfactant (MAK foam)

Product	Apparent color	Specific gravity	Viscosity (cP)	pH
MAK foam	Bright brown	1.00 ~ 1.10	Max. 70	8 ~ 11

2.3 Test Conditions

The main purpose of the current study is to evaluate the TBM performance corresponding to foam injection parameters. Operating conditions of the experiment were kept constant to eliminate mechanical factors in the test: i.e., the penetration rate of 45 mm/min, the blade rotation speed of 10 rpm and the screw conveyor speed of 120 rpm. A total of 13 experimental cases were performed with different foam injection parameters as summarized in Table 2. For selecting the case, preliminary slump tests

(ASTM C143, 2015) were conducted, which is a convenient and rapid tool for determining the optimum workability of conditioned soil. Because it is generally known that the conditioned soil with a slump value of 10 to 20 cm possesses acceptable workability for EPB TBM tunneling (Peila et al., 2009), the foam injection condition satisfying this criterion was selected as the standard case for comparison (Case 3, 18.9 cm of slumps). Based on this case, conditioning parameters of the other cases were determined to evaluate the effect of FIR (Case 1 to 5), FER (Case 3 and 6 to 9) and C_f (Case 3 and 10 to 13), respectively.

Table 2. Experimental cases for evaluating effect of foam injection parameters

Case #	FIR, Foam Injection Ratio (%)	FER, Foam Expansion Ratio	C_f, Surfactant Concentration (%)
1	40	15	3
2	45	15	3
3	50	15	3
4	55	15	3
5	60	15	3
6	50	10	3
7	50	12.5	3
8	50	17.5	3
9	50	20	3
10	50	15	1
11	50	15	2
12	50	15	4
13	50	15	5

3. TEST RESULTS

3.1 Effect of Foam Injection Ratio (FIR)

Fig. 3 shows the torque data obtained during excavation tests with varying FIR from 40% to 60% at 5% intervals (Case 1 to 5). Since all of the excavation was conducted in the vertical direction, and the bottom of the mold was closed by a steel plate, the measured torque value slightly increased as the excavation proceeded. When the excavation chamber passed through the connected section of each stacked mold, the discontinuous drop of torque data appeared. However, despite these unavoidable experimental noises, the overall tendency can be identified from the measured torque for examining the effect of conditioning parameters. As shown in Fig. 3, it can be seen that the measured torque decreases with the increment of FIR. However, when FIR exceeds 50%, the reduction in the measured torque is noticeably moderated. Therefore, it can be found that the optimum FIR value is about 50% for reducing mechanical resistance with the least amount of foam injection.

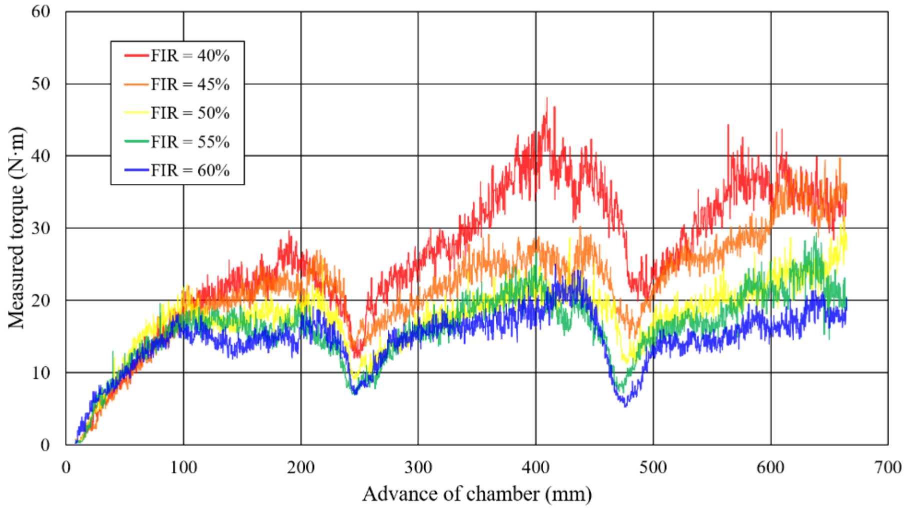

Fig. 3 Measured torque values according to advance of chamber with different FIR

Fig. 4 shows the relationship between the FIR values and the abrasion of the outermost cutter bit. Because the travel distance of the outermost cutter bit was the longest during the test, the largest wearing should occur at the outermost cutter bit, and thereby the trend of weight reduction according to different conditioning parameters was prominent. Similar to the trend of the measured torque, Fig. 4 reveals that the measured wearing decreases steadily as the FIR value increases. However, at FIR values above 50%, the efficiency of wearing reduction by the foam injection somewhat decreases. Therefore, it can be seen that 50% of FIR is the optimal foam injection ratio, which can achieve effective mechanical wearing reduction with the minimal foam injection.

