KSCE Journal of Civil Engineering (2019) 23(4):1829-1838
Copyright ⓒ2019 Korean Society of Civil Engineers
DOI 10.1007/s12205-019-1484-1

Tunnel Engineering
pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Soil Conditioning of Weathered Granite Soil used for EPB Shield TBM: A Laboratory Scale Study

Tae-Hwan Kim*, Byung-Kyu Kim, Kang-Hyun Lee***, and In-Mo Lee******

Received July 26, 2018/Revised October 24, 2018/Accepted December 18, 2018/Published Online January 30, 2019

Abstract

Soil conditioning is one of the key factors for successfully excavating tunnels by utilizing the Earth Pressure-Balanced (EPB) shield Tunnel Boring Machine (TBM) for increasing the tunnel face stability and extraction efficiency of the excavated soils. Since the characteristics of weathered granite soil, abundant in the Korean peninsula (also in Japan, Hongkong and Singapore), is different from those of either sand or clay, conditioning agents applicable to either sand or clay cannot be directly used for the weathered granite soil. In this study, conditioning agents are mixed with the weathered granite soils and the properties of the resulting mixture are evaluated in a laboratory-scale experiment to derive and propose the most suitable conditioning agent as well as the most appropriate agent mix ratios. It was confirmed through an experimental study that the EPB shield TBM could be operated in good condition by injecting 22–67% foam depending on the water content of the excavated soils. In addition, it was also found that the range of particle size gradation of the weathered granite soils, under which the conditioning agent foam can be applicable, is wider than the existing application ranges proposed thus far for properly operating the EPB shield TBM.

Keywords: *conditioning, Earth Pressure-Balanced (EPB), granite, foam, workability, permeability, compressibility*

1. Introduction

An Earth Pressure-Balanced (EPB) shield Tunnel-Boring Machine (TBM) achieves face stability during tunneling operation by filling the working chamber with the excavated soil and applying chamber pressure, called face support pressure, at the back of the cutter head. Many studies have been underway with respect to the soil conditioning in which various soils are mixed with conditioning agents to expand the application range of an EPB shield TBM or to derive an optimum mix ratio of the conditioning agent for a given soil (Budach and Thewes, 2015; Peila *et al.*, 2013; Martinelli *et al.*, 2015). The appropriate mix ratio of the conditioning agent added to the excavated soil can be derived through trial-and-error, although the mix ratio may vary depending on the characteristics of the soil even if the particle-size gradation curve is similar. In particular, since the characteristics of the weathered granite soil, which is abundant in the Korean peninsula (also abundant in Japan, Hongkong and Singapore), are different from those of either sand or clay, the conditioning agents applicable to either sand or clay cannot be directly used in weathered granite soil. In this study, conditioning agents are mixed with the weathered granite soil of the Korean peninsula, and the properties of the resulting mixture are evaluated in a laboratory-scale experiment to derive and propose the most suitable conditioning agent as well as the most appropriate agent mix ratios.

After conditioning, the behavior of the excavated soil, which provides the face support pressure in the working chamber, is significantly different. Many studies have been conducted to evaluate the properties of conditioned soil, such as workability, permeability coefficient, and compressibility, as these are closely related to the face stability and the extraction efficiency during tunnel operation. Several researchers have conducted slump tests to evaluate the workability of the conditioned soil, and in general, the workability was found to be reasonable when the slump value was between 10 and 20 cm (Budach and Thewes, 2015; Peila *et al*., 2009; Budach, 2012; Pena Duarte, 2007; Quebaud *et al*., 1998). Furthermore, Wilms (1995) suggested the maximum value of the permeability coefficient was required to be effectively functioning as the excavated material to prevent groundwater inflow into the working chamber from the tunnel face when tunneling below the groundwater level. Laboratory-scale studies have also been conducted to evaluate the permeability coefficient of conditioned soils (Borio and Peila, 2010; Budach and Thewes, 2015). In addition, Maidl (1995) proposed a laboratory-scale

---

*Ph.D. Candidate, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 02841, Korea (E-mail: kth1226@korea.ac.kr)
**Member, Ph.D. Candidate, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 02841, Korea (E-mail: orbitm23@korea.ac.kr)
***Member, Deputy Principal Researcher, Safety & Disaster Prevention Research Division, Korea Expressway Corp. Research Institute, Hwaseong 18489, Korea (E-mail: tunnelslope@ex.co.kr)
****Member, Professor, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 02841, Korea (Corresponding Author, E-mail: inmolee@korea.ac.kr)

experimental method for measuring the compressibility. The minimum requirement of the compressibility of the conditioned soil was proposed to be functioning as the appropriate chamber materials during EPB shield TBM tunneling so that the face support pressure is applied uniformly to the tunnel face in the working chamber and the excavated materials are efficiently extracted from the chamber through screw conveyor (Budach, 2012). Budach and Thewes (2015) performed a laboratory experiment to obtain the compressibility values of various mixtures of sandy soils. Recently, Mori *et al.* (2018) conducted a study on the effect of increasing the chamber pressure on the compressibility of the conditioned soil by obtaining the relationship between the ratio of the void ratio (e) of the conditioned soil divided by the maximum void ratio (e_{max}) of a non-conditioned soil and the chamber pressure.

In this study, conditioning agents are mixed with the weathered granite soil of the Korean peninsula, and the properties (i.e., workability, permeability coefficient, and compressibility) of the resulting mixture are evaluated in a laboratory-scale experiment to derive and propose the most suitable conditioning agent as well as the most appropriate agent mix ratios. Moreover, the ranges of particle size gradation in which the foam can be used as the conditioning agent are also studied in this paper. Since the particle breakage of the weathered granite soil is more significant than that of the sand, the application range of soil sizes for usage of the foam as the conditioning agent might be different from that proposed thus far (Budach and Thewes, 2015).

