INVESTIGATION ON FOAM STABILITY AND FOAM-CONDITIONED SOIL PROPERTIES UNDER PRESSURE IN EPB TBM TUNNELING

by

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A thesis submitted to the Faculty and the Board of Trustee of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Civil and Environmental Engineering).

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ABSTRACT

Proper soil conditioning is very important in earth pressure balanced (EPB) tunneling as it improves face stability and tunnel boring machine (TBM) performance. Foam is one of the most commonly used soil conditioning agents to modify the excavated soil properties. A critical characteristic of foam-conditioned soil is its stability, i.e., the ability to maintain the engineering properties throughout the residency time (30-90 min) in the mixing chamber. It is very important to understand the fundamentals of foam stability and foam-conditioned soil properties.

This thesis examines foam stability under pressure through a novel foam generation – pressure chamber – foam capture testing system. A series of foam experiments was performed to examine the physical phenomenon of foam degradation and time-dependent foam properties under pressure. Test results suggest that liquid loss is not an effective indicator for characterizing foam stability, while foam volume loss is a more appropriate measure of foam stability. Results also reveal that foam liquid drainage is significantly retarded at higher chamber pressure.

For the stability of foam-conditioned under pressure, a comprehensive suite of experiments was conducted for foam-conditioned soil to investigate the fundamentals of foam-soil interaction and engineering properties of foam-conditioned soil. A foam-soil capture device was used to capture bubble-grain images at a microscale under pressure. A pressurized testing chamber (PTC) was used to examine the stability of the mechanical properties of foam-conditioned soil. Test results reveal that changes in bubble size distribution for foam in foam-soil mixtures are much less than foam itself, indicating that soil particles help stabilize foam bubbles. Test results present that the engineering properties of foam-conditioned soil are relatively stable over 60 min.

This thesis also investigates the mechanisms of foam-soil separation in the EPB mixing chamber through a series of soil conditioning tests. Parameters including molding water content...
\( w_o \), initial foam injection ratio \( FIR_o \), and fines content are varied to examine soil’s capacity for foam and foam-soil separation. Test results suggest that there is more expelled foam as molding water content and initial foam injection ratio increase. Test results also indicate that fines content increases the soil’s capacity for foam and water. In addition, results show that agitation and cyclic loading-unloading of pressure can induce foam-soil separation in conditioned soil.
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CHAPTER 1
GENERAL INTRODUCTION

1.1 Motivation

Proper soil conditioning is critically important in earth pressure balanced (EPB) tunnel boring machine (TBM) tunneling. Soil conditioning refers to the use of suitable conditioning agents such as foam, polymer, and bentonite to modify the properties of excavated soil. Foam is the most widely used soil conditioning agent in EPB tunneling. The desired properties of foam-conditioned soil include elasticity, compressibility, reduced shear strength, abrasivity, and permeability (Budach and Thewes, 2015; Milligan, 2000; Mori et al., 2018; Peila, 2014; Thewes et al., 2012; Vinai et al., 2008). By mixing foam with soil in the mixing chamber of an EPB TBM, foam bubbles expand the pores between soil particles and therefore the conditioned soil becomes more compressible; as a result, better control of fluctuation of the chamber pressure can be attained and thus face stability at the cutter head can be improved. By injecting foam in front of the cutting head, low torque requirement and less tool wear can be realized, and it reduces power supply during excavation process. In addition, foam bubbles in the conditioned soil can inhibit the inflow of groundwater when tunneling under the groundwater table.

The stability of foam and foam-conditioned soil is an important aspect in EPB TBM tunneling. The term “stability” here refers to the continuance of desired material properties without change. For effective EPB tunneling, it is critical to maintain the properties of foam and foam-conditioned soil throughout residency time in the chamber. The normal residency time ranges from 30-90 minutes. Conditioned soil in the chamber is subjected to tens to hundreds of loading cycles due to material inflow and discharge fluctuations as well as rotation of material from lower pressure in the upper portion of the chamber to higher pressure in the lower portion of the chamber.
It is therefore important for foam and foam-conditioned soil to behave elastically and maintain their properties over time in the chamber.

In tunneling practice, foam stability is often characterized by the foam liquid half-life, defined as the time necessary for foam to lose one-half of its initial liquid fraction. While there is no standardized testing procedure (e.g., ASTM, DIN). EFNARC (2005) recommends using foam liquid drainage as a measurement of foam stability. However, this testing method can only measure liquid drainage at atmospheric conditions, while foam and foam-conditioned soil in realistic are always subjected under pressure in the mixing chamber of an EPB TBM. Moreover, it is unclear whether liquid drainage implies a concomitant reduction in the aforementioned desired engineering properties. And, at a fundamental level, it is unclear what is physically happening to foam during liquid drainage.

The stability of a foam-soil mixture is different from that of foam only. Previous research has shown that a foam-soil mixture can be remarkably stable (Hajialilue Bonab et al., 2014; Langmaack, 2000). However, so far there is very limited experimental research regarding the stability of foam-conditioned soils. The influence of foam properties such as bubble size distribution on the stability of foam-conditioned soils is unclear. Also, little is known about the mechanism and conditions that cause foam bubble migration from soils.

In addition, air bubble accumulation at the top of the EPB mixing chamber has been consistently noticed and dealt with in tunneling practice. An air bubble is normally caused by foam bubbles separation and migration from EPB muck. Such air bubble cannot counterbalance the lateral effective stress from the to-be-excavated ground because it has negligible shearing resistance. This can result in inadequate face support and possibility of local ground collapse and material flowing into the chamber (Alavi Gharahbagh et al., 2013). There is limited literature about
the air bubble issue. And, the factors and mechanisms that cause the air bubble, namely foam-soil separation and bubble migration in the EPB mixing chamber have not been addressed.

1.2 Research Objectives

To improve understanding of foam stability and foam-soil interaction behavior under pressure in EPB TBM tunneling, the following research objectives will be investigated:

1. Examine time dependent foam properties (liquid volume loss, foam volume loss, bubble size distribution, foam expansion ratio, compressibility) under pressure.
2. Explain the physical phenomenon of foam instability (or degradation) and characterize how liquid loss influence foam properties.
3. Examine the stability of foam-conditioned soils under pressure at bubble scale. Understand the mechanisms of bubble-grain interaction and how soil particles influence foam stability.
4. Investigate the stability of engineering properties of foam-conditioned soil on the aspect of compressibility, shear strength, pore pressure, and effective stress with elapsed time.
5. Investigate soils’ capacity for foam with various conditioning parameters. Explain conditions and mechanisms that cause foam-soil separation from conditioned soil.

1.3 Thesis Organization

This thesis is divided into six chapters including three paper chapters. Chapter 2 presents the background and literature review on the state of soil conditioning research. The background knowledge about foam properties and foam stability are introduced. Previous research on foam-conditioned soil properties are presented. Chapter 3 presents the paper titled “An Experimental Examination of Foam Stability under Pressure for EPB TBM Tunneling”. This paper was published in the Tunneling and Underground Space Technology journal. The paper presents the
experimental research on foam stability examination under pressure. The testing system and test method are introduced. Test results of bubble size analysis as well as the liquid and foam volume loss are discussed. The influences of pressure and foam expansion ratio on foam stability is examined. Chapter 4 is titled as “Experimental Study on the Stability of Foam-Conditioned Sand under Pressure in the EPB TBM Chamber”. It shows test results of the stability of foam-conditioned soil under pressure. Bubble size and pore size distributions in foam-soil mixtures with elapsed time are investigated. Stability of the engineering properties of foam-conditioned soil are presented. Mechanisms of soil particles stabilizing foams are discussed. Chapter 5 is titled as “Experimental Investigation of Foam-Soil Separation for Foam-Conditioned Soil in the EPB Mixing Chamber”. This chapter presents the experimental research on soil’s capacity for foam and bubble migration for foam-conditioned soil. Mechanisms that cause foam-soil separation are discussed. Chapter 6 shows the summary of the main findings in this research and provides some suggestions for future work.

1.4 References


EFNARC, 2005, Specification and guidelines for the use of specialist products for mechanised tunnelling (TBM) in soft ground and hard rock.


Milligan, G., 2000, Lubrication and soil conditioning in tunneling, pipe jacking and microtunneling, a state of the art review: Geotechnical Consulting Group, G.W.E. Milligan.


CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

This chapter presents the background and literature review for this research. Background about foam and foam stability is presented. Previous research about foam-conditioned soil properties and testing methods are introduced in detail. Literature about foam stability in foam-soil mixtures and mechanisms of particle stabilizing foam are reviewed.

2.1 Foam and Foam Stability

2.1.1 Background knowledge about foam

Foam is defined as a gas phase dispersed within a liquid phase and stabilized by surfactant adsorbed at the gas-liquid interface. Surfactants lower the surface tension at the air-liquid interface to stabilize foam bubbles. Surfactants have the molecules with a combination of a hydrophobic chain and a hydrophilic head. At a liquid-gas interface, surfactant molecules orient themselves so that the hydrophilic head is in an aqueous environment, and the hydrophobic chain is in a non-aqueous environment. As it is shown in Figure 2.1, the surfactant molecules form oriented monolayers and concentrate at the air-water interface. Similarly, the surfactant molecules will reside themselves at the interfaces when foam bubbles are generated through a foam generator.

![Illustration of surfactants at an air-water interface](from Langmaack, 2000).
Surface tension is the maximum energy a fluid can store without breaking apart (Lu and Likos, 2004). Surface tension has the unit of energy per unit area or force per unit length. It results from imbalanced intermolecular forces (i.e., van der Waals forces). The attractive van der Waals forces between molecules in a liquid are felt equally by all molecules except those in the interfacial region (i.e., air-water interface). This imbalance pulls the molecules of the interfacial region toward the interior of the liquid. The contracting force at the surface is known as the surface tension (Schramm and Wassmuth, 1994b). As shown in Figure 2.2, a model of wire frame with a soap film (with unit length $l$) is used to better explain surface tension. The work required to expand the surface against the contracting force (or surface tension) is equal to the increase in surface free energy ($dG$) that accompanies this expansion,

$$\text{work} = \gamma l \, dx = \gamma \, dA$$  \hspace{1cm} (2.1)$$

$$dG = \gamma \, dA$$  \hspace{1cm} (2.2)$$

where the slide wire is moved a distance $dx$ and the increase in area $dA$ equals $l$ times $dx$. The above relationships show why surface tension can either be expressed as force per unit length or energy per unit area.

Figure 2.2 Surface tension: a surface-contracting force per unit length and a surface energy per unit area. Reprinted with permission from (Schramm and Wassmuth, 1994b). Copyright (1994) American Chemical Society.
One factor that influences surface tension is surfactant concentration. With increasing in concentration, surface tension decreases significantly. With the further increasing of concentration, surfactant molecules start forming micelles and the concentration approaches to the critical micelle concentration (CMC). CMC is defined as the concentration at which micelle formation becomes significant (Schramm and Wassmuth, 1994b). In this case, little changes of surface tension can be found as concentration increases. Another factor affecting surface tension is temperature. Generally surface tension of a liquid decreases as temperature increases (Lu and Likos, 2004).

Surface tension in a foam bubble tends to collapse the bubble, and the gas pressure inside the bubble balances this (Eren, 2004). An interface between a gas phase and a liquid phase that surrounds the bubble, will have gas pressure \( P_G \) and liquid pressure \( P_L \). For spherical bubbles of radius \( R \) in a foam as shown in Figure 2.3,

\[
\Delta P = P_G - P_L = 2\gamma / R
\]

so that \( \Delta P \) varies with the radius \( R \). Eq. 2.3 is known as the Young-Laplace equation (Schramm and Wassmuth, 1994b).

Figure 2.3 The law of Young-Laplace relates pressure difference to mean curvature for a foam bubble in equilibrium.
2.1.2 Foam stability

There are three main mechanisms that cause foam instability: liquid drainage, coarsening, and coalescence (Fameau and Salonen, 2014). Immediately after foam generation, liquid in the foam tends to drain due to the force of gravity. The liquid drains by flowing downward through the liquid-films, the interior of the lamellae. Figure 2.4a shows the schematic of foam drainage. Coalescence is defined as the process of the rupturing of the thin liquid film that separates two adjacent bubbles (Stevenson, 2012). As shown in Figure 2.4b, when the two bubbles touch each other, and if the film between them is unstable, the film will break and lead to the merging of the two bubbles. Foam coarsening is defined as the process of the growth of large bubbles at the expense of smaller bubbles (Figure 2.4c). This process is due to the pressure differences between bubbles with different sizes. The pressure differences drive the diffusion of gas from smaller bubbles with higher internal pressure to larger bubble through the thin films which separate them. These three mechanisms are interdependent and can accelerate on another (Fameau and Salonen, 2014). For example, foam drainage process can lead bubbles get closer, and it causes the rupture of the thin liquid films between bubbles.

(Schramm and Wassmuth, 1994b) defined foam stability as the resistance to the processes of film thinning and coalescence (film rupturing). In film thinning, the liquid-films that separate bubbles thin and bubbles approach closely together. In coalescence, the films between bubbles rupture and bubbles merge together to form larger bubbles. The authors also state that foam stability is largely determined by drainage and rupture of the thin film. (Quebaud et al., 1998) described foam stability as the capacity to maintain a constant volume and keep the liquid of the matrix from flowing out.
In tunneling industry, foam stability is often characterized by the foam liquid half-life, defined as the time necessary for foam to lose one-half of its initial liquid fraction. The rationale for using liquid drainage time as a measure of foam stability for EPB soil conditioning is not addressed in the literature. It may be, as alluded to in Quebaud’s definition, that the rationale is that significant liquid drainage results in significant foam volume reduction. While there is no standardized testing procedure (e.g., ASTM, DIN), EFNARC (2005) recommends using a filter-funnel with 80 g foam to measure foam liquid half-life, and the device is shown in Figure 2.5. The half-life (or liquid drainage) method is widely used in characterizing foam stability for soil conditioning in tunneling (Milligan, 2000; Psomas and Houlsby, 2002; Quebaud et al., 1998; Thewes et al., 2012). In addition to liquid drainage, Langmaack (2009) addressed that the remaining foam volume can also be used to measure foam stability since the remaining foam
volume is more relevant and valid to judge the stability of the foam-soil mixture. The author
presented measurements of foam volume in 30 minutes for two types of foam. The results showed
very little decreases in foam volume for both foams in 30 minutes.

![Figure 2.5 Traditional funnel test for measuring foam half-life.](image)

The traditional foam half-life (or liquid drainage) test can only be conducted at atmospheric
conditions, while foam and foam-conditioned soils in realistic are always subjected under pressure
in the mixing chamber of an EPB TBM. So far, there is very limited research about foam behavior
such as foam stability under pressure. The term ‘stability’ implies continuance of desired
properties without change. It is unclear whether liquid drainage implies a concomitant reduction
in these desired engineering properties. And, at a fundamental or root level, it is unclear what is
physically happening to foam during liquid drainage.

2.2 Properties of Foam-conditioned Soil

2.2.1 EPB pressurized environment

Earth pressure balanced (EPB) tunnel boring machines (TBM) are increasingly being used
in many tunneling projects. The EPB machine (EPBM) is mostly used in soft ground tunneling,
and its use has been extended to coarse-grained soils ground conditions. The key components of an EPBM include cutter head, working chamber, and screw conveyor (Figure 2.6). During the EPBM excavation, the working chamber is usually fully filled with excavated conditioned soils. The TBM advance rate and screw conveyor excavation rate are both manipulated to build up face support pressure on the cutter head to counter-balance the ground and water pressure as shown in Figure 2.7. Therefore, the conditioned soil in the excavation chamber is always in a pressurized environment.