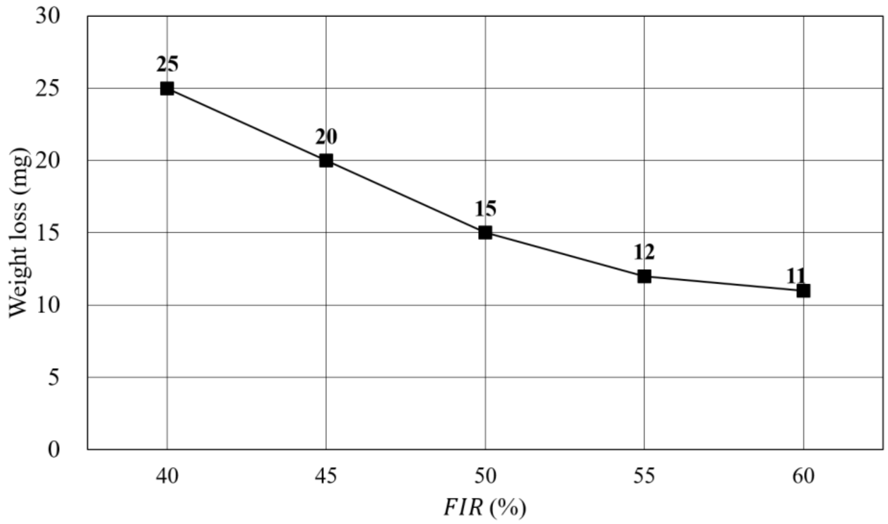

Fig. 4 Measured weight loss of outermost cutter bit with different FIR

Fig. 5 gives the relation between the slump value and FIR by performing the slump test for the discharged muck after each experiment. As illustrated in Fig. 5, the slump value significantly increases with FIR until 50% of FIR. In other words, for the slump value of conditioned muck, a typical foam injection ratio exists, which causes remarkable changes in plastic flowability of the muck. As a result, it can be seen that the optimal conditioning can be achieved under 50% to 60% of FIR based on 10 to 20 cm of the slump value criterion.

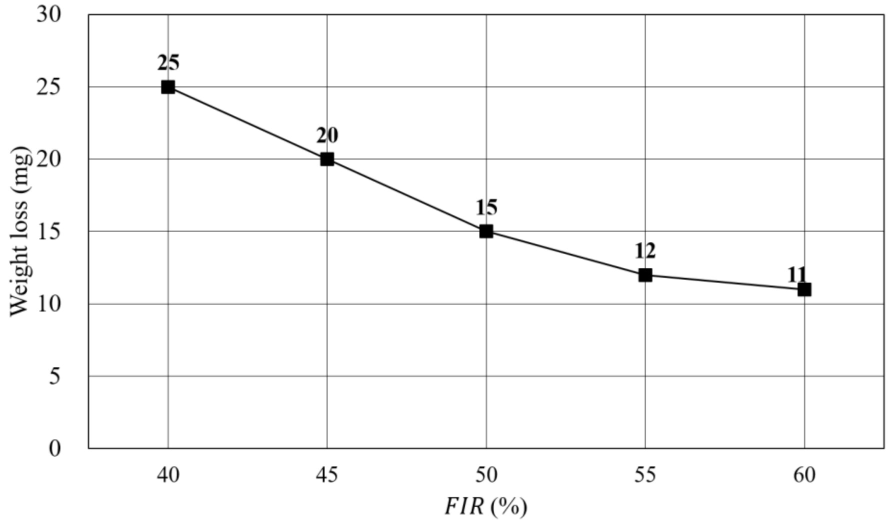

Fig. 5 Slump value of discharged muck with different FIR

3.2 Effect of Foam Expansion Ratio (FER)

The effect of FER was evaluated by varying the FER values from 10 to 20 at 2.5 intervals (Case 1 and 6 to 9). Fig. 6 shows the torque data obtained during the excavation tests with different FER. It is noted from the results that as FER decreases, the measured torque decreases, which is caused by increasing the injected surfactant liquid volume relative to air volume at the same value of FIR.