Conditioning agents used for the EPB shield TBM tunneling include foam, water, polymer, bentonite, anti-clay polymer, water absorbing polymer, etc. The conditioning agents are selected in each job site based on the soil type, groundwater level, and characteristics of the EPB shield TBM. The objectives of soil conditioning during the EPB shield TBM tunnel operation are as follows:

1) Sufficient workability can be obtained through the plasticization and fluidization of the excavated soil, and this facilitates a smooth flow from the cutter head to the screw conveyor.
2) Groundwater inflow into the working chamber can be prevented by decreasing the permeability coefficient of the excavated soil in the working chamber.
3) A uniform face-support pressure can be maintained and controlled by increasing the compressibility of the excavated soil in the working chamber.
4) The torque of the cutter head and screw conveyor and the friction between the conditioned soil and the machine parts of the TBM can be reduced by decreasing the internal friction angle.

Foam, which is composed of water, air, and a foaming agent, was used in this study, as it is the most representative and economical conditioning agent. Foams are produced when foaming agents are diluted in water according to the target concentration factor and sprayed together with air using a foam generator. Such foams are usually sprayed from a device attached on the EPB shield TBM to the front of the cutter head, inside the working chamber, and to the screw conveyor.

Foams have different properties depending on the chemical composition of the foaming agent, concentration, and expansion ratio. When foams are generated, polymers can also be added to improve the stability, strength, and degree of lubrication of the foams. The parameters used to describe the qualities of foams and the associated equations are as follows (Budach and Thewes, 2015):

$$c_f = \frac{Q_f}{Q_L} \times 100(\%) \tag{1}$$

$$FER = \frac{Q_F}{Q_L} \tag{2}$$

$$FIR = \frac{Q_F}{Q_s} \times 100(\%) \tag{3}$$

$$PIR = \frac{Q_P}{Q_s} \times 100(\%) \tag{4}$$

$$LIR = \frac{FIR}{FER} + PIR(\%) \tag{5}$$

where c_f is the concentration of the foaming agent within foaming liquid (%), FER is the foam expansion ratio (dimensionless), FIR is the foam injection ratio (%), PIR is the polymer injection ratio (%), LIR is the liquid injection ratio (%), Q_f is the flow rate of the foaming agent (m^3/min), Q_F is the flow rate of foam at support pressure (m^3/min), Q_L is the flow rate of the foaming liquid (foaming agent + water) (m^3/min), Q_P is the flow rate of the polymer suspension (m^3/min), and Q_S is the flow rate of the excavated soil (m^3/min), respectively.

Among the properties of the conditioned soil, the workability, permeability coefficient, and compressibility are by far the most important factors that must be evaluated when choosing an agent as the conditioning agent for a given soil for an effective EPB shield TBM operation. The methods for determining these properties are as follows.

A slump test is a test method used in concrete engineering in accordance with ASTM (2015), which is a method employed in the field of soil conditioning to evaluate the plasticity and/or workability of a conditioned soil. As mentioned in the previous section, it was found that sufficient workability is achieved if the slump value of the conditioned soil is between 10 cm and 20 cm. Therefore, this study attempts to derive the optimum mix ratio required to obtain a slump value between 10 cm and 20 cm by appropriately mixing conditioning agents with weathered granite soils.

The permeability coefficient (*K*) of the weathered granite soil (not conditioned) is commonly obtained via a constant head permeability test based on ASTM (2006), and the permeability coefficient of the conditioned soil can also be determined using a similar test method. According to Wilms (1995), the permeability coefficient of the conditioned soil existing in the working chamber of the EPB shield TBM, when tunneling below the groundwater level, must be lower than $K = 1 \times 10^{-3}$ cm/s to prevent the groundwater inflow from the tunnel face to the chamber. Therefore, in this study, the samples were mixed at the appropriate mix ratio obtained through a slump test and the permeability coefficient was measured by conducting a permeability test. Then, a long-term behavior of the permeability coefficient was observed over a longer period of time taking into account the view that the low permeability has to be maintained for an extended period of time (e.g., 90 min or longer) to accommodate the time for the segment assembly and other unknown times delaying the TBM operation (Budach, 2012).

One of the reasons that the conditioned soil should have a high compressibility value, besides the purpose of uniformly applying the face support pressure, is to make the excavated material maintain a relatively high damping ratio in order to appropriately respond (as a cushion) to the irregular pressure changes inside the working chamber, which might occur from the interactive action between the penetration speed of the TBM cutter head and the extraction capacity of the screw conveyor (Budach and Thewes, 2015). As mentioned above, Maidl (1995) proposed a test method to obtain the compressibility value by measuring the change in volume by applying an air pressure after filling a transparent cylinder with the conditioned soil. Further, Budach (2012) proposed that the conditioned soil must have a compressibility of 1.9%/0.5 bar in order to operate the EPM shield TBM successfully. Therefore, in this study, the volumes of the conditioned soil subject to the variation of the confining pressures were measured to check the suitability of the conditioning agent added to the weathered granite soil from the viewpoint of compressibility.

The void ratio of soil is related to the compressibility, and in this regard, it has been shown that the void ratio of conditioned sand mixed with foam in the tunneling chamber is usually larger than the maximum void ratio of unconditioned natural sand, and this reduces the friction of the cutter head (Bezuijen *et al*., 1999). Recently, the changing behavior of conditioned soil from the condition $e > e_{max}$ to $e < e_{max}$ was researched instead of simply focusing on the condition $e > e_{max}$ (Mori *et al*., 2018). In that study, as the chamber pressure was increased, the void ratio had the possibility of changing from the condition $e > e_{max}$ to $e < e_{max}$, and it was confirmed that the shear strength of the conditioned soil increased due the increase in the effective stress when $e < e_{max}$. Therefore, in this study, the void ratio (e) of the conditioned soil subject to the chamber pressure was compared with the maximum void ratio (e_{max}) of the weathered granite soil (unconditioned) for assessing the behavior of the conditioned granite soil with the increase in chamber pressure.