Figure 2.6 Schematic of an EPB TBM (1 cutting wheel, 2 excavation chamber, 3 bulkhead, 4 thrust jacks, 5 screw conveyor, 6 segment erector, 7 segmental concrete lining) (Herrenknecht, 2016).

Figure 2.7 Schematic of counter balanced pressures provided by EPBM (Mooney et al., 2017b).
2.2.2 Lab testing for foam-conditioned soil

Various testing methods for soil conditioning have been devised and developed to investigate the properties of foam-conditioned soils. Although these testing methods have not been standardized in tunneling industry, they are turned out to be useful to understand the foam-conditioned soil behaviors.

(1) Compressibility test

The increase of the compressibility of excavated soils through the addition and mixing of foams can improve the workability and homogeneity of excavated soils. The more compressible and plastic foam conditioned soil in the pressure chamber of a TBM enables the bulkhead to be responsive to the pressure fluctuations, resulting a better control of the face stability. More specifically, if there is a small difference between the excavation rate and muck removal rate, it will cause large pressure changes in the working chamber if the soil is incompressible. Increase in compressibility causes a “softer” response in which the pressure in the working chamber can be more easily kept constant.

Bezuijen et al. (1999) reported a setup for testing the foam-conditioned sand (Figure 2.8). The setup can be applied to conduct two different types of tests. The first test series which was called the mixing tests, compressibility, permeability and viscosity of the foam-conditioned soil can be measured. The setup for this test series is shown on the left hand side of Figure 2.8. The second test series simulates the tunneling with an EPB-shield. The equipment for this series of test is shown on the right hand side of Figure 2.8. For this setup, total pressure was measured on the top plate. Pore pressures were measured in the container and the screw conveyer. In addition, torque on the rotor was measured and the foam injection volume can be controlled.
The compressibility test results from Bezuijen et al. (1999) for foam-conditioned sand are shown in Figure 2.9. In the initial compression process, air in the foam-soil mixture dominates the behavior, and there are no grain contacts. The displacement of the mixture in this process is negative. Up to a certain loading pressure, soil grains contacts start influencing the compression behavior and the displacement become positive. In addition, the results show a reduction of slope from loading to unloading, the authors stated that this could be caused by implosion of air bubbles.

Psomas and Houlsby (2002) performed the compressibility tests for foam-conditioned sand using a Rowe cell. The Rowe cell was 75 mm in diameter, and the maximum allowable vertical pressure was 240 kPa. The pressure and displacement of the soil sample were measured electronically through a data acquisition unit. Figure 2.10 shows the compressibility test results.
for foam-conditioned fine sand with different FIR but using the same foaming agent. It is found that the curves of the foam-sand mixtures lie above the loosest dry sand curve ($e_{max}$ curve). The results also show that the higher the FIR used, the larger the void ratio for samples under loading condition, and the foam-sand mixtures can sustain high final void ratio (higher than $e_{max}$ of the sand) while high vertical pressure is applied. The effect of FIR on the volume change for foam conditioned sand is also shown in Figure 2.11.

Figure 2.9 Result of the compression test (Bezuijen et al., 1999).

Figure 2.10 Foam/sand compression testing results (Psomas and Houlsby, 2002).
Mori et al. (2018) examined the compression behavior for two types of foam-conditioned granular soils under applied total pressure. A developed pressurized testing chamber (PTC) was used to measure the compressibility of conditioned soils as shown in Figure 2.12. During the tests, pore pressure and effective stress were monitored. Results show that the compressibility decreases with increasing total and effective stress. In addition, the authors found that effective stress starts to develop below a transitional $e/e_{max}$ ratio, which was found to be 1.2 for both tested soils. Above this transitional ratio, the compressibility of foam-conditioned soil is governed by air compressibility, and below this ratio it is governed by the effective stress. Test results present that the compressibility above $e/e_{max}$ ratio is mostly above 10%/bar for both tested soils, which is more than the minimum 3.8%/bar suggested for a metro-sized EPB TBM. In the transition region ($e/e_{max} = 1.0-1.2$), the compressibility decreases below the desired value even before $e_{max}$ is reached.

Furthermore, Mooney et al. (2017b) investigated the engineering properties including compressibility, shear strength, and abrasivity of foam-conditioned through a series of experiments by using the pressurized testing chamber (PTC) as shown in Figure 2.12. These engineering properties of conditioned sand were found to be ideal when the soil’s void ratio $e$ was above the
ASTM-determined maximum void ratio $e_{max}$ and dry density $\rho_d$ was below the minimum dry density $\rho_{d-min}$. To maintain this ideal void ratio/dry density condition, the foam injection ratio at pressures $FIR_p$ should be more than 45%, meaning that the at least 45% of foam by volume must be mixed with the excavated soil.

Figure 2.12 Pressurized testing chamber (PTC) used to characterize foam-conditioned soil properties (Mori et al., 2018).

(2) **Shear strength test**

The shear strength of soils influences the wear of cutting tools and the energy supply during excavation. The addition of conditioning agent such as foam reduces the shear strength of soils, thus it results in the reduction of tool wear and significant savings of energy. Bezuijen et al. (1999) measured the shear strength of the foam-conditioned sand and concluded that the shear strength is related to the final porosity of the mixture. A lower final porosity showed higher shear strength. In addition, Bezuijen et al. (1999) found that the shear strength of the foam-conditioned sand does
not change much in time. They concluded that the sand-water-foam mixture stayed stable with time compared to the pure foam which degrades very fast into liquid and air.

Messerklinger et al. (2011) designed and developed a pressurized vane shear apparatus to investigate the shear strength of fine-grained soils conditioned with foams and polymers (Figure 2.13). The apparatus has a torque sensor located inside the pressure cell, which can minimize machine friction losses to obtain accurate torque measurement.

![Figure 2.13 Pressurized vane shear test apparatus (Messerklinger et al., 2011).](image)

Mori et al. (2018) conducted a series of vane shear tests for foam-conditioned granular soils using the above-mentioned PTC. Test results shows that the vane shear strength follows the Mohr-Coulomb criterion and increases with increasing effective stress. Moreover, results present that above the transitional $e/e_{max}$ ratio the vane shear strength is below 10 kPa and only increases up to 20 kPa in the transitional region. Mori et al. (2018) concluded that granular soil transitions from foam-like (or air governed) behavior to soil-like (or effective stress governed) behavior. Enough foam should be required to increase soil’s void ratio not only above $e_{max}$, but also above
the transitional $e/e_{max}$ ratio.

(3) **Abrasivity test**

The purpose of the abrasivity test is to study the friction between the foam-conditioned soil and the cutting tools, to give an indication of possible reduction of tool wear and power consumption due to the lubrication by adding foam into soils. Although currently there is no standard method for soil abrasivity testing, researchers have developed testing methods to determine soil abrasivity.

Nilsen et al. (2007) proposed a new soil abrasion test method, the NTNU Soil Abrasion Test (SAT), which is a further development of the existing abrasion tests for rock. Similar to the NTNU SAT test, Thuro et al. (2007) used the LCPC abrasive meter for determining soil abrasivity. Both tests used dry soil samples in limited soil particle sizes. It is found that these two tests cannot catch up all driving factors for soil abrasivity directly.

Jakobsen et al. (2013) developed a new abrasivity test device called the Soft Ground Abrasion Tester (SGAT) as shown in Figure 2.14. The authors reported that the apparatus had the capability of evaluating how soil abrasivity influenced by water content, air pressure, compaction or soil density, and the addition of soil conditioning agents. The main finding of this research was that the tool wear using the SGAT apparatus is influenced by the nature of the soil (e.g. mineralogy, quartz content, grain size distribution, soil density, etc.), the moisture content of the soil, and the type and method of soil conditioning (e.g. $FER$, $FIR$). Furthermore, the authors found that there is a clear relation between the tool wear and the torque, and the rpm by the SGAT apparatus.

Alavi Gharahbagh et al. (2014) developed a soil abrasion testing system (Penn State Soil Abrasion) with a rotating propeller and a soil abrasion index to evaluate the abrasivity of foam-conditioned soils under pressure (Figure 2.15). The authors investigated the influence of different
parameters on soil abravisity including pressure, wear tool material hardness, soil types, and soil conditioning. Test results showed that the use of proper soil conditioning can reduce the wear of cutters by orders of magnitude while it can reduce the torque by over 50%.

Figure 2.14 Scheme of the new Soft Ground Abrasion Tester (SGAT) (left) and photo of the setup (right) (Jakobsen et al., 2013).

Figure 2.15 Penn State Soil Abrasion testing device (Alavi Gharahbagh et al., 2014).
(4) Permeability test

Reduction of the permeability of excavated soils can stop the inflow of groundwater and therefore reduce the possibility of face collapse due to water inflow. The permeability of a conditioned soil can be measured in a constant-head permeameter as normally used for measurements on soils. Milligan (2000) suggested that the permeability of the soil $k$ must be maintained below $10^{-5}$ m/s for proper control of water flow through an EPBM. Quebaud et al. (1998) conducted the permeability test for foam-conditioned soil using the constant head method. The results showed a substantial reduction in permeability by over two orders of magnitude after conditioning. One deficiency of this test is that foam drains out from the soil when water flows through the foam-conditioned soil. Therefore the permeability measurement by this method may not be accurate. Bezuijen et al. (1999) stated that the permeability of the sand-water-foam mixture depends greatly on the degree to which pore water is replaced by foam. A larger volume of replaced water means a lower permeability at equal final porosity. When 83% replacement was achieved, the permeability of the tested sand decreased from $5 \times 10^{-4}$ m/s to $2.5 \times 10^{-6}$ m/s. The authors explained that the reduction in permeability is caused by the foam bubbles which act as small grains that fill up the pores in the sand.

Borio and Peila (2010) proposed a laboratory procedure for testing the permeability of foam-conditioned soil. The test was conducted by measuring of the time required for a pre-defined amount of water (two liters) to pass through a standard sample (Figure 2.16). The permeability testing results of this study is shown in Figure 2.17. The results show that the higher the $FIR$ in the sample, the more time it takes for water to pass through the sample. It means that the sample is more impermeable with higher $FIR$. In addition, the results show that using foam with lower $FER$ (or more ‘wet’) to condition the testing sand results in lower permeability.
(5) Slump test

Slump test is normally used for measuring the plastic fluidity of fresh concrete. Similarly, the slump test has been widely applied in soil conditioning of EPBM tunneling to provide a measurement of the plasticity of foam-conditioned soil (Budach and Thewes, 2015; Duarte, 2007; Langmaack, 2000; Maidl, 1995; Peila, 2014; Quebaud et al., 1998; Vinai et al., 2008). Quebaud et al. (1998) suggested a slump value of 12 cm is considered to characterize the optimal fluidity of a
foam-conditioned soil. Vinai et al. (2008) concluded that suitable behavior (plastic and ‘pulpy’) was only found for some water content and FIR combinations. The authors also concluded that a slump of about 15-20 cm was an index of a suitable mix. Peila (2014) summarized a comparative table to show the behavior of conditioned soil using slump tests on sandy gravel (Figure 2.18), and the author stated that the suitable behavior (plastic and ‘pulpy’) of conditioned soil showed in the slump test should be without any foam or fluid loss.

The slump test is simple to be performed and it provides a good indicator of the overall behavior of conditioned soil. Also, because of its simplicity and economy, it can be applied both in preliminary design stage and at the job site to keep the conditioning under control during excavation (Peila et al., 2009).

Figure 2.18 Comparative table for the definition the behavior of conditioned soil using slump tests on sandy gravel (Peila, 2014).
(6) Other testing methods

In addition to the above testing methods to characterize the properties of foam-conditioned soil, some researchers developed several other testing methods, such as the foam penetration test (Bezuijen et al., 1999; Maidl, 1995; Quebaud et al., 1998), mixing test (Bezuijen et al., 1999; Quebaud et al., 1998), and screw conveyer test (Peila, 2014; Peila et al., 2007; Vinai et al., 2008). The purpose of the foam penetration test is to determine how far ahead of the cutter head the foam injected at the face could penetrate into the ground (Milligan, 2000). The mixing test was conducted using a pan mixer or a small concrete mixer to mix the testing soil and foam with different FIR for measuring the power consumption during the mixing process. The screw conveyer test evaluated the suitability of conditions soils to be extracted from a pressurized chamber by a laboratory screw conveyer device. Peila (2014) reported that the soil is considered to be correctly conditioned if the screw conveyer is able to regularly extract soil and the soil has a regular pressure and easy to be controlled, and if the torque of the screw is regular and not too high with reference to some standard values.

2.3 Foam Stability in Foam-conditioned Soils

2.3.1 Experimental study on foam-soil interaction

Duarte (2007) investigated the influence of sand in the stability of foam by measuring the liquid drainage from the foam-sand mixture. Tests were carried out with the foam-sand mixture at atmospheric pressure and also under higher pressures. The testing devices are shown in Figure 2.19. A funnel equipped with a plug and a tube of 6 mm internal diameter, 95 mm length and with 211 holes on its wall of 0.5 mm diameter. From these holes liquid drained from the conditioned sand. For the liquid drainage tests under higher pressure, an acrylic plunger was used and a dead weight was placed on top of the piston to provide pressure. The pressures on the conditioned soils
were 12.6 kPa and 25.7 kPa respectively. A very high foam injection ratio, between 400% and 600%, was used for the mixtures in order to have some liquid drainage. Testing results show that the two pressures applied did not change the behavior of the foams in the conditioned sand regarding the drainage time. It was also observed during the tests that the pressure applied seemed to push out foam from the conditioned sand. Therefore it was difficult to obtain a liquid drainage through the pipe. In addition, the fact that sand absorbed some of the foam liquid when it was mixed with foam was not taken into account in the drainage time measurements. This phenomenon will increase the drainage time.

Figure 2.19 Devices for testing foam liquid drainage in foam-soil mixtures (a) a funnel used for tests at atmospheric pressure and (b) an acrylic plunger used for tests at higher pressures (Duarte, 2007).

Özarmut and Steeb (2015) investigated the rheological properties of particle stabilized foam and presented the microstructure of foam-glass beads mixtures. Instead of using tunneling foam and soil, polymer-stabilized shaving foam and glass beads were used in the study because of their easy accessibility and time stability. The authors stated that shaving foam stability is higher than the other liquid foam due to its higher amount of polymers, and non-stabilized foam is not
able to preserve its microstructure in time. The microstructure of the shaving foam and the solid glass particles mixtures was obtained by applying microscope to take images. In the study, the mean bubble diameter of the foam is equal to 51.8 μm. The volume fraction of solid glass particles is 30% in the foam-solid particles mixtures. The microstructure of the foam-glass beads mixture is shown in Figure 2.20. The image on the left side was captured after 2 min, and the right one after 57 min. Although foam was mixed with solid particles, the coarsening (in yellow circle) and coalescence (in red circle) of the foam can be clearly observed. In addition, the authors performed the flow curve test to obtain the type of flow behavior for different volume fraction of solid glass particles (0-30%). They observed a solid-like response when at large solid particles volume fractions (>30%). They explained with an adsorption process of the surfactants at the surface of the glass beads destroying the liquid foam morphology and therefore the foam-particle mixture. To overcome the adsorption phenomenon additional water can be added for larger solid volume fractions. However, the authors only focused on the mixture of foam and dry-solid glass particles.