However, contrary to the effect of the FIR parameter described in the previous section, the reduction in the measured torque becomes almost marginal when FER is smaller than 15. Therefore, it is considered that the optimum FER for reducing mechanical resistance is observed around 15. Besides, compared to FIR, FER shows a clear optimal injection value for enhancing TBM performance in a specific ground condition.

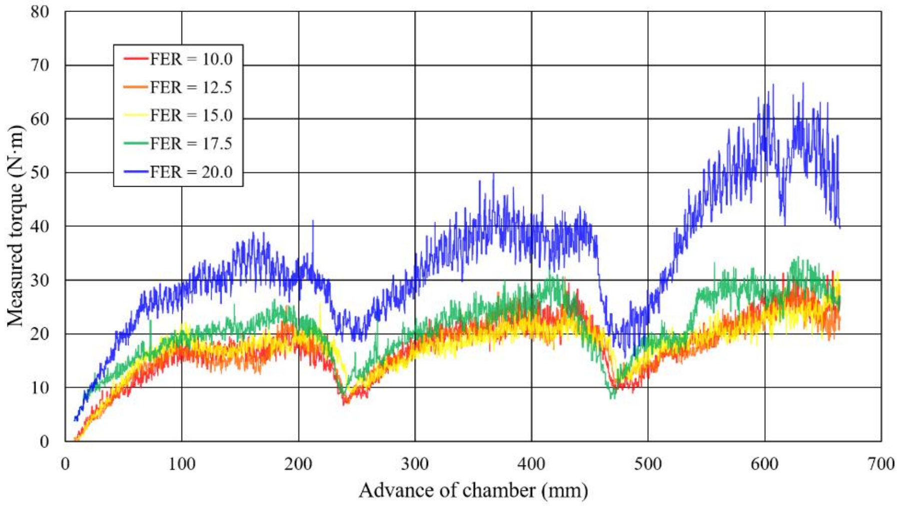

Fig. 6 Measured torque values according to advance of chamber with different FER

Fig. 7 presents the relationship between the FER values and the abrasion of the outermost cutter bit, which shows a similar trend to the measured torque data. When FER is less than 15, the efficiency of wearing reduction by the foam injection slightly decreases. In addition, a clear optimum FER value is not shown, as indicated by the measured torque data with different $FER's$ in Fig. 6. Nevertheless, the result still implies that the optimum wearing reduction can be attained around 15 of FER.

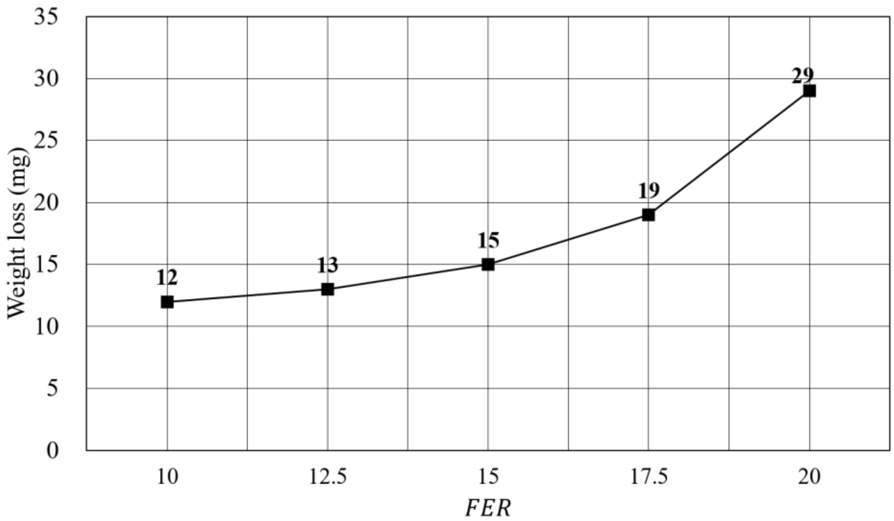

Fig. 7 Measured weight loss of outermost cutter bit with different FER

Fig. 8 shows the measured slump value corresponding to the FER value. As FER increases, the slump value gradually decreases, and then rapidly drops when FER becomes larger than 15. It also shows that there is a specific FER exists, similar to the FIR parameter, which induces a distinct change in workability of the muck. Accordingly, it can be found that the optimal workability also can be obtained at 15 of FER or less based on 10 to 20 cm of the slump criterion.