2. Experiments

2.1 Experimental Equipment and Process

The most important equipment for performing conditioning agent mixing experiments using foams is the foam generator. For this study, the laboratory-scale foam generator shown in Fig. 1(a) was produced, which was able to control the Foam Expansion Ratio (FER) via gauges governing the amount of foam solution and air volume, respectively. Since the Foam Injection Ratio (FIR) is proportional to the ratio of the volume of foam to the volume of excavated soil, consistent injection per unit time is important for keeping the FIR constant The results of an experiment to measure the foam injection amount per second at each expansion ratio are shown in Fig. 2. In this experiment, the initial water content of each weathered granite soil sample was set to 10% considering the fact that the natural water content of the saturated soil is more than 11% and less than 21% in most cases. Then, after foams were generated for each FIR, additional water was added up to a designated water content and these were mixed together with an agitator. Immediately after mixing, the slump test, permeability test, and compressibility test were conducted, respectively. The detailed experimental methods are described below.

The slump tests were conducted based on ASTM (2015), which is the standard used in concrete engineering. The equipment used for the permeability test is shown in Fig. 1(b). The experimental process was similar to that of the constant head permeability test. In this study, the head difference was calculated by measuring the top and bottom water pressures when water is flowing from the top to the bottom. The calibration result for the water pressure


(a) (b)

Fig. 1. Experimental Apparatus used in Laboratory-scale Tests: (a) Laboratory-scale Foam Generator, (b) Permeability Test Apparatus

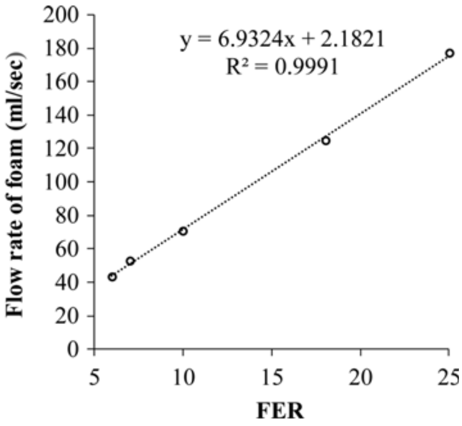


Fig. 2. Flow Rate of Foam versus FER

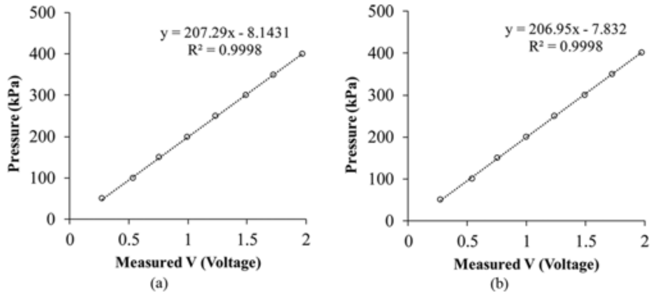


Fig. 3. Water Gauge Calibration Results: (a) Top Water Gauge, (b) Bottom Water Gauge

gauge is shown in Fig. 3. In this permeability test, attention should be paid so that the filters installed both at the top and bottom of the sample are fully saturated before the test, because the permeability coefficient is low enough to be easily affected by the filter saturation status. Furthermore, since the foam itself may also be drained over a long period of time in the experiment, long-term changes in the permeability coefficient were observed over a longer period.

A transparent cylinder was used for the compressibility measurement. The air pressure was increased by an amount of 0.5 bar in each step, and then the change in the volume of the conditioned soil was measured to obtain the compressibility of the conditioned soil with respect to the confining pressure. After the compressibility test, the conditioned soil was oven-dried in order to obtain its void ratio (*e*).

2.2 Weathered Granite Soils and Foams used in Experiments

2.2.1 Characteristics of Weathered Granite Soils

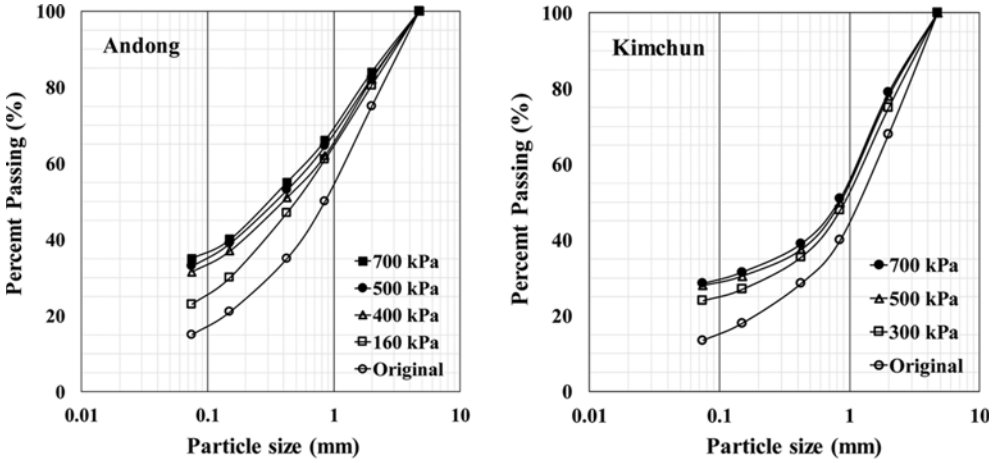
The weathered granite soil is a representative residual soil physically and chemically weathered from the rock origin of granite and/or granitic gneiss that occupies more than two-thirds of the Korean peninsula. The generally understood characteristics of this soil are as follows.

First, the particle size gradation of the weathered granite soil has a wide spectrum, from coarse-sized particles (sand-like) to fine-sized particles (clay-like) depending on the rock origin and weathering process; however, the characteristics of these soils are unique, neither sand nor clay. Second, the particle crushing characteristics of the weathered granite soil appear more dominant compared to that of the sand. This phenomenon will be discussed in more detail at the end of this section. Third, the weathered granite soil has a complicated relationship with water depending on the water content and/or degree of saturation. Firstly, the natural water contents of the saturated granite soils (below the groundwater table) in Korea are within the range of 11–21% in most cases (POSCO E&C, 2010). Particle crushing possibility will increase if the water content of the granite soils is increased by adding water, resulting in an increase in the compressibility and lowering the shear strength (Ham *et al.*, 2004).

Since the soil conditioning process is the most affected by fine particle contents passing through the #200 sieve, among the many geotechnical characteristics, this study focuses on the particle crushing characteristics of the weathered granite soils. Furthermore, since the weathered granite soil exhibits very different behaviors depending on the water content, the conditioning-agent mixing ratio will be derived by controlling the water content along with the foam itself.