Figure 2.20 Microstructure of dry solid glass beads-foam mixtures captured after 2 min (left side) and 57 min (right side) (Özarmut and Steeb, 2015).
2.3.2 Mechanisms of particles in stabilizing foams

The use of particles as foam stabilizing materials, with or without surfactants, has been received great interest in recent decades (Hunter et al., 2008). It is well known that solid particles play an important role in the stabilization of foams. Mechanisms of particles stabilizing foams are complex, but overall the reliance of particles to create a steric barrier to coalescence is a major contribution to foam stabilization (Hunter et al., 2008). Additionally, particles on the film between bubbles cause retardation of liquid drainage and therefore increase foam stability. Bridging of particles between bubbles is also a very important process, the bridging particles could be either a monolayer or a bilayer as shown in Figure 2.21. In-depth stabilization mechanisms such as particle detachment energy and maximum capillary pressure will be introduced in the following section.

![Figure 2.21 Particle stabilized foam (Hunter et al., 2008).](image-url)
(1) Particle detachment energy ($\Delta G$)

The particle detachment energy ($\Delta G$) is a useful factor that theoretically affects particles of different contact angles stabilizing foams. The detachment energy is related to the free energies involved in removing an absorbed particle from an air-water interface. As particles build a steric barrier to coalescence, it is obvious that strong particle detachment energy will result in more force being required to disrupt the particle layers and allow coalescence. Figure 2.22 shows the schematic of a solid particle at an air/oil-water interface. The energy required to move the particle from the equilibrium into the bulk water can be calculated as shown in Eq. 2.4 (if buoyancy/gravity effects are neglected).

$$\Delta G = \pi R^2 \gamma_{AW} (1 - \cos \theta)^2$$  \hspace{1cm} (2.4)

where $R$ is the particle radius, $\gamma_{AW}$ is the surface tension at an air-water interface, $\theta$ is the particle contact angle. This energy is considerably large (on the order of $10^3$ kT for a 10 nm particle, 1 kT = $4.1 \times 10^{-21}$ J) at angles of around 90°, but falls quite rapidly as the contact angles decreases or increases. At $\theta < 30^\circ$ or $\theta > 150^\circ$, the contact energy is negligible, suggesting that in principle these particles would not create stable foams.

Figure 2.22 Particle at an air/oil-water interface (Hunter et al., 2008).
(2) Maximum capillary pressure of coalescence ($P_{c}^{\text{max}}$)

Another mechanism that can explain particle stabilized foams is the capillary pressure between two bubbles (Horozov, 2008; Hunter et al., 2008). Hunter et al. (2008) stated that particles residing between two interfaces affect foam stability by reducing the thinning of the drainage interfilm. In particular we consider the pressing force required to bring two bubbles to coalescence with particles holding them apart. This pressing force is described as the capillary pressure, or the pressure difference between the bubbles and the interfilm liquid. Figure 2.23 shows a schematic of particles residing in an interfilm between droplets (or bubbles). If the capillary pressure is zero, the contact line between the particle and bubbles is flat. As drainage occurs, the bubbles form a meniscus around the particles. As drainage increases, the meniscus profile continues to curve around the particles, and the film thickness $H$ decreases. Accordingly, the capillary pressure increases. When $H$ reaches to zero, the bubbles touch each other, and the pressure associated with coalescence is given as the maximum capillary pressure ($P_{c}^{\text{max}}$). Kaptay (2006) proposed an equation for calculating $P_{c}^{\text{max}}$ as shown in Eq. 2.5.

![Figure 2.23 Particles residing in a droplet-droplet interfilm (Kaptay, 2006).](image-url)
where \( P \) is a theoretical packing parameter, which is used to associate the influence of particle concentration and structure on the capillary pressure. Eq. 2.5 indicates that particle size ‘\( R \)’ is inversely proportional to \( P_{c}^{\text{max}} \), showing smaller particles with higher curvature are more effective to prevent bubble coalescence. Also, contact angle directly influences the maximum capillary pressure based on Eq. 2.5. This predicts highest \( P_{c}^{\text{max}} \) values for contact angles equal to zero, and lowest values for contact angles equal to 90°. This is an opposing trend to detachment energy theory, but here makes sense as obviously the more a particle resides in the interfilm, the more the liquid film has to drain around it until coalescence.

(3) Particle-particle interaction

Hunter et al. (2008) concluded that particle-particle forces such as electric double layer repulsion and dipole-dipole repulsion, as well as van der Waals attraction and capillary forces are very important to overall stability of foams, and many dominate interactions over particle-interface attachment. More detailed discussions about particle-particle interaction can be found in (Hunter et al., 2008).

2.3.3 Experimental study on particle stabilized foam

Lots of experimental research has been conducted for particle stabilized foam, particularly in the colloid and interface field. Binks and Horozov (2005) used near spherical fumed silica nanoparticles (mean diameter equals to 30 nm) to investigate the effect of particle hydrophobicity on foam stability in the absence of any surfactant. The authors found that the foams were wet and even after several days contained about 60% water. The foams were very stable to collapse. Particle stabilized foam was imaged through optical microscope and the images reveal that the foam contained micron-sized non-spherical bubbles (5-50 μm) surrounded by branched particle
aggregates. The authors stated that particle aggregation increased the viscosity of the aqueous phase which resulted in slower drainage of the foam films and increased foam stability.

Horozov (2008) discussed the influence of particle size on foam stability. The author concluded that smaller particles should stabilize the foam film better but their attachment to the liquid surface is weaker and vice versa. Therefore, particles should not be very small or too big in order to stabilize foam. The particle size range for foam stabilization through experimental research is between several tens of nanometers and several micrometers. In addition, the author concluded that particle shape, size, concentration and hydrophobicity have been identified as the main factors for the foam stabilization.

2.4 References


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CHAPTER 3

AN EXPERIMENTAL EXAMINATION OF FOAM STABILITY UNDER PRESSURE FOR EPB TBM TUNNELING

Modified from a paper published in *Tunneling and Underground Space Technology* journal

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3.1 Abstract

Foam as a soil conditioning agent has been extensively employed in earth pressure balanced (EPB) tunnel boring machines (TBM) to change the mechanical and hydraulic properties of soils for effective excavation. Foam stability is a critical parameter that influences the performance of foam and foam-conditioned soils. This paper examines foam stability under pressure through a novel foam generation – pressure chamber – foam capture testing system. A comprehensive suite of foam experiments was performed to examine the physical phenomenon of foam degradation and time-dependent foam properties under pressure. Testing results suggest that foam liquid loss is not an effective indicator for characterizing foam stability, while foam volume loss is a more appropriate measure of foam stability. Results also reveal that foam liquid drainage is significantly retarded at higher chamber pressure because foam bubbles are smaller and more uniform. Bubble size was not appreciably different in dry and wet foams.
3.2 Introduction

Foam is routinely used to modify the in-situ soil properties during excavation in EPB TBM tunneling. The desired properties of foam-conditioned soil include elasticity, high compressibility, low shearing resistance, low permeability and flowability/workability (Budach and Thewes, 2015; Milligan, 2000; Mori et al., 2018; Peila, 2014; Thewes et al., 2012; Vinai et al., 2008). When foam is homogeneously mixed with soil, the foam bubbles create particle or clod separation that transforms the in-situ soil into a compressible, elastic medium with sufficiently low permeability and greatly reduced shearing resistance. Sufficient compressibility is needed so that unavoidable changes in TBM advance rate or screw conveyor discharge rate does not translate into significant chamber pressure fluctuations (Mooney et al., 2016; Mori et al., 2017; Psomas, 2002; Quebaud et al., 1998). Conditioned soil in the chamber is subjected to tens to hundreds of cycles of loading due to such advance rate/discharge fluctuations as well as potential rotation of material from lower pressure in the upper portion of the chamber/cutterhead openings to higher pressure in the lower portion of the chamber/cutterhead openings. It is therefore important that the foam behaves elastically, i.e., that plastic strain does not accumulate with loading cycles. Further, the foam serves to restrict water flow through the soil’s pores.

A critical characteristic of foam in conditioned soil is its stability, i.e., the ability of foam to maintain its structure and the aforementioned properties when mixed with soil throughout residency time in the chamber. During normal operations, residency time can vary from 30-90 min depending on the diameter of the TBM, depth of the excavation chamber, advance rate, etc. Because foam stability greatly affects foam-conditioned soil behavior in EPB TBM tunneling, it is important to understand the fundamentals of foam stability in the context of EPB TBM tunneling. Define foam stability as the resistance to the processes of film (bubble wall) thinning.
and coalescence (film rupturing). In film thinning, the liquid films that separate bubbles thin and bubbles approach closely together. In coalescence, the films between bubbles rupture and bubbles merge together to form larger bubbles. State that foam stability is largely determined by liquid drainage and rupture of the thin film. Quebaud et al. (1998) describe ‘foam persistence’ (akin to the meaning of stability) as the capacity to maintain a constant volume and keep the liquid of the matrix from flowing out. As we demonstrate later, maintaining constant volume and limiting liquid drainage are quite different behaviors.

In tunneling, foam stability is typically characterized by its foam liquid half-life, defined as the time necessary for foam to lose one-half of its initial liquid fraction due to drainage. While there is no standardized testing procedure (e.g., ASTM, DIN), the EFNARC (2005) recommends using a filter-funnel filled with 80 g foam subjected to atmospheric pressure to measure liquid drainage and determine foam liquid half-life. The EFNARC (2005) half-life (or liquid drainage) method is widely used and referenced in characterizing foam stability for soil conditioning in tunneling (Milligan, 2000; Psomas, 2002; Quebaud et al., 1998; Thewes et al., 2012).

The rationale for using liquid drainage time as a measure of foam stability for EPB soil conditioning is not well addressed in the literature, but perhaps can be related to non-tunneling based fundamental studies of foam (Rand and Kraynik, 1983). It may be, as alluded to in Quebaud’s definition that the prevailing assumption is that significant liquid drainage results in significant foam volume reduction. To the author’s knowledge, only one publication, by Langmaack (2009), suggests that the foam volume can be used in addition to liquid drainage since the remaining foam volume is more relevant to judge the stability of the foam-soil mixture. The author reports approximately 5% foam volume loss of two different foams over 30 minutes. Unfortunately liquid loss was not reported.
The term ‘stability’ implies the continuance of desired properties without change. It is unclear whether liquid drainage implies an accompanying degradation in desired engineering properties, i.e., elasticity, compressibility, etc. And, at a fundamental level, it is unclear what is physically happening to foam properties during liquid drainage. Further, the traditional liquid drainage test is conducted under atmospheric pressure, while in practice foam and foam-conditioned soils are almost always subjected to pressure in the tool gap, excavation chamber and screw conveyor of an EPB TBM. This paper addresses these issues by examining foam stability in the context of sustained performance as described above. A comprehensive suite of experiments was conducted using a novel foam generation – chamber pressure – foam capture device testing system that allows the measurement of macroscopic and microscopic foam properties under pressures typically experienced in tunneling. The physical phenomena of liquid drainage is characterized and its relationship to foam performance is examined. Finally, the implications on tunneling practice are discussed.

3.3 Test Equipment

A novel foam generation – pressure chamber – foam capture device testing system was developed to perform a comprehensive suite of foam experiments. Figure 3.1 shows a schematic of the laboratory foam generation system and foam testing devices. A liquid flow controller and an air mass flow controller were used to produce a foam solution plus compressed air mixture with the desired foam expansion ratio ($FER$). The foam generator was comprised of closely packed 3 mm glass beads. The foam solution was prepared by mixing water with a commercially available surfactant at a desired concentration ($c_f$). In this study, $c_f = 5\%$ was used for all the foam tests. The foam solution-air mixture then flowed through a 20 cm long and 1.5 cm inside diameter laboratory-scale foam generator.
A 45 cm tall, 11.4 L pressure chamber was used to simulate the pressurized environment that exists in the tool gap, mixing chamber, and screw conveyor during EPB tunneling. Foam behavior with elapsed time, such as liquid drainage, foam and air volume loss, foam compressibility, $FER$, and liquid volume fraction can be measured under pressures up to 5 bar (gauge pressure). Foam was injected into the pressure chamber under a desired pressure with a controlled $FER_p$ (the subscript $p$ implies the chamber pressure) and foam flow rate. This was achieved by adjusting the air flow rate at the air mass flow controller such that it delivered the correct air flow to liquid flow ratio at the prescribed chamber pressure. The foam column height was constant (40 cm) for all of the pressure chamber tests in this study. The literature has shown that foam column height influences foam liquid drainage and liquid drainage-based half-life (Rand and Kraynik, 1983; Saint-Jalmes and Langevin, 2002). We verified this finding through a series of foam liquid drainage tests; the results are presented in Appendix.

A foam capture device was inserted immediately downstream of the foam generator to capture the generated foam for image analysis. The foam capture device, shown in Figure 3.2, is 5 cm in diameter and 0.6 cm thick (deep). A back-pressure regulator downstream of the foam capture device allows the capture of foam at the desired pressure, e.g., equal to the exit pressure of the generator or equal to the chamber pressure. The device was placed on its side to incorporate gravity-driven liquid drainage in the experiment. Once captured, the foam is imaged with elapsed time using an optical microscope. The optical microscope was focused on the uppermost region of the foam sample to eliminate the influence of gravity driven liquid drainage of overlying foam. The imaging area (1 cm × 0.7 cm) is shown Figure 3.2a. This allows detailed analysis of bubble size and bubble size distribution with elapsed time under pressure. A more detailed description of
the foam capture device can be found in Mooney et al. (2016). Detailed testing procedures for the pressure chamber and foam capture tests are shown in Appendix.

Figure 3.1 Schematic of the laboratory foam generation system and foam testing devices (pressure chamber and foam capture device).

Figure 3.2 Schematic of the foam capture device.
3.4 Time Dependent Foam Behavior under Pressure

3.4.1 Atmospheric pressure

A series of tests was performed to characterize foam properties with time, first at atmospheric pressure \( p = 0 \) bar gauge and then at higher pressure \( p = 2 \) and \( 4 \) bar gauge. Testing included foam liquid loss (the traditional approach to measure foam stability), foam compressibility, and foam bubble size distribution over a 60 min duration. In this series, surfactant concentration \( c_f = 5\% \) was used to generate foam. The foam expansion ratio was kept constant over all chamber pressures, i.e., \( FER_p = 20 \). Figure.3a shows the liquid volume, foam volume and air volume loss with time at atmospheric pressure. Definitions for these parameters are shown in Eq. 3.1-3.3.

\[
\text{Liquid loss} = 100 \times \frac{\Delta V_l}{V_{l,0}} \tag{3.1}
\]

\[
\text{Foam loss} = 100 \times \frac{\Delta V_f}{V_{f,0}} = 100 \times \frac{V_{f,0} - V_f}{V_{f,0}} \tag{3.2}
\]

\[
\text{Air loss} = 100 \times \frac{\Delta V_a}{V_{a,0}} = 100 \times \frac{V_{a,0} - V_a}{V_{a,0}} \tag{3.3}
\]

where \( V_{l,0} \) is the total volume of liquid for a foam sample in the chamber, \( V_{f,0} = V_{f,0}/FER \), \( V_{f,0} \) is the initial volume of foam in the chamber, \( \Delta V_l \) is the accumulated volume of drained liquid at time \( t \), \( \Delta V_f \) is the change of foam volume at time \( t \), \( V_f \) is the volume of foam at time \( t \), \( \Delta V_a \) is the change of air volume at time \( t \), \( V_{a,0} \) is the initial air volume and \( V_{a,0} = V_{a,0} - V_{f,0} \), and \( V_a \) is the volume of air at time \( t \). The foam liquid drains faster in the first 40 min and slows after 40 min. The resulting foam volume loss with time is very small compared to the liquid volume loss. For example, at \( t = 35 \) min, 50\% liquid has drained from the foam, however, the corresponding foam volume loss at this time is only 3\%. At \( t = 60 \) min, 74\% liquid has drained from the foam, but the foam volume loss
is only 4%. The decrease in foam volume is very small but the liquid loss is significant. In addition, air loss during the test, calculated as foam volume loss minus liquid volume loss, was determined to be negligible (less than 2%) during the foam aging process as shown in Figure 3.3a, indicating that the foam loss is strictly due to the liquid loss from the foam and not due to release of air. Both liquid loss and foam loss are normalized by their maximum values, and the resulting normalized liquid and foam loss are shown in Figure 3.3b. The normalized liquid loss and foam loss present similar behavior over time. This is due to the negligible air loss in the foam degradation process, thus the foam loss mainly results from the liquid loss from the foam.