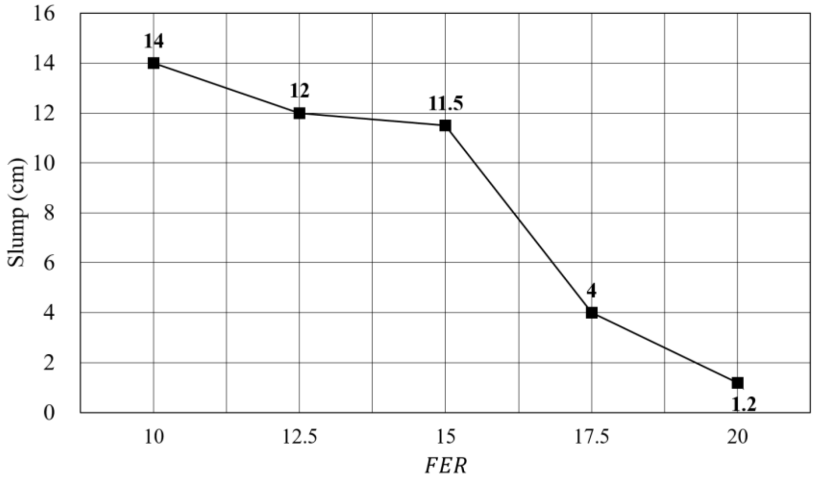

Fig. 8 Slump value of discharged muck with different FER

3.3 Effect of Surfactant Concentration (C_f)

For evaluating the effect of surfactant concentration, C_f was changed from 1% to 5% at 1% intervals (Case 1, 10 ~ 13). Fig. 9 shows the measured torque during the excavation tests. The C_f parameter shows less significant influence on the reduction in the torque value compared with FIR or FER. Especially, when C_f is larger than 2%, there are negligible effects of C_f on the torque reduction. Therefore, a surfactant concentration of at least 2% can provide sufficient TBM operation with fairly reduced mechanical resistance.

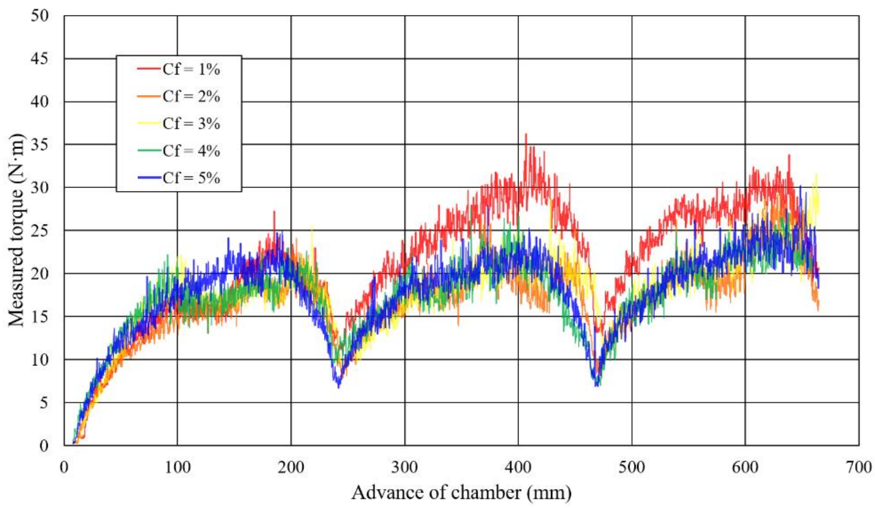

Fig. 9 Measured torque values according to advance of chamber with different C_f

Fig. 10 presents the measured weight loss of the outermost cutter bit after each excavation test corresponding to the C_f value. As a result of the measured torque with different C_f, the acceptable abrasion reduction can be secured above 2% of C_f.