In terms of the particle-crushing characteristics, the main causes of particle crushing in the weathered granite soil may be due to fissures and/or voids existing in the soil particle itself when subject to confining pressures; the particle-crushing phenomenon may be more dominant with more mineral contents of mica and feldspar rather than quartz (Lee *et al.*, 2013).

Lee *et al.* (2013) investigated the crushing characteristics of the weathered granite soil versus the degree of weathering by artificially weathering granite soil via a hydrofluoric acid solution. Standard compaction experiments were then conducted using



(a) (b)

Fig. 4. Particle Crushing when subjected to Confining Pressure: (a) Sample 1 (Andong), (b) Sample 2 (Kimchun)

samples produced with varying degrees of weathering. After the experiments were completed, the particle-size gradation curve was obtained to determine the change in fine particle contents passing through the #200 sieve depending on the water content. The results showed that the fine particles increase from 1.6 % to up to 9.6 % by compaction. The particle crushing effect was less serious with the increase in the weathering process; its effect was the most serious when the water content of the soil was around the optimum moisture contents.

Kim *et al*. (1994) analyzed the engineering characteristics of the weathered granite soil by performing the triaxial compression test. The particle-size gradation curve was drawn after conducting an isotropic consolidation test, and is shown in Fig. 4; it indicates that the particle size becomes smaller as the applied confining pressure is increased, in particular, the percentage passing through the #200 sieve increases. This figure clearly indicates that the particle crushing is significant when subjected to confining pressures.

2.2.2 Properties of Soil Samples and Foams

Two weathered granite soils are used in this experiment: one is the relatively fine (Soil 1) and the other is coarse (Soil 2); the particle-size gradation curves of these two samples are shown in Fig. 5. As mentioned above, the mixing method of the conditioning agent is greatly influenced by the particle size gradation curve of the soil, in particular the fine particle contents passing through the #200 sieve. Thus, to reduce the error in the experiment, soil samples were prepared and mixed to produce every 98 N units of samples. The physical properties of the weathered granite soil used in the experiment are given in Table 1. The maximum void ratio (e_{max}) among the physical properties was derived based on ASTM (2000).

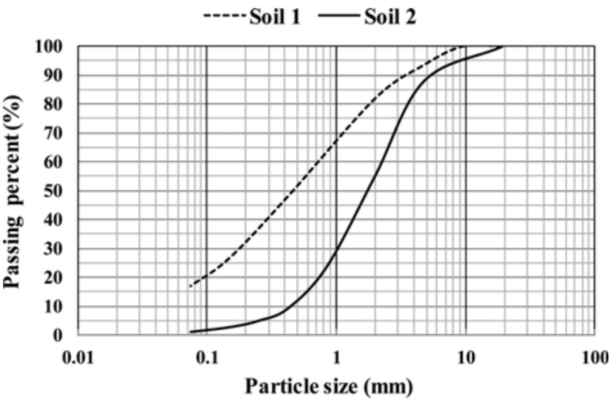


Fig. 5. Particle Size Gradation Curves of the Two Weathered Granite Soils

Table 1. Physical Properties of Two Types of Weathered Granite Soils

	Soil 1	Soil 2
Percent passing through a #200 sieve (%)	17.1	1.2
Initial water content (%)	10	10
Dry unit weight (kN/m^3), γ_d	16.70	19.08
Permeability coefficient (cm/s)	2.93×10^{-4}	1.40×10^{-3}
Consistency	NP	NP
G_s	2.62	2.64
Unified classification	SM	SP
e_{max}	1.04	0.99

Note: γ_d value was obtained from the compaction test, ASTM (2012)

As mentioned above, since the particle-crushing characteristics of the weathered granite soil are dependent on the mineral composition, the X-ray diffraction test was conducted. The results of the X-ray diffraction test are shown in Fig. 6. Fig. 6 shows that Soil 1 contains both andesine and muscovite and Soil 2 contains quartz, albite, and microcline.

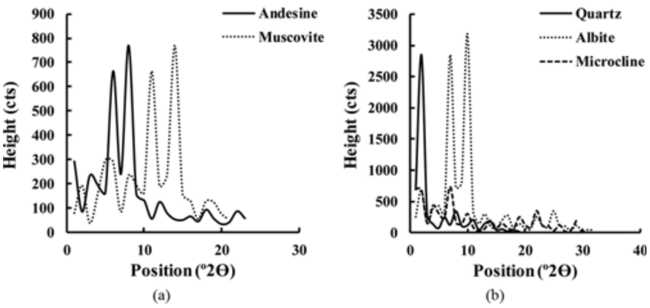


Fig. 6. X-ray Diffraction Test Results: (a) Soil 1, (b) Soil 2

The properties of the foam used in this experiment are given in Table 2. A foam product made of biodegradable surfactant and most frequently used in practice was adopted and used for this study. The same concentration factors FER and FIR were applied for both soils.

Table 2. Properties of the Foam used in the Experiment

Parameter	Value
Type	MAK Foam
Density	1.02–1.03
PH	8–9
c_f (%)	2
FER	10
FIR (%)	22, 45, 67, 88
Supply pressure (bar)	6

3. Results and Discussion

3.1 Slump Test

To determine the appropriate mix ratio that provides the desired workability for the EPB shield TBM operation, slump tests were conducted by mixing soil samples with conditioning agents. Fig. 7 shows the results of slump tests by mixing Soil 1 and foam starting with the initial water content of 10 %. This mixture was found to be extremely sticky and workability was insufficient because of very low value of water content, even when the Foam Injection Ratio (FIR) was as high as 88%. It means that the water content should be kept much higher. The results of the slump tests by varying the water content as well as the FIR are shown in Figs. 8 and 9. The slump values are shown in Fig. 8, and pictures

Fig. 7. Soil Sample with Water Content of 10 % (FIR = 88%)

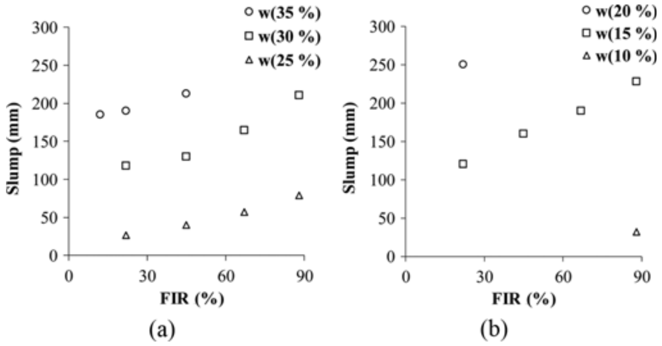


Fig. 8. Slump Values with the Variation of Water Content and FIR: (a) Soil 1, (b) Soil 2

of the slump tests are shown in Fig. 9.