Figure 3.3 (a) Time dependent liquid, foam and air loss, and (b) normalized liquid and foam loss for $FER_0 = 20$ foam evaluated at atmospheric pressure.

To investigate the nature of time dependent liquid loss and foam loss, we examine the bubble size distribution over time. A foam sample with $FER_0 = 20$ was imaged using the foam capture device. Figure 3.4a shows three examples of imaged foam bubbles at $t = 0, 30, 60$ min. The images show that there is a significant increase in bubble size over time. The rate of bubble size increase is greater from $t = 0$ to $30$ min than $t = 30$ to $60$ min. The process of bubble size increase over time is due to coalescence and coarsening, and gravity-driven liquid drainage
Liquid in the foam tends to drain due to the force of gravity, thinning the bubble walls. Coalescence is the rupturing of the thin liquid film that separates two adjacent bubbles. Coarsening is the process of the growth of large bubbles at the expense of smaller bubbles and is driven by the diffusion of gas from smaller to larger bubbles. Figure 3.4a also shows that foam initially consisted of spherical bubbles at \( t = 0 \) min; thereafter, bubbles become polyhedral at \( t = 30 \) and 60 min due to increased liquid loss.

The bubble images were analyzed using a commercial image analysis software AmScope to obtain the area-equivalent bubble diameter \( D \) of bubbles, and the corresponding empirical foam bubble size probability and cumulative distributions (Figure 3.4b and c). The Weibull probability density function (PDF) was used to fit the empirical probability distributions because it provided the best fit compared to the other statistical distributions such as normal and log-normal (Magrabi et al., 1999). As shown in Figure 3.4b, the Weibull PDF shows a satisfactory fit to the measured bubble size distributions with elapsed time. The PDF curves reveal that the probability of smaller bubbles \( (D < 0.2 \text{ mm}) \) decreases and the distribution becomes wider over time. Accordingly, the cumulative distribution curves shift to the right over time. These results indicate that bubbles become bigger and foam becomes less uniform in bubble size over time. Furthermore, the time evolution of average bubble diameter was determined from the bubble image analysis and the results are shown in Figure 3.4d. The average bubble diameter increases 120\% in the initial 30 min, and the rate of bubble size growth is noticeably reduced after 30 min (only 30\% increase).

Although the 2D-imaged foam degradation differs from 3D degradation (Marchalot et al., 2008), the 2D bubble images are analyzed to verify if foam liquid loss is properly reflected in the bubble images. From image analysis, the diameter and area of air bubbles in a finite image area
can be obtained, and thus the area-based liquid fraction (ratio of liquid area to image area) can be calculated for each foam image. Moreover, the liquid volume fraction at each time interval, defined as the ratio of liquid volume to foam volume \( \varphi = V_l/V_f \), can be determined throughout the pressure chamber test since the liquid volume and foam volume are measured. Figure 3.4e presents the percent decrease in liquid fraction calculated from the 3D chamber test as well as from 2D image analysis. As shown, the percent change in liquid fraction obtained from the 2D image analysis decreases with elapsed time, indicating that the bubble images capture liquid loss in foam over time. The response is not identical to that of the 3D chamber test measurements because the image analysis is unable to capture the changes in the third dimension.

Changes in \( FER \) during the pressure chamber test, here atmospheric pressure, are shown in Figure 3.5a. \( FER \) increases from 20 to 74 over 60 min due to continuous liquid drainage from the foam. The liquid volume fraction decreases from 0.050 to 0.014 (72% decrease) in 60 min.

The time dependent behavior of foam compressibility can also reflect the stability of a foam sample. In this study, foam compressibility was investigated by conducting cyclic loading in the pressure chamber. Foam compressibility \( C_{foam} \) is defined as the fractional volume change of foam \( (\Delta V_f/V_f) \) divided by the pressure change \( \Delta p \), as shown in Eq. 3.4. \( C_{foam} \) was determined by cycling the chamber pressure 1 bar. The foam was cycled up to twelve times in 60 min. As shown in Figure 3.5b, \( C_{foam} \) increases with elapsed time, i.e., a 6% increase in \( C_{foam} \) from \( t = 0 \) to 60 min. This increase in \( C_{foam} \) is mainly due to foam liquid loss with time that reduces the incompressible liquid fraction of the foam. Therefore, the volume fraction of air in the foam increases, resulting in an increase in \( C_{foam} \). Also shown in Figure 3.5b is the compressibility of air \( C_{air} \) per ideal gas law (assuming the temperature is constant during the test), as shown in Eq. 3.5, where \( p_{ch} \) is the absolute air pressure in the chamber.

44
Figure 3.4 Time dependent bubble images and bubble size analysis for \( FER_0 = 20 \) foam evaluated at atmospheric pressure.

\[
C_{\text{foam}} = 100 \times \frac{\Delta V_f}{V_f \times \Delta p} \quad (3.4)
\]

\[
C_{\text{air}} = 100 \times \frac{1}{p_{sh} + \Delta p} \quad (3.5)
\]
Figure 3.5 (a) Changes in liquid fraction and FER with time, and (b) foam compressibility with time for foam with $FER_0 = 20$ at atmospheric pressure.

3.4.2 Elevated pressure

Time dependent foam behavior (bubble size, liquid and foam loss, and compressibility) was also investigated at $p = 2$ and 4 bar. Foam was injected into the pressurized chamber while maintaining constant $FER_p = 20$ (and a separate set with $FER_p = 10$). As shown in Figure 3.6a, liquid volume loss rates decrease substantially with the increase in chamber pressure. For example, at $t = 30$ min, the liquid loss is 41% at $p = 0$ bar, 15% at 2 bar, and 13% at 4 bar. Figure 3.6b shows the measured liquid loss half-life ($T_{50}$) at various pressures for both $FER_p = 20$ and 10 foams. As shown, $T_{50}$ increases with increase in chamber pressure, and the increased rate of $T_{50}$ is more prominent ($T_{50}$ is doubled) from 0 to 2 bar for both foams. In addition, $FER_p = 20$ constantly shows higher $T_{50}$ than $FER_p = 10$ foam. The result suggests that drier foam has longer liquid loss half-life than wet foam. More detailed comparison for the two foams will be addressed in the later part of the paper.
Figure 3.6 Time dependent liquid, foam and air loss, and normalized liquid and foam loss for \( FER_p = 20 \) foam; and liquid loss half-life for \( FER_p = 20 \) and 10 foams at \( p = 0, 2, \) and 4 bar pressures.

Foam volume loss follows a similar trend with liquid volume loss as shown in Figure 3.6c, at \( t = 30 \) min, foam loss decreases from 2.2\% at \( p = 0 \) bar to 0.8\% at \( p = 4 \) bar. In addition,
accumulated air volume loss are less than 1.5% as shown in Figure 3.6d, revealing the very small foam volume loss is due solely to foam liquid drainage. The normalized liquid volume loss and foam volume loss shown in Figure 3.6e reveal a more constant rate of liquid drainage with time as pressure increases.

To understand why increased pressure reduces the rate of liquid and foam loss, foam bubbles were imaged at $p = 0, 2, \text{ and } 4$ bar with constant $FER_p = 20$. The foam bubble images over time and under pressure are shown in Figure 3.7. The images reveal that foam bubbles are smaller and more uniform with increased chamber pressure, even though the $FER$ was held constant at each pressure. This can be explained by the pressure conditions in the foam generator that is strongly dependent on chamber pressure. Higher chamber pressure translates into higher pressure upstream in the foam generator. As shown by Mooney et al. (2017a), bubble size generated is a function of fluid velocity through the generator, bead size in the generator, and pressure in the generator. Here, the increased foam generator pressure produces smaller bubbles.

The bubble image analysis shows that foam bubbles are smaller and more uniform at higher pressure, and the growth in bubble size with time is noticeably slower with increase in chamber pressure. Based upon the foam degradation mechanisms, foam bubbles with uniform sizes are more stable due to less gas diffusion between bubbles. Another plausible explanation is that it takes more time for liquid to drain from smaller bubbles than from larger bubbles due to increased surface area, and therefore liquid drainage travel path is longer in smaller bubbles.

Changes in $FER$ and liquid fraction $\phi$ were estimated from the pressure chamber tests and are shown in Figure 3.9a and b. These results show that chamber pressure significantly retards the increase in $FER$ and decrease in liquid fraction over time. For example, Figure 3.9a shows that $FER$ increases from 20 to 74 over 60 min at atmospheric pressure. At 4 bar, $FER$ increases only
from 20 to 34 over a 60 min period. Consistent with the ideal gas law prediction, foam compressibility \( (C_{\text{foam}}) \) reduces considerably with increased chamber pressure, as shown in Figure 3.9c.

Figure 3.7 Bubble images with elapsed time for \( FER_p = 20 \) foam at \( p = 0, 2, \text{ and } 4 \) bar gauge pressures.
Figure 3.8 Bubble size analysis for $FER_p = 20$ foam at $p = 0$, 2, and 4 bar pressures.
Figure 3.9 Influence of pressure on $FER$, liquid fraction, and compressibility for $FER_p = 20$ foam at $p = 0$, 2, and 4 bar gauge pressures.
3.5 Influence of Foam Expansion Ratio on Foam Behavior

To investigate the influence of FER on foam behavior, a series of tests was conducted on foam with $FER_p = 10$ to compare with $FER_p = 20$ test results. The influence of FER on bubble size distribution is first presented. Figure 3.10a and b show the comparison of bubble images at $t = 0$ min for the two foam samples at $p = 0, 2$ and $4$ bar. In general, there is little observed difference in bubble size for the two foams from the bubble images. Any difference in bubble size between the two foams would result from variations in foam generation pressure, air and liquid velocities and viscosity. In contrast to the significant influences of chamber pressure and types of foam generator on bubble size, test results reveal that the effect of FER on bubble size is negligible in this study. The corresponding cumulative bubble size distribution curves for the two foams at $t = 0, 30$ and $60$ min are shown in Figure 3.10c. Both bubble size distribution curves shift to the right with time as bubbles grow due to coarsening, coalescence and liquid drainage. The growth of bubble size with time for both FERs can be also be examined by the normalized bubble size distribution as shown in Figure 3.10d. The magnitude of increase in bubble size for $FER_p = 10$ foam is noticeably more than for $FER_p = 20$ foam at pressures. The result reveals that $FER_p = 10$ foam bubbles degrade more quickly than $FER_p = 20$ foam. The findings are consistent with the results from Magrabi et al. (1999), which shows that bubble size growth in drier foam is not as significant as wet foam. According to Magrabi et al. (1999), liquid drainage plays a dominant role in controlling bubble growth in the initial stage of foam degradation process, and then both drainage and coalescence control and in the later phase only coalescence control bubble growth. As there is more liquid to drain for $FER_p = 10$ foam and thus bubbles grow in size more rapidly than the drier foam.
Figure 3.10 Comparison of bubble size distribution for \( FER_p = 10 \) and 20 foams under pressure.
Figure 3.11 shows the growth of average bubble size with time for both foams under pressure. The average $FER_p = 10$ foam bubble size in each condition is smaller than the average $FER_p = 20$ foam bubble size. At $p = 0$ bar, the difference between the average bubble sizes for the two foams become less over time. In addition, the percent increases in $D_{ave}$ for $FER_p = 10$ foam with time in the three pressure conditions are all larger than in the $FER_p = 20$ foam. For example, at $p = 0$ bar, $D_{ave}$ of $FER_p = 10$ foam increases 232% in 60 min, while $D_{ave}$ of $FER_p = 20$ foam increases 185%; at $p = 4$ bar, $D_{ave}$ of $FER_p = 10$ foam increases 99% in 60 min and 92% for $FER_p = 20$ foam. The result reveals the bubble size growth for $FER_p = 10$ foam is more than $FER_p = 20$ foam, although its $D_{ave}$ is less than $FER_p = 20$.

![Figure 3.11 Average bubble diameter for $FER_p = 10$ and 20 foams with time under pressure.](image)

Figure 3.12 presents the stability test results for the two foams under various pressures. The initial foam column heights in the pressure chamber were kept the same for both foams. Multiple tests were performed to insure repeatability in the results. As shown in Figure 3.12a, $FER_p = 10$ foam consistently shows greater liquid loss than $FER_p = 20$ foam at all pressures over time. This is expected because the $FER_p = 10$ foam is wetter. This can further be explained by the
bubble size analysis result which shows that $FER_p = 10$ foam bubbles grow in size more rapidly than $FER_p = 20$ foam bubbles. The difference in liquid loss between the two foams becomes less with the increase in pressure. Foam volume loss for both foams at 0, 2, and 4 bar is shown in Figure 3.12b. In general, $FER_p = 10$ foam exhibits higher foam volume loss than $FER_p = 20$ foam, and the difference is more prominent at atmospheric pressure. Air volume loss of $FER_p = 10$ foam is slightly higher than $FER_p = 20$ foam (Figure 3.12c), but in general the values are negligible (less than 2%). Results from the pressure chamber tests are consistent with the bubble size analysis results for the two foams in the study.

Changes in $FER$ and liquid fraction ($\phi = FER^{-1}$) for the two foams with elapsed time are shown in Figure 3.12d and e, respectively. There is a sharp contrast in liquid fraction change in the two foams. The wetter $FER_p = 10$ foam loses liquid fraction at a significantly greater rate than the drier $FER_p = 20$ foam at all pressures. At $p = 0$ bar, there is a dramatic decrease in liquid fraction for $FER_p = 10$ foam in contrast to a gradual decline for $FER_p = 20$ foam. Similar trends are observed for the two foams at 2 and 4 bar. When combined with the image analysis results that show generally similar bubble size behavior, these results suggest there is excess unnecessary liquid in $FER_p = 10$ foam.

The compressibility ($C_{foam}$) over time for the two foam samples show that $FER_p = 20$ foam is slightly more compressible than $FER_p = 10$ foam at all pressures (Figure 3.12f), as is expected, because $FER_p = 10$ foam lower air fraction than $FER_p = 20$ foam. The compressibility $C_{foam}$ of the two foams become similar over time as the liquid fraction of the foams become closer. The pressure dependent $C_{foam}$ increases slightly with time, mainly due to foam liquid loss with time that reduces the incompressible liquid fraction of the foam. Consequently, the volume fraction of air increases, resulting in an increase in $C_{foam}$. 
Figure 3.12 Comparison of the pressure chamber test results for $FER_p = 20$ and 10 foams under pressure.
3.6 Discussion and Conclusions

The results of a detailed study on foam stability have been described. A combination of macroscopic foam sample behavior tests, with elapsed time and at various pressures, together with microscopic bubble size analysis tests has revealed the time-dependent behavior of foam and the reasons for such behavior. The main findings include that liquid loss is significantly retarded at higher chamber pressures, that foam volume loss accumulation is minimal over time compared to significant liquid volume loss observed, and that drier foam has a longer liquid drainage half life and improved liquid loss stability.

We observed that higher pressure environments yield smaller, more uniform foam bubbles. This uniformity and smaller bubble size lead to less diffusion and coalescence, as well as a longer, more tortuous drainage path. This is why liquid drainage is significantly slowed at higher chamber pressures.