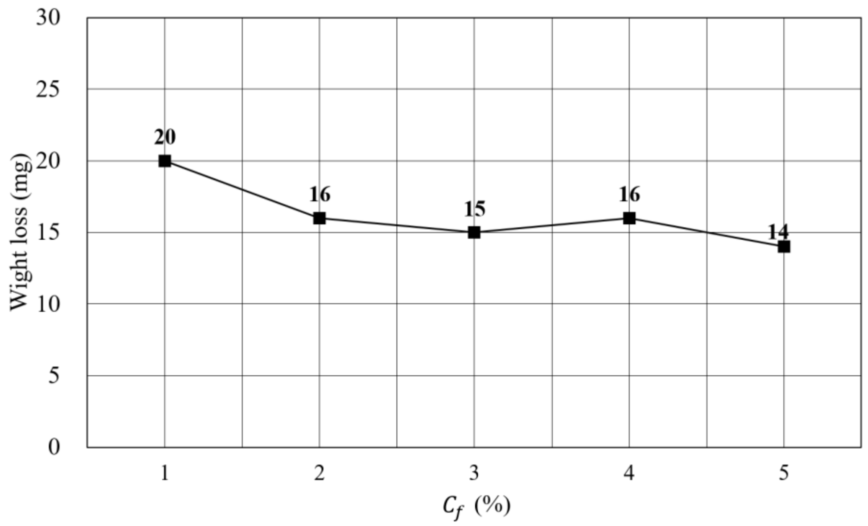

Fig. 10 Measured weight loss of outermost cutter bit with different C_f

Fig. 11 illustrates the slump values of the discharged muck according to the C_f values. Since the C_f value does not show noticeable influence on plastic flowability compared to the FIR and FER variable, there are no sudden changes in the relation between the slump value and C_f. It is shown that sufficient workability of the excavated soil will be guaranteed above 3% of C_f.

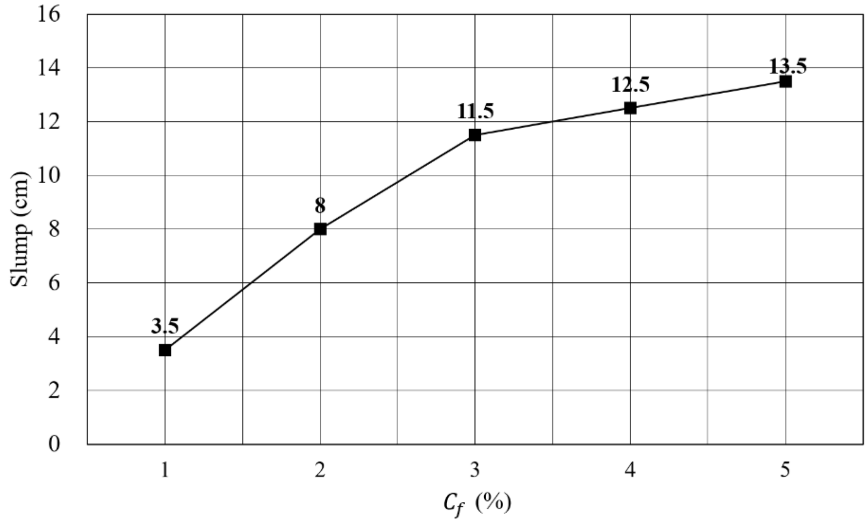

Fig. 11 Slump value of discharged muck with different C_f

4. CONCLUSIONS

In this study, in order to analyze the influence of foam injection conditions on the performance of EPB TBM, a laboratory excavation apparatus was designed, and a series of experiments were performed with the artificial sand specimen. All of the experiments were carried out by varying the FIR, FER and C_f value, which are generally adopted for regulating the foam injection in EPBs. In this paper, the measured torques, the abrasion of aluminum cutter bits and the slump values were compared to estimate the mechanical resistance and wearing during EPB TBM operation, and the workability of conditioned soil, respectively. The key findings of this study can be summarized as follows.

1) As the FIR value increases, the overall measured torque and the degree of wearing decrease. However, when FIR increases larger than 50%, the effect of FIR becomes less significant. In consideration of workability, the slump value criterion was satisfied with 50 to 60% of FIR.

2) With respect to FER, the overall measured torque and the abrasion decrease with a decrease in FER. Especially, when FER is less than 15, the measured torque becomes almost identical to each other with the similar level of wearing reduction. In terms of workability, the slump criterion was satisfied when FER is less than 15.

3) Concerning the C_f parameter, when C_f is larger than 2%, there is little effect of C_f on the torque and wearing reduction. Regarding workability, the slump criterion was satisfied above 3% of C_f.

4) Based on the experimental results, it can be concluded that the optimal TBM performance can be achieved under the foam injection conditions of FIR = 50%, FER = 15 and C_f = 3% when excavating the artificial sand soil considered in this paper. It is noted that there is an optimum foam injection condition enhancing the EPB TBM performance in a specific ground condition. Therefore, when designing an EPB TBM tunnelling project, the optimum foam injection conditions should be carefully determined by the laboratory experiments as suggested in this paper, which can reduce construction risks and costs.

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