As shown in Fig. 8(a), when the water content was as low as 25% for Soil 1, the required slump was not achieved even if the FIR was increased from 22 to 88%. This means that due to the insufficient water content in the conditioned soil, sufficient workability was not achieved even if a large amount of foam was injected. On the other hand, when the water content was as high as 35%, a high slump value of approximately 20 cm was obtained even when the FIR was as low as 22%. This indicates that if the water content is high, even low FIR can cause it to be too fluid like.

To obtain the upper bound values of water contents depending on the fine particle contents, the water content in which the slump value reaches 20 cm was measured for each soil (un-conditioned) having different percentage passing through the #200 sieve, say 1.2%, 6.5%, 11.8%, and 17.1%. The experimental results are shown in Fig. 10 (solid line). It should be considered that the water contents of the conditioned soils should not exceed the upper bound values shown in Fig. 10 depending on the fine particle contents passing through the #200 sieve. If the natural water contents are larger than the upper bound values by chance (which will seldom occur), it can be adjusted by adding a water-absorbing polymer, which is a type of polymer compound that converts watered soil into a gel state when it contacts water.

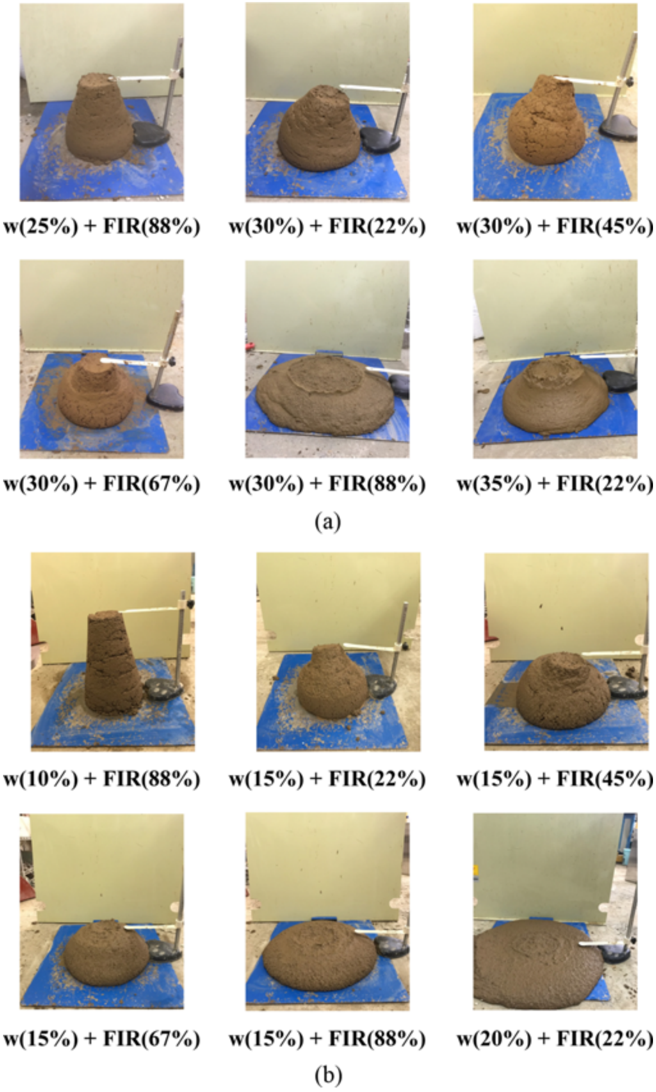


Fig. 9. Soil Samples with the Variation of Water Content (w) and FIR: (a) Sample 1, (b) Sample 2

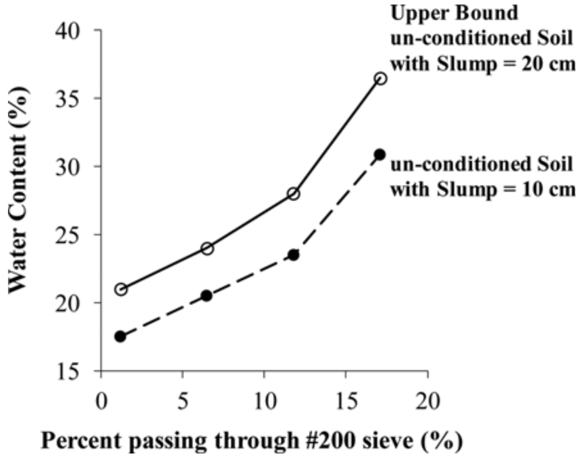


Fig. 10. Water Contents of Unconditioned Soils depending on Fine Contents (Slump Values of 10 and 20 cm, Respectively)

Moreover, the water content in which the slump value reaches 10 cm was also measured for each soil (un-conditioned) having different percentages passing through the #200 sieve, say 1.2%, 6.5%, 11.8%, and 17.1%. Experimental results are also shown in

Fig. 10 (dotted line). Since the water content in which the slump value of conditioned soil reaches 10 cm decreases with the increase in FIR values, lower bound values of the water contents cannot be designated in advance. However, at least, it can be said that if the water content is chosen from this curve (or little bit less), the slump values will always be greater than 10 cm; it will become larger with higher FIR values.