Test results show that the influence of $FER$ on bubble size is negligible in this study. The bubble image analysis shows that drier $FER_p = 20$ bubbles degrade more slowly over time compared to $FER_p = 10$ foam bubbles. Because drier foam has less liquid to drain and the gravity-driven liquid drainage plays a dominant role in the initial phase of foam aging. For similar reasons, drier foam accumulates less liquid loss than wet foam. These results suggest that there is excess unnecessary liquid in wetter $FER_p = 10$ foam.

An important practical finding from this study is that liquid volume loss accumulation, used in the tunneling industry as a measure of foam stability, is strongly influenced by pressure. The liquid loss half-life more than doubled from $p = 0$ bar (atmospheric pressure) to $p = 2$ bar. Because most if not all EPB soil conditioning occurs under pressures greater than atmospheric pressure and extending up to 5-6 bar, the liquid drainage half-life of foam in-situ is much greater
than the EFNARC atmospheric pressure test indicates. To the effect that liquid loss half-life is used in design, this should be adjusted to the excavation chamber pressures anticipated along the tunnel project alignment.

Perhaps a more significant finding, however, is that liquid volume loss, the basis upon which the tunneling industry evaluates foam stability as evidenced by the EFNARC test, is not matched by appreciable foam volume loss. Despite the significant levels of liquid loss accumulation over elapsed time observed in all tests, foam volume loss was found to be minimal (less than one tenth of liquid loss) and air volume loss was found to be negligible (less than 2% over 60 minutes). This finding was made through a series of unload-reload tests over time in an attempt to agitate the foam and test its desired properties. Considering the intended goals of soil conditioning, the persistence of foam volume and more specifically occluded air volume within foam bubbles is what maintains the desired conditioned soil behavior. For example, the reduction in shear strength that leads to workability/flow, reduced abrasivity, torque, etc., is maintained by expanding soil particles to reduce interparticle friction. Reduced permeability is maintained by filling the soil voids with occluded air in bubbles. The persistence of these desirable engineering properties, i.e., the definition of stability, is directly controlled by the persistence of occluded air and not the liquid drainage. This calls into question the use of liquid loss as a measure of foam stability. Our findings suggest that foam volume loss should be used as the more appropriate measure. The specifics of such a test could follow the procedure used in this study, including evaluation at the pore water and chamber pressures anticipated along the project alignment.

3.7 Acknowledgments

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CHAPTER 4

EXPERIMENTAL STUDY ON THE STABILITY OF FOAM-CONDITIONED SAND
UNDER PRESSURE IN THE EPB TBM CHAMBER

4.1 Abstract

Proper soil conditioning is critical for effective EPB TBM tunneling. Foam as a soil conditioner has been extensively used in EPB TBM tunneling to change the excavated soil properties. A critical characteristic of foam-conditioned soil is its stability, i.e., the ability to maintain the engineering properties throughout the residency time (30-90 min) in the mixing chamber. A comprehensive suite of experiments was conducted for foam-conditioned soil at both microscale and macroscale to investigate the fundamentals of foam-soil interaction and engineering properties of foam-conditioned soil. A foam-soil capture device and an optical microscope were used to capture bubble-grain images at a microscale under pressure. A pressurized testing chamber (PTC) was used to examine the stability of the mechanical properties of foam-conditioned soil. The compressibility, vane shear strength, pore pressure, and effective stress of foam-conditioned soil with elapsed time were obtained from the PTC test. Test results reveal that there are less changes in bubble size distribution for foam in the foam-soil mixtures than foam itself, indicating that soil particles help stabilize foam bubbles. Mechanisms of soil particles stabilizing foams are discussed in the paper.

4.2 Introduction

In earth pressure balanced (EPB) tunnel boring machine (TBM) tunneling, soil conditioning is critical for effective TBM performance. Foam as a soil conditioning agent has been widely used in EPB TBM tunneling to change the mechanical and hydraulic properties of
excavated soils. High compressibility and elasticity, low shearing resistance, abrasivity, and permeability, and improved flowability are the desired properties of foam-conditioned soil (Budach and Thewes, 2015; Milligan, 2000; Mori et al., 2018; Peila, 2014; Thewes et al., 2012; Vinai et al., 2008). A lot of research has been conducted to study the properties of foam-conditioned soil including compressibility, shear strength, abrasivity and rheological properties (Bezuijen et al., 1999; Budach and Thewes, 2015; Mooney et al., 2016; Mori et al., 2018; Peila, 2014; Peila et al., 2007; Psomas and Houlsby, 2002; Quebaud et al., 1998; Thewes et al., 2012; Vinai et al., 2008). Research has also been conducted on the stability of foam itself, both under atmospheric pressure (Rand and Kraynik, 1983; Schramm and Wassmuth, 1994a) and at pressures experienced in the excavation chamber (Wu et al., 2018).

However, little is mentioned in the literature about the stability of foam-conditioned soil in the EPB TBM chamber. The stability of foam-conditioned soil, defined as the persistence of desired engineering properties, is a critical characteristic. In EPB tunneling, foam must maintain its desired engineering properties from the time of injection at the cutterhead, through the mixing process in the excavation chamber, and into the screw conveyor for transport to the belt conveyor. This period constitutes 30-90 minutes depending on TBM size, production rates and cycle times (excavation plus ring build). In addition, the accumulated air in the crown of the excavation chamber is a common and significant concern, and it is unclear if this comes from foam bubble instability when mixed with soil or from small bubble migration upwards through soil void space. Here the foam bubble instability means the burst or collapse of bubbles when mixed with soil. And for each case, what are the mechanics and characteristics that govern instability and migration.

To improve understanding of foam-conditioned soil stability, a series of soil conditioning experiments was performed under pressure with investigation at both the bubble scale and macro
sample scale. A foam-soil capture device was developed to investigate foam bubble stability in foam-soil mixtures under pressure. Foam bubble size distributions of foam-soil mixtures were obtained with elapsed time, and the results were compared with the foam-only scenario. Further, a pressurized testing chamber (PTC) was used to investigate the stability of the mechanical properties of foam-conditioned soil including compressibility, vane shear strength, and effective stress with elapsed time.

4.3  Background

Previous research has found that pressure has a significant influence on both foam and foam-conditioned soil properties (Mooney et al., 2016; Mooney et al., 2017b; Mori et al., 2018; Williamson G.E. et al., 1999; Wu et al., 2018). A foam-conditioned soil that shows ideal properties under atmospheric pressure ($p = 0$ bar gauge) can behave poorly at higher pressure. Mooney et al. (2017b) conclude that the foam-conditioned soil exhibits foam-controlled behavior when the chamber pressure is below a transition stress and soil-like behavior when the chamber pressure is above this transition stress. As the chamber pressure increases and reaches the transition stress, considerable grain-grain contact initiates and thereafter controls behavior. The authors state that the transition stress is influenced by the foam injection ratio ($FIR$) that is pressure dependent. Also, research has found that foam-conditioned soil in EPB tunneling shows ideal properties when its void ratio is above the maximum void ratio/porosity (Bezuijen et al., 1999; Maidl, 1996; Mori et al., 2018). When the void ratio is greater than the maximum void ratio $e_{\text{max}}$, the soil grains are nominally in contact with each other and the effective stress is very low.

The pressure dependent conditioning parameter foam expansion ratio ($FER_p$) is defined as the volumetric fraction of generated foam to the used surfactant solution (Eq. 4.1); and the pressure dependent foam injection ratio ($FIR_p$) is the volumetric fraction of generated foam to excavated...
soil (Eq. 4.2). Both $FER_p$ and $FIR_p$ at pressure $p$ can be determined by $FER_0$ and $FIR_0$ at atmospheric pressure ($p = 0$ bar gauge) according the ideal gas law, as shown in Eq. 4.3 and 4.4 (Mooney et al., 2016; Mori et al., 2018).

\[
FER_p = \frac{V_{F,P}}{V_L} = \frac{V_{A,P} + V_L}{V_L} \quad (4.1)
\]

\[
FIR_p = \frac{V_{F,P}}{V_{ES}} \quad (4.2)
\]

\[
FER_p = 1 + (FER_0 - 1) \frac{1}{p+1} \quad (4.3)
\]

\[
FIR_p = FIR_0 \frac{FER_p}{FER_0} \quad (4.4)
\]

where $V_{F,P}$ is the volume of foam at pressure of $p$, $V_L$ is the volume of liquid (foaming agent), $FER_0$ is the foam injection ratio at atmospheric pressure, $V_{ES}$ is the volume of excavated soil, and $FIR_0$ is the foam injection ratio at atmospheric pressure.

### 4.4 Test Method and Plan

#### 4.4.1 Testing pressure

A foam-soil capture device was developed and an optical microscope with high resolution (1 µm/pixel) was used to investigate the grain-bubble interaction and bubble size distribution of foam-conditioned soil under pressure. The device, shown in Figure 4.1 is an extension of the foam capture device developed to examine foam-only behavior (Wu et al., 2018). The foam-soil capture device is made of clear acrylic to visualize the foam-conditioned soil sample. The sample container captures a 5 cm diameter and 1 cm thick (deep) foam-conditioned soil sample.
Figure 4.1 Foam-soil capture device and microscope for microscale study: (a) front view and (b) side view of the testing system; and (c) schematic of the foam-soil capture device.

The sample preparation procedure includes the following: (1) add the desired additional water content to 30 g of natural soil; (2) mix the soil with the desired $FER_0$ and $FIR_0$ under atmospheric conditions; (3) fill the capture device with foam-conditioned soil and fasten the Plexiglas lid under an O-ring seal with the set screws. Figure 4.2a shows the picture of a foam-conditioned soil sample in the capture device at atmospheric pressure ($p = 0$ bar). Once the sample is ready in the capture device, the desired air pressure is applied and the foam-soil capture device is placed on its side to incorporate the effect of gravity in the experiment. Figure 4.2b shows the conditioned soil sample after applying 1 bar air pressure.
Figure 4.2 Pictures of a foam-conditioned soil sample in the capture device (a) at atmospheric pressure and (b) after applying desired air pressure (here $p = 1$ bar).

It has to be noted that the externally applied air pressure in conditioned soil is different than the internal air pressure within a foam bubble. Figure 4.3a shows the schematic of foam-conditioned soil at the grain scale that is compressed by an external pressure $p$. This means that the pore liquid pressure $p_L = p$. For a foam bubble with radius $r$ as shown in Figure 4.6b, its internal air pressure $p_A$ and external liquid pressure $p_L$ follow the Young-Laplace equation: $p_A - p_L = 2\gamma/r$, where $\gamma$ is the surface tension. In this case, $p_A > p_L = p$. In addition, the intergranular or effective stress of foam-conditioned soil is negligible and can reach a maximum in accordance with the self-weight of the soil grains. There is no capability in the foam-soil capture device to externally apply effective stress.

To take bubble-scale images of foam-conditioned soil with elapsed time, a microscope is mounted to capture foam-soil images. The position of the microscope is adjusted to focus on the uppermost region of the conditioned soil as indicated in Figure 4.2b. Then images are taken with elapsed time (i.e., every 5 min) for 60 min test period. The imaging area is 5.3 mm × 3.9 mm for each image with a resolution of 1 μm/pixel. Bubble sizes of each foam-soil image is analyzed through a commercial image analysis software (AmScope) to obtain the bubble size distribution.
To compare the foam bubble stability in foam-conditioned soil and bubbles in foam only condition, foam samples were also captured and imaged at the same pressures, and bubble images for the foam only conditions were also analyzed to obtain bubble size distributions.

Besides the microscopic study on the stability of foam-conditioned soil, mechanical properties of conditioned soil were also investigated. A pressurized testing chamber (PTC) (Figure 4.4) was used to measure the compressibility, vane shear strength, and pore (liquid) pressure of conditioned soil by applying total pressure to the sample. The PTC device was described in detail in (Mori et al., 2018; Mori et al., 2015). The PTC testing involved the application of a total vertical stress to a 4 L sample of conditioned soil (or untreated soil) via a rigid top platen and external spring. The loading is undrained so that excess pore pressure induced during loading has no drainage path to dissipate. The axial deformation of the sample is recorded during the test.

The compressibility of conditioned soil was measured by applying a 1 bar increment of total vertical stress to the sample, and the compression of the sample can be measured through the
The compressibility test was performed every 10 min in a 60 min time period to study the stability. The compressibility \( C \) of the sample can be calculated from Eq. 4.5:

\[
C = 100\% \times \frac{\Delta V_t}{V_{t,0}\Delta \sigma_{vt}}
\]

(4.5)

where \( V_{t,0} \) is the initial total volume of foam-conditioned soil before each loading, \( \Delta \sigma_{vt} \) is the change of the applied total vertical stress, here \( \Delta \sigma_{vt} = 1 \) bar, \( \Delta V_t \) is the change of total volume of foam-conditioned soil.

A 70 mm × 70 mm shear vane was used to measure the vane shear strength of foam-conditioned soil at desired total vertical stress. The vane shear strength \( \tau_v \) is estimated according to ASTM D2573 from the torque measured by a torque wrench, Eq. 4.6:

\[
\tau_v = \frac{T}{\pi d_v^2(h_v + \frac{d_v}{6})} = \frac{6T}{4\pi d_v^3}
\]

(4.6)

where \( T \) is the measured torque, \( d_v \) is the diameter of the vane, and \( h_v \) is the height of the vane. Because the shear stress is also dependent on the shear rate, a constant low rotation speed of approximately 1 rpm was used for all vane shear tests. The vane shear testing was performed every 10 min in a 60 min time period. A pore pressure transducer was connected onto a port on the top platen to measure the pore pressure of conditioned soil during testing.

For all the PTC tests in this study, the test soil was pre-conditioned to a saturated water content of 19.5% with an in-situ density of 2.1 g/cm\(^3\), \( FIR_p = 50\% \) and \( FER_p = 10 \) under total pressure of \( p = 0 \) bar, 1 bar and 2 bar. The saturated water content \( w = 19.5\% \) was used in the PTC tests. In this case, the foam-conditioned sand pores outside of the bubbles should be “saturated” based on the assumption that foam bubbles are occluded air. The test soil and foam with desired volume were mixed in a mixing bowl at atmospheric condition until a homogeneous consistency is reached, and then the conditioned soil sample is placed into the PTC chamber.
4.4.2 Test methodology

In tunneling practice, foam is typically injected from the cutterhead face into the tool gap and from the bulkhead into the excavation chamber (plenum) under pressure. However, in laboratory testing, it is difficult to homogenously mix foam and soil under pressure while injecting foam into a pressurized environment. The need for homogeneously mixed conditioned soil requires that the foam and soil be mixed under atmospheric pressure and then placed under pressure in the testing devices. Because this is different than what is done in practice, we investigated the difference of foam bubble size for foam produced at a certain pressure and foam that are generated at atmospheric pressure and then compressed to that pressure. This verification helps us to understand if the laboratory preparation method for foam-conditioned soil is valid comparing to practice.
The foam capture device proposed by Wu et al. (2018) was used in this study to capture foam bubble images at different pressure conditions. The bubble images were analyzed using the image analysis software (AmScope) to obtain bubble size distributions. Figure 4.5a shows the image of foam bubbles that are generated at atmospheric pressure and then are compressed by 1 bar air pressure, and Figure 4.5b shows the foam bubbles are generated at 1 bar pressure. The corresponding bubble size distribution curves for the two foam samples are shown in Figure 4.5c. As shown, the bubble size distribution curves for the two foam samples are very close. Similar comparison tests were performed at 2 bar. As shown in Figure 4.6, the bubble size distribution for foam that is compressed at 2 bar air pressure is close to the one that is generated at 2 bar.