Figure 8(a) again shows that when the water content was 30% for Soil 1, the slump values were between 10 cm and 20 cm if foams were injected with the FIR value of 22–67% indicating sufficient workability. Similarly, in the case of Soil 2, sufficient workability was achieved by injecting 22–67% foam when the water content was approximately 15% (Fig. 8(b)). Based on these results, when mixing the weathered granite soil with the foams, it was found that the water content as well as the FIR of the foam affects the slump value of conditioned soil.

3.2 Permeability Test

Based on the results of the slump test, the foam mix ratio (FIR = 22, 45, or 67%) dependent upon the corresponding water content that produced a slump value of 10–20 cm providing sufficient workability was considered the optimum mix ratio. Thus, these mix ratios were used for permeability tests. Results of the permeability tests are summarized in Table 3. As shown in Table 3, the permeability coefficient of Soil 2 after conditioning decreased by approximately 10^{-3} orders compared to that of the unconditioned soil, resulting in the range of 10^{-6} cm/s, which is far below the required permeability coefficient = 1×10^{-3} cm/s proposed by Wilms (1995). On the other hand, it can be noted that since Soil 1 (unconditioned) already meets the permeability coefficient criteria proposed by Wilms (1995), the permeability coefficient of the conditioned Soil 1 need not be measured. Fig. 11 shows the results of the permeability test observing a longer period up to 10 hours for Soil 2. Even though, the permeability coefficient tends to increase with the elapse of time, the final values were far below the thrust value of 1×10^{-3} cm/s.

3.3 Compressibility Test

Compressibility tests were performed for the conditioned soil mixed with the optimum mix ratio suggested in the slump test, and the measured compressibility values of the two soil samples subject to each confining pressure are shown in Fig. 12. The average compressibility value per 0.5 bar was calculated from this figure and the calculated results are summarized in Table 3. Table 3 shows that even though the compressibility of both unconditioned soils does not meet the required value of 1.9%/0.5 bar proposed by Budach (2012), the conditioned soils meet the requirement regardless of the FIR values. It was also found that as the FIR value is increased, either the entrapped air was compressed or the amount of foam increased, thereby resulting in a higher compressibility value.

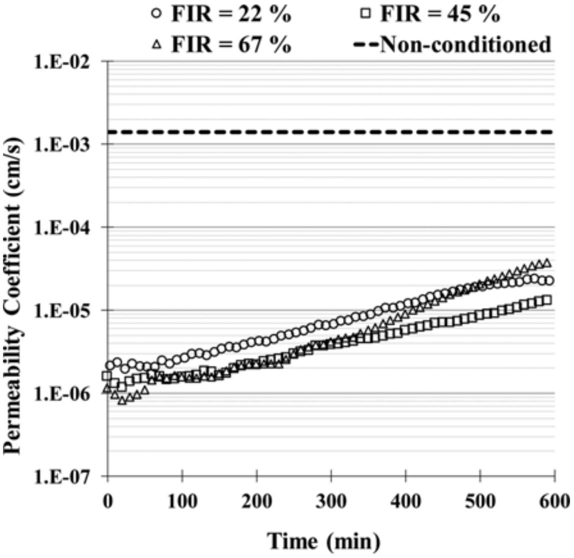


Fig. 11. Change in the Permeability Coefficient of the Conditioned Soil with the Lapse of Time

Figure 13 shows the relationship between the e/e_{max} values versus the confining pressures. As shown in the figure, if the chamber pressure is equal to or larger than 1.5 bar, the e/e_{max} value is less than one. Even though the average compressibility values of the conditioned soils meet the requirement value of 1.9%/0.5 bar, it should be considered that if the e/e_{max} value is less than one, the effective stress of the conditioned soil in the working chamber will begin to increase, and consequently, the shear strength in the conditioned soil will also increase (Mori *et al.,* 2018). Therefore, it can be inferred from these results that the shear strength in the EPB shield TBM chamber will start increasing if the chamber pressure is higher than 1.5 bar.

Table 3. Properties of the Conditioned Soil depending on the Foam Mix Ratio

Soil	FER	FIR (%)	w (%)	Slump (mm)	Permeability coefficient (cm/s)	Compressibility (% / 0.5 bar)
Weathered granite soil 1 (Sample 1)	0	0	10	None	2.93×10^{-4}	0.48
	10	22	30	118	-	3.18
	10	45	30	130	-	4.36
	10	67	30	165	-	5.02
Weathered granite soil 2 (Sample 2)	0	0	10	None	1.40×10^{-3}	0.24
	10	22	15	120	2.16×10^{-6}	2.74
	10	45	15	160	1.62×10^{-6}	4.04
	10	67	15	190	1.17×10^{-6}	4.84

3.4 Comparison with Previously Proposed Application Ranges

Budach and Thewes (2015) proposed the ranges of particle-size gradation curves that need soil conditioning as shown in Fig. 14. As shown in the figure, they divided the applicable ranges into three zones: Zones I, II, and III; even though only foams are enough as a conditioning agent at Zone I, polymers and fines are needed in addition to foams in Zones II and III. It is because in these zones the soils are coarse enough not to have sufficient fine particle contents (no cohesive contents either). They suggested that in the ranges outside the three proposed zones, it is not easy to apply a uniform face support pressure to the tunnel face during the TBM operation.

The particle-size gradation curves of Soil 1 and Soil 2 used in this study (before soil conditioning) are also shown in Fig. 14. Also shown are those after soil conditioning, in which the conditioned soils were oven-dried and sieve analysis was conducted.

It can be seen that the particle size gradation curve of the conditioned soil moved to the left side as shown in Fig. 14 due to the particle crushing characteristics of the weathered granite soil that occur during soil conditioning, and the percentage passing through the #200 sieve increased. This phenomenon is much more dominant in the coarser Soil 2 than the finer Soil 1.