Results from Figure 4.5 and Figure 4.6 show that the bubble size distribution for foam that are compressed at a certain pressure is very close to the one for foam that are generated at that pressure. Therefore, it is reasonable to assume that the foam-soil sample preparation method in this study is valid to represent the foam properties in tunneling practice.

Figure 4.5 (a) Image of foam bubbles that are generated at atmospheric pressure ($p = 0$ bar) and compressed at $p = 1$ bar air pressure, (b) image of foam bubbles generated at $p = 1$ bar pressure, and (c) the corresponding bubble size distribution curves for the two foams.
Figure 4.6 (a) Image of foam bubbles that are generated at atmospheric pressure and compressed at $p = 2$ bar air pressure, (b) image of foam bubbles generated at $p = 2$ bar pressure, and (c) the corresponding bubble size distribution curves for the two foams.

4.4.3 Test soil and conditioning parameters

A poorly graded medium sand (SP) was used for all tests. The grain size distribution curve for the sand is shown in Figure 4.7. The $D_{10}$, $D_{50}$ and $D_{90}$ for the sand are 0.28, 0.76 and 2.0 mm, respectively. The minimum ($e_{\text{min}}$) and maximum ($e_{\text{max}}$) void ratios for the sand are 0.52 and 0.76, respectively, according to ASTM D4253 and D4254.

Figure 4.7 Grain size distribution of the test sand.
The test sand is air dried with a water content of 0.6%. For the soil conditioning testing, water is added to the sand to bring it to the desired water content. The desired water content is normally the in-situ soil water content in a specific project adjusted for water replacement. Since we are not simulating a specific project in this study, we chose a reasonable water content of 15% and a moist density of 2.01 g/cm\(^3\) for the microscopic study. Moreover, we used the saturated water content of 19.5% and a density of 2.1 g/cm\(^3\) of the test soil for the PTC tests to accurately measure pore (liquid) pressure in foam-conditioned soil samples (assuming foam bubbles are occluded air).

Foam was produced using a laboratory foam generating system that is able to precisely control the flow rates of foam solution and compressed air with a desired foam expansion ratio \((FER_0)\). A more detailed description of the foam generating system is presented in Wu et al. (2018). A common industrial surfactant was used to produce foam. The surfactant was diluted in water prior to foaming with a concentration of 5% by volume.

Based on the previous study of foam-conditioned soil under pressure (Bezuijen et al., 1999; Mori et al., 2018), the conditioned soil exhibits ideal properties for EPB tunneling when above its maximum void ratio. In this study, \(FER_p = 10\) and \(FIR_p = 50\%\) were used for each test. According to Equation 3 and 4, the corresponding \(FER_0\) and \(FIR_0\) are shown in Table 4.1.

<table>
<thead>
<tr>
<th>(p) (bar)</th>
<th>(FER_p)</th>
<th>(FER_0)</th>
<th>(FIR_p) (%)</th>
<th>(FIR_0) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>19</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>28</td>
<td>50</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 4.1 Soil conditioning parameters used for tests at different pressures.
4.5 Microscopic Study on the Stability of Foam-conditioned Soil

4.5.1 Test results

Figure 4.8a shows an image of foam-conditioned sand at atmospheric pressure \((p = 0 \text{ bar gauge})\) with conditioning parameters of \(FIR_0 = 50\%\) and \(FER_0 = 10\). The void ratio of this conditioned sand sample is 0.80. As shown, the foam bubbles appear in the pores between soil grains and serve to expand the grain structure of the sand. Some large bubbles exhibit non-spherical shapes because of surrounding soil grains. According to the scale in Figure 4.8a, most of the bubble sizes are around 0.10-0.20 mm, though there are several large bubbles with diameters between 0.4-0.5 mm. The largest bubble diameter in this image is 0.55 mm. The image analysis software AmScope was used to obtain the area-equivalent bubble size distribution which is shown in Figure 4.8b. The bubble size distribution is relatively uniform. Bubble diameters range from 0.02 mm to 0.55 mm, and the average bubble diameter is 0.14 mm in this image.

For comparison, the soil particle size distribution and the estimated pore size distribution of the conditioned soil are also plotted in Figure 4.8b. Soil particle size ranges from 0.07 mm to 9.0 mm. Soil particles have more widely distributed sizes compared to foam bubbles. Soil pore radius \(r_i\) can be estimated from a known soil particle size distribution and soil void ratio according to Eq. 4.7 from Arya and Paris (1981) and Arya et al. (1999):

\[
r_i = 0.816 R_i \sqrt{en_i (1-\alpha_i)}
\]

where \(R_i\) is the mean particle radius for the \(i\)th particle-size fraction, \(e\) is the void ratio, \(\alpha_i\) is the scaling parameter, here \(\alpha_i = 1.3\) is used for sand as Arya and Paris (1981) suggested, \(n_i\) is the number of spherical particles \((\text{g}^{-1})\), for each fraction of the particle-size distribution is calculated from

\[
n_i = \frac{3w_i}{4\pi \rho_s R_i^3}
\]
where \( w_i \) is fraction solid mass (g/g), \( \rho_s \) is the particle density (g/cm\(^3\)).

As shown in Figure 4.8b, the estimated pore size (diameter) distribution curve for foam-conditioned sand is widely distributed, ranging from 0.02 mm to 9.0 mm. The pore sizes of conditioned sand are larger than the bubble sizes. For example, 80% of the pores are larger than 0.1 mm, the mean bubble size. Further, 50% of the pores are larger than 0.30 mm, while 90% of the foam bubbles are smaller than 0.30 mm. This suggests that foam bubbles would see little resistance to migration. However, the larger pore size distribution is not sufficient for bubbles to migrate. Foam bubbles remain trapped in the pore space when the bubbles are surrounded by soil particles. Continuous pathways of voids filled with soil water enables bubbles to migrate on top due to the buoyance force and the effect of gravity, and the diameter of such continuous pathway should be at least on the same order with the diameter of bubbles.

![Figure 4.8](image)

**Figure 4.8** (a) Foam-soil interaction image \((p = 0 \text{ bar}, FIR_0 = 50\%)\), and (b) particle size distribution of the test sand, bubble size distribution of foam in the conditioned sand, and the estimated pore size distribution of the conditioned sand.

To investigate the stability of foam bubbles in the void space, images of foam-conditioned sand were captured with elapsed time. Figure 4.9a shows the bubble-grain images at \( t = 0, 30 \) and
60 min at atmospheric pressure \((p = 0 \text{ bar})\). The bubble size increases with elapsed time, especially for bubbles pressing against each other in the void space. For bubbles sandwiched between soil particles, little change in bubble size was observed over time. For example, as shown in Figure 4.9a, the highlighted bubble in purple increases in size with elapsed time as bubble degradation occurs between this bubble and its surrounding bubbles. Bubble size increases with time is due to coalescence, coarsening, and gravity-driven liquid drainage (Fameau and Salonen, 2014; Magrabi et al., 1999; Schramm, 1992; Weaire and Hutzler, 1999). Coalescence involves the binding of two or more foam bubbles where the interfacial film drains and is eventually ruptured forming a single large bubble (Hunter et al., 2008). Coarsening is the process of the growth of large bubbles at the expense of smaller bubbles and is driven by the diffusion of gas from smaller to larger bubbles. Liquid in the foam tends to drain due to the force of gravity, thinning the bubble walls. For the highlighted bubble in the green dashed circle, there is negligible change in bubble size over 60 min. This is because the bubble is sandwiched by soil particles that provide a barrier from other bubbles. More detailed analysis on the mechanisms of particle stabilizing foam will be introduced in Section 4.5.2.

The corresponding cumulative bubble size distributions with elapsed time are shown in Figure 4.9b. As shown, bubbles size increases and the cumulative bubble size distribution curve shifts to the right from \(t = 0 \text{ min}\) to 30 min. There is little change in bubble size distribution from \(t = 30 \text{ min}\) to 60 min. For comparison, the soil particle size distribution and pore size distribution are also shown in Figure 4.9b. We assume the void ratio of foam-conditioned soil does not change over time so the pore size distribution is the same. As shown, the pore size distribution is consistently larger than bubble size distribution over time, although the bubble size increases over time.
Figure 4.9 (a) Foam-soil interaction with elapsed time \((t = 0, 30, \text{ and } 60 \text{ min})\) at \(p = 0\) bar and \(\text{FIR}_0 = 50\%\), and (b) bubble size distribution curves of foam in conditioned soil with elapsed time, in comparison with the particle size distribution of the test sand and the estimated pore size distribution.

Foam-soil interaction was also investigated at applied pressures of \(p = 1\) and 2 bar. The bubble-soil particle images with elapsed time \((t = 0, 30, \text{ and } 60 \text{ min})\) for 1 bar and 2 bar are shown in Figure 4.10a and b, respectively. As shown, bubble sizes are much smaller at 2 bar than those at 1 bar. At both pressures, foam bubbles become larger with time and the number of bubbles decreases. The corresponding bubble size distribution at \(p = 1\) and 2 bar are shown in Figure 4.10c and d, respectively. With elapsed time, the bubble size distribution shifts to the right and bubble size slightly increases at both pressures. The pore size distributions for the conditioned soil at \(p = 76\)
1 bar and 2 bar should be the same as the pore size at \( p = 0 \) bar. Because the void ratio of the conditioned soil is the same at all pressures by keeping \( FER_p \) and \( FIR_p \) constant. Similar to the \( p = 0 \) bar condition, the pore size distributions at both \( p = 1 \) bar and 2 bar are larger than the bubble size distributions with elapsed time. With the same pore size distribution, it is more readily for smaller bubbles to migrate from conditioned soil at higher pressure. We observed that some foam bubbles escaped from the conditioned soil sample after we applied pressure onto the sample for both \( p = 1 \) bar and 2 bar tests. Such initial bubble migration (or separation) occurs very fast (within 1-2 min) after the pressure is applied. As we started taking images, we did not observe apparent bubble migration with time as shown in Figure 4.10a and b. Further bubble migration requires agitation or pressure changes for the conditioned soil in the chamber. This study did not incorporate agitation in all the tests.

The stability of foam mixed with soil was compared with the stability of foam by itself (foam-only). Foam samples were prepared with a similar procedure with the foam-conditioned soil samples. Foam with the desired \( FER_0 \) was generated and placed into the capture device, and then the desired pressure was applied to the sample. \( FER_p \) was kept constant (here \( FER_p = 10 \)) at all pressures. The capture device was placed on its side to allow the effect of gravity. Foam bubbles were imaged by the microscope with elapsed time. Bubble images were then analyzed to obtain bubble size distributions.

Figure 4.11 shows the accumulated bubble size distributions and probability density function (PDF) of foam-only and foam in soil. The Weibull probability density function was used to fit the empirical probability distributions because it provided the best fit compared to the other statistical distributions such as normal and log-normal (Magrabi et al., 1999). As shown in Figure 4.11a, at \( p = 0 \) bar, bubble size in the foam-soil mixtures increases slightly with elapsed time, while
Figure 4.10 Foam-soil interaction with elapsed time ($t = 0$, $30$, and $60$ min) at $p = 1$ and $2$ bar, and bubble size distribution curves of foam in conditioned soil with elapsed time, in comparison with the particle size distribution of the test sand and the estimated pore size distribution.

It increases significantly in the foam only condition. The PDF curves illustrate that the probability of smaller bubbles ($D < 0.2$ mm) decreases and the distribution becomes wider over time for both foam-soil and foam only conditions. However, the PDF curves for bubbles in foam only condition
change more significantly than those in the foam-soil condition as indicated in Figure 4.11b. At $p = 1$ bar, there is a negligible change in bubble size for bubbles of 60% smaller ($D < 0.15$ mm) in the foam-soil condition. Larger bubbles ($D > 0.15$ mm) increase in size with elapsed time (Figure 4.11c). Similar to the $p = 0$ bar condition, bubble size increases more significantly in the foam only condition than in the foam-soil condition for both the accumulated bubble size distribution curves and PDF curves (Figure 4.11c and d). Foam bubble size decreases significantly at $p = 2$ bar for both foam-soil and foam only (Figure 4.11e). There is a very slight change in bubble size distribution for both foam-soil condition and foam only, but more changes in bubble sizes are found in the foam-only condition. Similar trends are observed in the PDF curves for both conditions as shown in Figure 4.11f.

Test results reveal that foam bubbles are more stable in the presence of soils, indicating that soil particles help stabilize foam bubbles. As mentioned previously, bubble size increases with time is due to coalescence, coarsening, and gravity-driven liquid drainage. These mechanisms also affect the stability of foam-conditioned soil. However, the mechanisms of soil stabilized foam are more complex as the solid phase is included in the air-water interface system. A detailed theoretical analysis of particle stabilized foam based on previous study is discussed in the following section.

4.5.2 Mechanisms of particles stabilizing foams

Solid particles play an important role in the stabilization of foams. The overall mechanism of particles stabilizing foams is that solid particles create a steric barrier to bubble coalescence and coarsening (Hunter et al., 2008). In addition, particles on the film between bubbles cause retardation of liquid drainage and therefore increase foam stability. In-depth stabilization mechanisms are introduced as follows.
Figure 4.11 Foam bubble size distribution with elapsed time for bubbles in foam-soil and foam only conditions at $p = 0$, 1, and 2 bar.

The particle detachment energy ($\Delta G$) is a factor that affects particles stabilizing foams (Hunter et al., 2008). The detachment energy is related to the free energies involved in removing
an absorbed particle from an air-liquid interface. As particles build a steric barrier to coalescence, it is obvious that strong particle detachment energy will result in more force being required to disrupt the particle layers and allow coalescence. The particle detachment energy ($\Delta G$) can be calculated as shown in Eq. 4.9 (if buoyancy/gravity effects are neglected).

$$\Delta G = \pi R^2 \gamma_{AW} (1 - \cos \theta)^2$$ (4.9)

where $R$ is the particle radius, $\gamma_{AW}$ is the surface tension at an air-liquid interface, $\theta$ is the particle contact angle.

Another mechanism that can explain particle stabilized foams is the capillary pressure between two bubbles (Horozov, 2008; Hunter et al., 2008; Kaptay, 2006). Here we consider the capillary pressure required to bring two bubbles to coalescence with particles holding them apart. Capillary pressure ($P_c$) is defined as the pressure difference between the bubbles ($P_1$) and the interfilm liquid ($P_2$). Figure 4.12 shows a schematic of particles residing in an interfilm between bubbles. As drainage occurs, the bubbles form a meniscus around the particles. As drainage increases, the meniscus profile continues to curve around the particles, and the film thickness $H$ decreases. Accordingly, the capillary pressure increases. When $H$ reaches to zero, the bubbles touch each other, and the pressure associated with coalescence is given as the maximum capillary pressure ($P_{c,max}$). Kaptay (2006) proposed an equation for calculating $P_{c,max}$ as shown in Eq. 4.10.

$$P_{c,max} = \pm P \frac{2\gamma_{AW}}{R} \cos \theta$$ (4.10)

where $P$ is a theoretical packing parameter, which is related to the influence of particle concentration and structure on the capillary pressure. Eq. 4.10 indicates that particle size $R$ is inversely proportional to $P_{c,max}$, showing smaller particles are more effective to prevent bubble coalescence.
Figure 4.12 Particles residing in a bubble-bubble interfilm effecting $P_c^{max}$ for coalescence (modified from Kaptay (2006)).

In addition, Hunter et al. (2008) concluded that particle-particle forces such as electric double layer repulsion and dipole-dipole repulsion, as well as van der Waals attraction and capillary forces are important to overall stability of foams. More detailed theoretical explanation of these particle-particle interactions at liquid-air interfaces can be found in Hunter et al. (2008).