Since Soil 1 belongs to Zone III, it is enough to add only the foam as the conditioning agent. On the other hand, even though Soil 2 is in Zones II and III (locally even outside the two zones), based on our research results, it was enough to use only the foams that are different from Budach and Thewes (2015) suggestions. According to their application ranges, polymers and/or fines should be added to this soil in addition to foams. However, our research results indicate that the optimum mix ratio could be achieved using the foam only on the condition that the water content is properly controlled. It is mainly because as the particle-size gradation curve is shifted to the left side due to the particle crushing characteristics of the weathered granite soil,

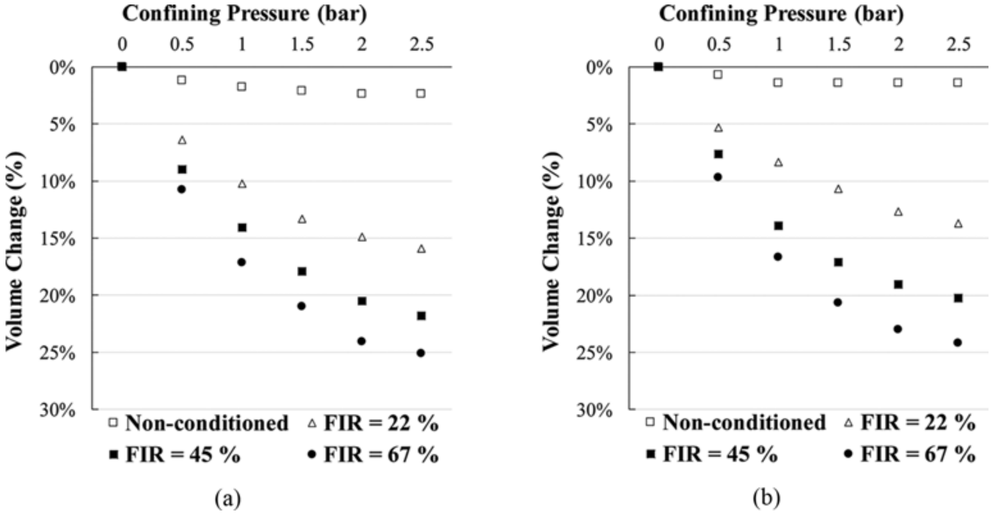


Fig. 12. Volume Change versus Confining Pressure: (a) Soil 1, (b) Soil 2

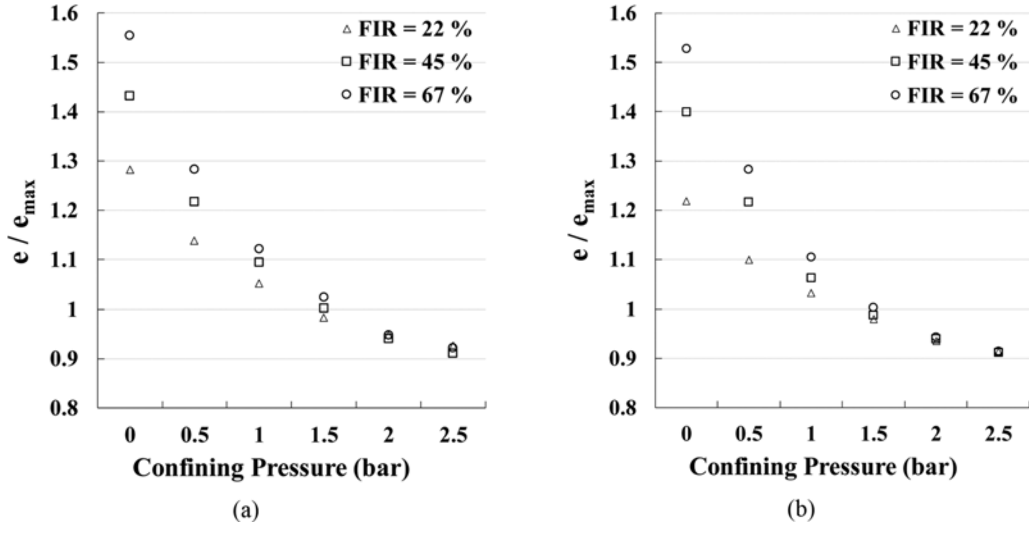


Fig. 13. Change in Void Ratio in the Conditioned Soil subject to Confining Pressure: (a) Soil 1, (b) Soil 2

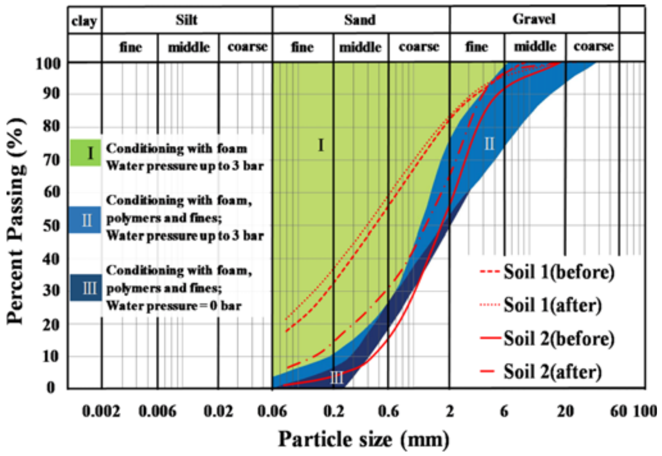


Fig. 14. Soil Conditioning depending on Particle-size Gradation Curves (Budach and Thewes, 2015)

thereby increasing the fine particle contents passing through the #200 sieve.

If a soil requires injection of other conditioning agents in addition to the foam, separate injection systems must be prepared in the EPB shield TBM. However, the findings of this study suggest that the range of the particle-size gradation curve can be expanded to the right side in Fig. 14 so that only the foam is needed for soil conditioning by properly controlling the water content in the case of the weathered granite soil enabling the economical TBM operation feasible without the need of additional injection systems.