The above-mentioned mechanisms can be applied to explain the stability of foam bubbles in soil. Test results has shown that there is much less change in bubble size for bubbles in foam-soil mixtures than foam itself. And for bubbles sandwiched between soil particles, there is negligible change in bubble size over time. On one hand, for soil grains attached on bubble films, it requires energy/force to remove the soil particles for bubbles to coalescence, and this energy should be larger than the particle detachment energy as shown in Eq. 4.9. On the other hand, as drainage occurs, foam liquid has to drain around soil particles to coalescence, and the pressure to coalescence has to be larger than the maximum capillary pressure $P_c^{max}$. In addition, soil particle size also influences foam stability in conditioned soil. According to Eq. 4.10, smaller soil particles result in higher $P_c^{max}$ and therefore bubbles are more stable. However, smaller particles have lower particle detachment energy $\Delta G$ according to Eq. 4.9. Therefore, in order to have stable foam-conditioned soil, soil particles should not be too small or too large. Further research needs to be
conducted to investigate the influence of soil particle size on foam stability. Previous research has found that foam with smaller and more uniform bubble is more stable (Wu et al., 2018). This finding is still applicable when foam is mixed with soil, especially for foam bubbles pressing against each other in the void space. For bubbles which are sandwiched between soil particles, the bubble-grain interaction mechanisms as mentioned above dominant the foam stability.

### 4.6 Stability of Engineering Properties

The above study investigates the stability of foam-conditioned soil at the microscale. This section discusses the stability of the engineering properties of foam-conditioned soil under pressure. The properties including compressibility, vane shear strength, and pore (liquid) pressure of conditioned soil were measured through a series of PTC tests. Figure 4.13 shows the PTC test results for foam-conditioned soil samples at different pressure conditions.

Figure 4.13a shows the test results of the compressibility of foam-conditioned soil with $FIR_p = 50\%$ and $FER_p = 10$ under total vertical stresses of 0 bar, 1 bar and 2 bar with elapsed time. At $t = 0$ min, the compressibility of foam-conditioned soil at atmospheric pressure ($p = 0$ bar) is $15.2 \%/bar$. There is little change in compressibility with elapsed time. At $p = 1$ bar, the compressibility is $7.9 \%/bar$ at $t = 0$ min, and it ranges between $7.0 \%/bar$ to $8.9 \%/bar$ over 60 min. Similarly, at $p = 2$ bar, the compressibility of foam-conditioned soil shows little change over time, ranging between $3.5-4.4 \%/bar$ over time. The results suggest that there are no significant changes in the compressibility of foam-conditioned soil in 60 min.

The void ratio $e$ of foam-conditioned soil under pressure can be calculated according to Eq. 4.11 and 4.12:

\[
n = \frac{V_v}{V_t} = 1 - \frac{V_s}{V_t} = 1 - \frac{m_d}{G_d V_t} \tag{4.11}
\]

\[
e = \frac{n}{1 - n} \tag{4.12}
\]
where $n$ is the porosity of the foam-conditioned soil at time $t$, $V_v$ is the volume of voids in the foam-conditioned soil, $V_t$ is the total volume of conditioned soil at time $t$, $m_d$ is the mass of solid of the test soil, $G_s$ is the specific gravity of the test soil. Figure 4.13b shows the void ratio of foam-conditioned soil at total pressure of 0 bar, 1 bar, and 2 bar with elapsed time. The maximum void ratio of the test sand $e_{\text{max}} = 0.76$ and $1.2e_{\text{max}} = 0.92$ are also indicated in Figure 4.13b for reference. According to Mori et al. (2018), foam-conditioned soil behavior is governed by the contained air when the $e/e_{\text{max}}$ ratio is larger than 1.2, and below $e_{\text{max}}$ the foam-conditioned soil behavior is governed by grain-to-grain interaction. As shown in Figure 4.13b, the void ratio of foam-conditioned soil at all testing total pressures are all above $1.2e_{\text{max}}$, and there are negligible changes in void ratio with elapsed time under pressures.

Figure 4.13c shows the vane shear strength for the conditioned soil with elapsed time. The results present that the vane shear strength does not change much with elapsed time. In addition, the vane shear strength increases slightly as the total pressure increases. However, the vane shear strength of foam-conditioned soil only ranges between 2.8 kPa to 4.6 kPa. This small vane shear strength range proves that the foam-conditioned soil is governed by the contained foam, not grain-to-grain stresses.

Figure 4.13d presents the pore pressure measurements and the actual applied total vertical stress with elapsed time. The actual total vertical stress is larger than the theoretical total vertical stress because of the friction between the top platen and the inner wall the PTC chamber. Results show that the pore pressures are very close to the values of applied vertical stress. The changes in pore pressure of the foam-conditioned soil are negligible over 60 min.

Figure 4.13e shows the calculated effective stress in the foam-conditioned soil under different pressures. In general, there is no significant change in the effective stress with elapsed
time and the values are within 0-15 kPa under pressure. Effective stress increases slightly with increased total pressure from 0 to 2 bar. Results suggest that effective stress does not build-up significantly with increasing total pressure by keeping $FIR_p$ and $FER_p$ constant under pressure. Results verify that the mechanical properties of the foam-conditioned soil are mainly governed by the contained air/foam, not the grain-to-grain stresses. Results also indicate that foam bubbles are stable in the conditioned soil to help maintain its engineering properties over time.

4.7 Conclusions

The stability of foam-conditioned soil was investigated through a series of tests at both microscale and macroscale. At the microscale, time elapsed bubble stability of foam-conditioned soil under pressure was evaluated using a foam-soil capture device and an optical microscope. At macroscale, PTC tests were conducted to assess the stability of the engineering properties of foam-conditioned soil under pressure.

The foam-soil interaction image analysis reveals that pore sizes are larger than bubble sizes of foam-conditioned soil. This suggests that bubbles would have little resistance to migration. However, foam bubbles would remain trapped in the conditioned soil if there are no continuous pathways in the pore space to enable migration.

Moreover, test results show that foam is more stable when it is mixed with soil than foam itself in terms of less changes in bubble sizes, indicating that soil particles help stabilizing foam bubbles. This is also evidenced through the foam-soil images which show that the changes in bubble sizes are negligible for bubbles sandwiched between soil particles. For bubbles pressing against each other in the void space, bubble size increases with elapsed time. The general mechanism of particles stabilizing foams is that soil particles create a steric barrier to bubble coalescence and coarsening. Detailed bubble-grain interaction mechanisms including the particle
Figure 4.13 Stability of the engineering properties of conditioned soil with elapsed time under applied total pressure of \( p = 0, 1 \) and 2 bar (\( FIR_p = 50\% \)).
detachment energy ($\Delta G$) and the maximum capillary pressure ($P_{c}^{max}$) are discussed in the paper. While this study is limited to one foam and one soil, it helps us understand the mechanisms of soil particles stabilizing foam and therefore we can generalize to a broader range of soils and foam characteristics.

The PTC test results suggest that the engineering properties of conditioned soil are relatively stable over time. There is no significant change in the compressibility of conditioned soil in 60 min at all total pressures. The compressibility decreases with increases in total pressure. There are negligible changes in void ratio with elapsed time under pressure. The void ratio values of foam-conditioned soil are all above $1.2e_{max}$ at all pressures. The vane shear strength of foam-conditioned soil is very low (2.8 - 4.6 kPa) at all pressures and it shows negligible changes with elapsed time. Pore (liquid) pressures were measured during the PTC tests. Test results show that there is little change in pore fluid pressure in 60 min. The effective stress of the foam-conditioned soil ranges between 0-15 kPa at all pressures with elapsed time. The effective stress does not build-up significantly with increasing total pressure by keeping $FIR_{p}$ and $FER_{p}$ constant under pressure. The results reveal that the behavior of the foam-conditioned soil is governed by the contained foam, not grain-to-grain stresses.

In summary, test results at both the microscale and macroscale reveal that foam bubbles are relatively stable when mixed with soil with elapsed time. It may not be appropriate using foam liquid loss (i.e., the EFNARC (2005) recommended foam half-life) to assess/predict the stability of foam-conditioned soil in the EPB chamber. Further, test results reveal that the phenomenon of air bubble on top of the EPB mixing chamber is not resulted from the instability of foam in conditioned soil. Soil conditioning parameters (i.e., $FIR$ and $FER$), soil types and properties (i.e.,
water content, particle size distribution), and chamber pressure could be the reasons resulting in an air bubble in the mixing chamber.

4.8 References


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CHAPTER 5

EXPERIMENTAL INVESTIGATION OF FOAM-SOIL SEPARATION FOR FOAM-CONDITIONED SOIL IN THE EPB MIXING CHAMBER

5.1 Abstract

In EPB TBM tunneling, contractors persistently notice and deal with the air bubble issue on top of the EPB mixing chamber. The presence of the air bubble in the chamber could cause the instability of face pressure and possibility of material inflow into the chamber. The formation of an air bubble is mainly resulted from two aspects: the immediate foam-soil separation when the excavated soil and foam get into the chamber, and bubble migration from the conditioned soil with elapsed time. In this study, soil’s capacity for foam is assessed through a series of soil conditioning tests using a transparent pressure cell. Parameters including molding water content $w_o$, initial foam injection ratio $FIR_o$, and fines content in a soil are varied to examine capacity for foam and foam-soil separation. Test results suggest that there is more expelled foam as molding water content and initial foam injection ratio increase. Test results also indicate that fines content increases the soil’s capacity for foam and water. In addition, agitation and cyclic loading-unloading of pressure induce bubble migration in foam-conditioned soil.

5.2 Introduction

In EPB TBM tunneling, foam has been extensively used to modify the properties of excavated soil. With proper soil conditioning, foam-conditioned soil will exhibit high compressibility, low shear strength, abrasivity, and permeability, improved workability, and thus improve face stability and TBM performance. Air accumulation at the top of the EPB mixing chamber has been consistently observed in tunneling practice. The air accumulated at the top
cannot counterbalance the lateral effective stress from the to-be-excavated ground because it air has negligible shearing resistance. This can result in inadequate face support and possibility of local ground collapse and material flowing into the chamber (Alavi Gharahbagh et al., 2013).

There is limited literature about chamber air accumulation in EPB tunneling. Alavi Gharahbagh et al. (2013) state that if the muck contains excessive foam, the excessive foam will travel to the top of the chamber and an air bubble will form. Mori et al. (2017) conclude that if the excavated soil is oversaturated with foam or the excavated soil and foam are not properly mixed, foam will percolate to the top of the mixing chamber and form an air bubble. Both of these studies suggest that soil or muck has a capacity for foam though this is not addressed in the papers. Further, the factors and mechanisms that cause the chamber air accumulation, namely foam-soil separation and bubble migration in the EPB mixing chamber have not been addressed.

Foam-soil separation in this study is defined as the physical separation of foam from foam-conditioned soil. The separated foam accumulates above the conditioned soil beginning almost immediately after mixing, at time $t = 0$. It is reasonable to envision that a soil has a capacity for foam. This capacity for foam can be defined as the residual foam injection ratio in the conditioned soil sample beyond which additional foam has separated. Foam separation is a time-dependent phenomenon that results from the changes in chamber pressure, agitation of foam-conditioned soil, and shearing process of mixing tools. In addition, foam bubble burst (or collapse) is normally considered as another mechanism for the formation of an air bubble in the mixing chamber. However, our recent research has found that foam bubbles are more stable when mixed with soil than foam itself over time (Wu et al., 2018b). So the effect of foam bubble burst on the formation of an air pocket should be minimal.
This paper investigates the mechanisms of foam-soil separation and bubble migration in the EPB mixing chamber through a series of soil conditioning tests. A transparent pressure cell is used to simulate the EPB mixing chamber under pressure. This study first investigates the foam-soil separation phenomenon in conditioned soils to understand the mechanisms that cause the immediate foam-soil separation when foam-soil mixtures are introduced into the mixing chamber. The influence of initial foam injection ratio ($FIR_o$), soil water content $w_o$, fines content, and chamber pressure on foam-soil separation are investigated. This paper also investigates the time dependent separation in foam-conditioned soil by applying constant agitation and cyclic loading-unloading of air pressure to the conditioned soil.

5.3 Background

Research has found that the conditioned soil shows ideal properties when its void ratio $e$ is greater than the maximum void ratio $e_{\text{max}}$ of the excavated soil (Bezuijen et al., 1999; Maidl, 1996; Mori et al., 2018). Soil grains are nominally in contact with each other and the effective stress is relatively low when $e > e_{\text{max}}$ (Mori et al., 2018). The required foam injection ration ($FIR$) to transform an in-situ soil to $e_{\text{max}}$ can be readily determined (Bezuijen, 2012; Mori et al., 2018).

Previous studies have found that the minimum required foam injection ratio under pressure ($FIR_p$) to reach $e_{\text{max}}$ is influenced by the soil water that is replaced by foam during foam injection. Bezuijen (2012) states that during EPB tunneling in saturated sand, excess pore water pressure at the tunnel face will lead to a water flow. Therefore, the original pore water will not remain in the soil, but is partly expelled. Bezuijen (2012) proposes that the replaced water ($\alpha'$) is influenced by the permeability of the excavated soil $k$, the TBM’s advance rate (drilling velocity) $v_d$, the difference in piezometric head from the tunnel face to a position far from the tunnel $\Delta \varphi$, and the tunnel radius $R$. That is, $\alpha' = (k\Delta \varphi)/(v_d R)$, where $\alpha'$ is dimensionless. Mori et al. (2018)
incorporated Be a relationship between the minimum required foam injection ratio under pressure $FIR_p$ and the water replacement factor $\alpha'$ as shown in Eq. 5.1:

$$FIR_p = (1 - n) + (e_{max} - \alpha'wG_s) \cdot 100\%$$

(5.1)

where $n$ is the in-situ porosity of the excavated soil, $\alpha'$ is the water replacement as defined above by Bezuijen (2012), $w$ is the soil water content, and $G_s$ is the specific gravity of the excavated soil. According the Eq. 5.1, it can be found that the required $FIR_p$ decreases as the water replacement factor $\alpha$ increases.

In this study, we investigate foam-soil separation and bubble migration in the EPB mixing chamber. As foam and the excavated soil are mixed, foam bubbles will replace part of the soil pore water due to mixing. In this case, we can define the replaced water fraction $\alpha$ as the volumetric ratio of expelled water to the initial pore water in the excavated soil. So the definition and physical meaning of replaced water fraction in this study are different than those of $\alpha'$ defined by Bezuijen (2012), which states that water replacement is due to excess pore water pressure.

5.4 Test Method and Plan

5.4.1 Testing device

A transparent pressure cell (Figure 5.1) was used to investigate both foam-soil separation and bubble migration. The height of the pressure cell is 33 cm, and its inner diameter is 7.6 cm. In this study, samples of foam-conditioned soil were prepared by mixing the test soil and foam with desired conditioning parameters ($FIR_0, FER_0$) at atmospheric pressure, and then placed into the pressure cell. The desired air pressure can be applied through the top cap of the pressure cell to the sample. To simulate the movement of conditioned soil in the EPB mixing chamber, the pressure cell is oscillated with a constant rate (here we use 20 rpm) to consistently agitate the conditioned soil during each test; the rotation direction is indicated in Figure 5.1. Foam migration and liquid
migration is observed and recorded by measuring the thickness of the migrated foam at the top of the sample with elapsed time.