4. Conclusions

In this study, the properties (i.e., the workability, permeability coefficient, and compressibility) of the weathered granite soil-foam-mixture are evaluated to derive and propose the most suitable conditioning agent as well as the most appropriate agent mix ratios. Moreover, the ranges of particle-size gradation curves in which the foam can be used as the conditioning agent are also studied. The conclusions drawn from this study are as follows:

1. When mixing the weathered granite soil with the foams, on condition that the water contents of the conditioned soils are within the reasonable range, it was found that the conditioned soils meet the slump requirement of 10–20 cm by mixing the foam with the FIR values of 22–67%.
2. All conditioned soil samples that meet the required slump value of 10–20 cm, meet the required permeability coefficient of 1×10^{-3} cm/s or less to prevent groundwater inflow from the tunnel face to the working chamber.
3. All the conditioned soils meet the required compressibility value of 1.9%/0.5 bar regardless of FIR values. Experimental results also show that the void ratio of the conditioned soil reduces to the value of e_{max} or less if the chamber pressure reaches 1.5 bar or higher, causing the increase in effective stress of the conditioned soils inside the working chamber.
4. Experimental study revealed that it was enough to use only foams with coarse granite soils, which are different from Budach and Thewes (2015) suggestions that polymers and/or fines should be added to the coarse soil in addition to foams. It is mainly due to the particle-crushing characteristics of the weathered granite soil, thereby increasing the fine particle contents passing through the #200 sieve.

Acknowledgements

This research was supported by a grant (Project number: 18SCIP-B066321-06, Development of Key Subsea Tunneling Technology) from Infrastructure and Transportation Technology Promotion Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

References

ASTM (2000). *Standard test methods for minimum index density and unit weight of soils and calculation of relative density*, D4254-00, ASTM International, West Conshohocken, PA, DOI: 10.1520/D4254-00.

ASTM (2006). *Standard test method for permeability of granular soils (constant head)* (withdrawn 2015), D2434-68, ASTM International, West Conshohocken, PA, DOI: 10.1520/D2434-68R06.

ASTM (2012). *Standard test method for laboratory compaction characteristics of soil using standard effort (12,000 ft-lbf/ft*^{3} *(600 kN-m/m*^{3}*))*, D698-12e2, ASTM International, West Conshohocken, PA, DOI: 10.1520/D0698-12E02.

ASTM (2015). *Standard test method for slump of hydraulic-cement concrete*, C143/C143M-15a, ASTM International, West Conshohocken, PA, DOI: 10.1520/C0143_C0143M-15A.

Bezuijen, A., Schaminee, P. E. L., and Kleinjan, J. A. (1999). “Additive testing for earth pressure balance shields.” *Proc. 12th Eur. Conf. on Soil Mechanics and Geotechnical Eng.*, Amsterdam, pp. 1991-1996.

Borio, L. and Peila, D. (2010). “Study of the permeability of foam conditioned soils with laboratory tests.” *American Journal of Environmental Sciences*, Vol. 6, No. 4, pp. 365-370, DOI: 10.3844/ajessp.2010.365.370.

Budach, C. (2012). *Untersuchungen zum erweiterten Einsatz von Erddruckschilden in grobkörnigem Lockergestein*, PhD Thesis, Bochum University, North Rhine-Westphalia, Germany.

Budach, C. and Thewes, M. (2015). “Application ranges of EPB shields in coarse ground based on laboratory research.” *Tunnelling and Underground Space Technology*, Vol. 50, pp. 296-304, DOI: 10.1016/j.tust.2015.08.006.

Ham, T. G., Cho, Y. S., and Kim, Y. S. (2004). “A study on the compression characteristics of decomposed granite soil based on single particle crushing property.” *Journal of the Korean Geotechnical Society*, Vol. 20, No. 8, pp. 103-111 (in Korean).

Kim, Y. J., Lee, I. M., and Lee, I. K. (1994). “Constitutive characteristics of decomposed Korean granites (1).” *Journal of the Korean Geotechnical Society*, Vol. 10, No. 3, pp. 55-78 (in Korean).

Lee, K. I., Yoon, Y. G., and Lee, J. W. (2013). “Particle crushing properties of decomposed granite soil due to changes in the degree of weathering.” *Journal of the Korean Geosynthetics Society*, Vol. 12, No. 1, pp. 1-10, DOI: 10.12814/jkgss.2013.12. 1.001 (in Korean).

Maidl, U. (1995). *Erweiterung der Einsatzbereiche der Erddruckschilde durch Bodenkonditionierung mit Schaum*. PhD Thesis, Bochum University, North Rhine-Westphalia, Germany.

Martinelli, D., Peila, D., and Campa, E. (2015). "Feasibility study of tar sands conditioning for earth pressure balance tunnelling." *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 7, No. 6, pp. 684-690, DOI: 10.1016/j.jrmge.2015.09.002.

Mori, L., Mooney, M., and Cha, M. (2018). "Characterizing the influence of stress on foam conditioned sand for EPB tunneling." *Tunnelling and Underground Space Technology*, Vol. 71, pp. 454-465, DOI: 10.1016/j.tust.2017.09.018.

Peila, D., Oggeri, C., and Borio, L. (2009). "Using the slump test to assess the behavior of conditioned soil for EPB tunneling." *Environmental and Engineering Geoscience*, Vol. 15, No. 3, pp. 167-174, DOI: 10.2113/gseegeosci.15.3.167.

Peila, D., Picchio, A., and Chieregato, A. (2013). "Earth pressure balance tunnelling in rock masses: Laboratory feasibility study of the conditioning process." *Tunnelling and Underground Space Technology*, Vol. 35, pp. 55-66, DOI: 10.1016/j.tust.2012.11.006.

Pena Duarte, M. A. (2007). *Foam as a soil conditioner in tunnelling: Physical and mechanical properties of conditioned sands*, PhD Thesis, Oxford University, Oxford, England, UK.

POSCO Engineering & Construction Co., Ltd. (2010). *Seoul subway line No. 9, soil report*, Pohang, Korea (in Korean).

Quebaud, S., Sibaï, M., and Henry, J. P. (1998). "Use of chemical foam for improvements in drilling by earth-pressure balanced shields in granular soils." *Tunnelling and Underground Space Technology*, Vol. 13, No. 2, pp. 173-180, DOI: 10.1016/S0886-7798(98)00045-5.

Wilms, J. (1995). *Zum Einfluss der Eigenschaften des Stützmediums auf das Verschleißverhalten eines Erddruckschildes*, PhD Thesis, Gesamthochschule Essen University, Nordrhein-Westfalen, Germany.