![Figure 5.1 Pressure cell for investigating foam-soil separation and bubble migration.](image)

5.4.2 Test soils

Three soil compositions were used in this study. Soil 1 is poorly graded clean sand, soil 2 is composed of 88% soil 1 and 12% silica silt (SIL-CO-SIL 250) by mass, and soil 3 is composed of 78% soil 1 and 22% silica silt by mass. Their grain size distribution curves are presented in Figure 5.2 and geotechnical properties are shown in Table 5.1. The maximum void ratio $e_{\text{max}}$ for each test soil was measured according to ASTM D4254. As shown in Table 5.1, $e_{\text{max}} = 0.94$ for soil 1, $e_{\text{max}} = 0.89$ for soil 2, and $e_{\text{max}} = 0.91$ for soil 3. $e_{\text{max}}$ first decreases with increasing fines content and then increases with further increases in fines content. Research has shown that fines content influences $e_{\text{max}}$ for silty sand (Chang et al., 2011). $e_{\text{max}}$ decreases as %fines increases from 0-20% (filling-of voids mechanism), and it increases when %fines > 20% (replacement-of-solids mechanism).
mechanism). Water is added to the test soils to reach the in-situ water content associated with a specific project. Since we are not simulating a specific project in this study, we selected molding water contents of $w_o = 15\%$, $17.5\%$, and $20\%$, where the subscript $o$ infers the initial (molding) water content. The corresponding soil saturated densities $\rho = 1.94 \text{ g/cm}^3$, $1.98 \text{ g/cm}^3$, and $2.02 \text{ g/cm}^3$ are used for the three test soils to keep the volume of excavated soil constant in all the soil conditioning tests.

Figure 5.2 Particle size distribution of the test soils.

### 5.4.3 Soil Conditioning Parameters

Foam was produced using a laboratory foam generating system that is able to precisely control the flow rates of foam solution and compressed air. A more detailed description of the foam generating system is presented in Wu et al. (2018). A common industrial surfactant was used to produce foam. The surfactant was diluted in water prior to foaming with a concentration of 3% by volume.
The pressure dependent conditioning parameter foam expansion ratio ($FER_p$) is defined as the volumetric fraction of generated foam to the used surfactant solution; and the pressure dependent foam injection ratio ($FIR_p$) is the volumetric fraction of generated foam to excavated soil. Table 5.2 shows the soil conditioning parameters and chamber pressures used in the testing.

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Poorly graded sand</td>
<td>Silty sand</td>
<td>Silty sand</td>
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<tr>
<td>Gravel (%)</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sand (%)</td>
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<td>78</td>
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<td>Coarse sand (%)</td>
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</tr>
<tr>
<td>Medium sand (%)</td>
<td>56</td>
<td>46</td>
<td>38</td>
</tr>
<tr>
<td>Fine sand (%)</td>
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<td>39</td>
<td>37</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>0</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>Specific gravity, $G_s$</td>
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<td>2.67</td>
<td>2.69</td>
</tr>
<tr>
<td>$e_{\text{max}}$</td>
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<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.52</td>
<td>0.43</td>
<td>0.32</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surfactant concentration by volume, $c_f$ (%)</td>
<td>3</td>
</tr>
<tr>
<td>$FER_p$ (-):</td>
<td>10</td>
</tr>
<tr>
<td>$FIR_p$ (%)</td>
<td>30, 50</td>
</tr>
<tr>
<td>Chamber pressure, $p$ (bar)</td>
<td>0, 1, 2 (gauge pressure)</td>
</tr>
</tbody>
</table>

Table 5.1 Geotechnical properties of the test soils.

Table 5.2 Soil conditioning parameters used in this study.
5.5 Foam-Soil Separation

5.5.1 Influence of soil conditioning parameters on foam-soil separation

A series of pressure cell tests was performed to assess the influence of soil conditioning parameters on foam-soil separation. In this study, foam-soil separation is defined as the immediate accumulation of expelled foam on top of the conditioned soil after sample placement into the pressure cell. Figure 5.3a shows an example of a foam-conditioned soil sample in the pressure cell. As shown in the magnified picture, the separated layers from the top to the bottom of the sample are foam, replaced soil water, soil without foam, and soil mixed with foam. A layer of soil without foam is commonly observed in a foam-conditioned soil sample. Foam in the upper part of the conditioned soil demonstrate a tendency to escape from the soil. Foam bubbles throughout the sample are buoyancy-driven to rise. These bubbles can migrate if there are continuous void channels to allow their escape. As shown in Wu et al. (2018b), the estimated pore size distribution of a foam-conditioned soil is larger than bubble size distribution in all cases in the study. However, if 10% of the smaller pores \((D < 0.01 \text{ mm})\) spread throughout the conditioned soil, then most of the foam bubbles with sizes greater than 0.01 mm would not escape from the soil.

Soil water is partially replaced (expelled) with foam during the foam-soil mixing process. The expelled foam and water from the conditioned soil can be quantified by measuring the height for each layer as shown in Figure 5.3b. \(H_{ef}\) is the height of the expelled foam on top, \(H_{ew}\) is the height of the expelled water, and \(H_{cs}\) is the height of the conditioned soil. In this study, the following parameters \((FIR, \alpha, n, e)\) are proposed to characterize foam-soil separation. \(FIR\) is defined as the capacity for foam, and it equals to the initial foam injection ratio \(FIR_o\) minus the expelled foam injection ratio \(FIR_{ef}\) as shown in Eq. 5.2. \(FIR_{ef}\) can be calculated from Eq. 5.3. \(\alpha\) is the replaced water fraction which equals to the volumetric ratio of the expelled water to the initial
water in the excavated soil, Eq. 5.4. \( n \) is the porosity of the conditioned soil (not including the replaced water and separated foam), Eq. 5.5. \( e \) is the void ratio of the conditioned soil, Eq. 5.6.

\[
FIR = FIR_o - FIR_{ef} \tag{5.2}
\]

\[
FIR_{ef} = 100 \times \frac{H_{ef} \times A}{V_{es}} = 100 \times \frac{H_{ef} \times A}{m_{es}/\rho} \tag{5.3}
\]

\[
\alpha = \frac{H_{ew} \times A}{V_w} \tag{5.4}
\]

\[
n = \frac{V_w}{V_t} = 1 - \frac{V_s}{V_t} = 1 - \frac{m_{ds}/G_s}{H_{cz} \times A} \tag{5.5}
\]

\[
e = \frac{n}{1-n} \tag{5.6}
\]

where \( V_{es} \) is the volume of the excavated soil, it equals to the volume of solid plus volume of water, not including the expelled water. \( m_{es} \) is the mass of the excavated soil, \( \rho \) is the in-situ density of the excavated soil, \( A \) is the cross-sectional area of the pressure cell, \( FIR_o \) is the initial foam injection ratio, \( V_w \) is the initial volume of water in the excavated soil, and \( V_v \) is the volume of voids in the conditioned soil, \( V_t \) is the total volume of the conditioned soil, \( m_{ds} \) is the mass of dry soil in the sample, and \( G_s \) is the specific gravity of the test soil.

The influences of molding water content (\( w_o \)) and initial foam injection ratio (\( FIR_o \), subscript \( o \) means the initial value) on foam-soil separation and capacity for foam were investigated at atmospheric pressure (\( p = 0 \) bar). Figure 5.4 shows the images of foam-conditioned soil samples with \( FIR_o = 50\% \) (Figure 5.4a-c) and \( FIR_o = 30\% \) (Figure 5.4d-e). Water was added to the test soils to reach molding water contents of \( w_o = 15\%, 17.5\%, \) and \( 20\% \). The pictures were taken immediately after the conditioned soil samples were placed into the pressure cell.
Figure 5.3 (a) Separated layers of a foam-conditioned soil sample in the pressure cell at $t = 0$, and (b) schematic of the foam-conditioned soil with separated foam height of $H_{ef}$, replaced water height of $H_{ew}$, and conditioned soil height of $H_{cs}$.

Figure 5.4a-c shows the images of conditioned soil samples with $FIR_o = 50\%$ for the three test soils. For soil 1 (clean sand) with a molding $w_o = 15\%$, a 6 mm thick layer of foam separated from the conditioned soil immediately after initial mixing as shown in Figure 5.4a. This separated foam was observed at time $t = 0$ (after the sample was placed into the pressure cell, sample placement time is about 1-2 min). A 1 mm layer of replaced water is evident between the separated foam and the conditioned soil. The retained $FIR$ of the conditioned soil samples can be determined through Eq. 5.2. The resulting conditioned soil $FIR = 45\%$ and retained water content $w = 14\%$. With molding water content increase to 17.5\%, 8 mm thick layer of foam and 5 mm water separated from the conditioned soil. The resulting $FIR = 43\%$ and retained water content $w = 15\%$. For molding $w_o = 20\%$, a 13 mm foam layer and 10 mm water layer separated from the conditioned soil. The resulting $FIR = 39\%$ and retained water content $w = 15\%$. Test results are also presented in Figure 5.5a and b for $FIR_o = 50\%$. The results show that the conditioned soil $FIR$ decreases with
increasing molding water content. The retained water content increases as the molding water content increases.

For the 88% sand + 12% silt (soil 2), there is no separated foam at molding $w_o = 15\%$; the foam remains homogeneously dispersed in the soil pores. Foam separation was observed when the molding $w_o$ increases to 17.5%. The resulting $FIR$ (capacity for foam) = 45\% and retained water content $w = 16\%$. For molding $w_o = 20\%$, the resulting $FIR = 41\%$ and $w = 17\%$. For the 78% sand + 22% silt (soil 3), no foam-soil separation was observed with molding $w_o = 15\%$. As $w_o$ increases to 17.5%, the resulting $FIR = 46\%$ and $w = 17\%$. And for $w_o = 20\%$, the resulting $FIR = 45\%$ and $w = 19\%$. Comparing the test images and results for the three test soils, it is observed that soil with greater fines content experiences less separated foam and water, i.e., higher retained $FIR$ and $w$.

The results show that the soil’s capacity for foam (and water) increases with fines content.

Figure 5.4d-f shows the test images for the conditioned soil samples with $FIR_o = 30\%$. As would be expected, there is less separated foam in all the conditioned soil samples compared to the samples with $FIR_o = 50\%$. The differences in replaced water between $FIR_o = 30\%$ and 50\% were not significant. The resulting conditioned soil $FIR$ and retained water content $w$ are shown in Figure 5.5c and d and will be discussed in the following section.

Figure 5.5 shows the results of resulting $FIR$ (capacity for foam), retained water content $w$, and replaced water fraction for foam-conditioned soil samples with molding water content $w_o = 15\%, 17.5\%$, and 20\% and $FIR_o = 50\%$ and 30\%. It should be noted that certain errors would be expected in the calculations of $FIR$ due to the measurement error of expelled foam height. The height measurement error is within 1 mm for all the tests, and the induced error in $FIR$ is +/- 1\%
Figure 5.4 Images of foam-conditioned soils with $FIR_o = 50\%$ (on the left side) and 30\% (on the right side) and molding water content of $w_o = 15\%$, 17.5\%, and 20\% at $t = 0$ and $p = 0$ bar.

$FIR$. As shown in Figure 5.5a, $FIR$ decreases with increasing molding water content for all the three soils. For example, for soil 1, $FIR = 44.8\%$ at $w_o = 15\%$, $FIR = 43.4\%$ at $w_o = 17.5\%$, and $FIR = 39\%$ at $w_o = 20\%$. For soil 2, $FIR = 50\%$ at $w_o = 15\%$ as there is no foam-soil separation, and it decreases to 45.2\% at $w_o = 17.5\%$ and 41.3\% at $w_o = 20\%$. A similar trend was observed
Figure 5.5 Test results of resulting $FIR$, retained water content $w$, and replaced water fraction $\alpha$ for foam-conditioned soil samples with molding water content $w_o = 15\%, 17.5\%$, and $20\%$ and $FIR_o = 50\%$ and $30\%$. 
for soil 3. Soil 3 presents the highest \( FIR \) values of the three soils. The results of retained water content \( w \) in conditioned soil with \( FIR_o = 50\% \) is shown Figure 5.5b. As described previously, the retained water content \( w \) increases with increasing molding water content \( w_o \) for the three test soils. Soil 3 shows the highest retained water content \( w \) than it of soil 1 and soil 2.

Results of the resulting \( FIR \) for \( FIR_o = 30\% \) are shown in Figure 5.5c. Similar to the results of \( FIR_o = 50\% \), \( FIR \) decreases with increasing water content, and soil with more fines shows higher \( FIR \). According to the results of \( FIR_o = 50\% \), the retained \( FIR \) values in the conditioned soils are all greater than 30\%. Therefore, no foam-soil separation would be expected when the test soils are conditioned with \( FIR_o = 30\% \). However, the actual resulting \( FIR \values for \( FIR_o = 30\% \) are all less than 30\% except for soil 2 and soil 3 with \( w_o = 15\% \) as observed in Figure 5.4d-f. This is because that the \( FIR \) values from \( FIR_o = 50\% \) tests were obtained with water replacement, and the retained water content in the conditioned soil \( w \) is less than molding water content \( w_o \). For the same test soil conditioned with \( FIR_o = 30\% \), foam will replace part of pore water and some foam bubbles would escape from the conditioned soil together with the replaced water. In addition, as discussed previously, bubbles in the upper part of the conditioned soil have a tendency to escape from the sample because there are more continuous void channels to allow their escape. Therefore, the resulting \( FIR \) is less than 30\% for conditioned soil samples with \( FIR_o = 30\% \).

Figure 5.5e shows a comparison of retained water content \( w \) for \( FIR_o = 50\% \) and 30\%. In general, results of the retained water content \( w \) in conditioned soil with \( FIR_o = 50\% \) are very close to the results for \( FIR_o = 30\% \). Moreover, the replaced water fraction can be obtained from Eq. 5.4 and the results for \( FIR_o = 50\% \) and 30\% are shown in Figure 5.5f. As shown, \( \alpha \) increases with increasing molding water content. The results also show that soil with more fines presents less
replaced water. Test results from both Figure 5.5e and f indicate that there appears to be no influence of $FIR_o$ on water replacement.

Figure 5.6a presents the results of $FIR$ with its corresponding replaced water fraction $\alpha$ for both $FIR_o = 30\%$ and $50\%$. As shown, $FIR$ decreases as $\alpha$ increases. $FIR = FIR_o$ when $\alpha = 0$ and $FIR < FIR_o$ when $\alpha > 0$. This suggests that foam-soil separation occurs along with water replacement. Since foam bubbles are much lighter than water, the replaced pore water from a conditioned soil serves as a carrier for bubbles to travel upwards with the driven of buoyancy force. It is reasonable to conclude that the expelled foam increases with increasing in replaced water. In other words, the resulting conditioned soil $FIR$ decreases with increasing in replaced water. Figure 5.6b shows the results of $FIR/FIR_o$ with the corresponding replaced water fraction $\alpha$. As shown, the data of $FIR_o = 30\%$ and $50\%$ follow the similar trend. In general $FIR/FIR_o$ decreases as $\alpha$ increases. $FIR/FIR_o$ decreases significantly as $\alpha$ increases from 0 to 0.05, and the changes of $FIR/FIR_o$ become less when $\alpha > 0.05$.

![Figure 5.6 Results of water replacement factor $\alpha$ plotted against (a) $FIR$ of the conditioned soil samples, and (b) percent ratio of $FIR/FIR_o$.](image)

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Further, void ratio of the foam-conditioned soil can be obtained through Eq. 5.5-5.6. Figure 5.7a-c show the void ratio results of the conditioned soils with various water contents for soil 1, soil 2, and soil 3, respectively. The maximum void ratio $e_{\text{max}}$ for each soil is plotted for reference. In general, void ratio decreases with increasing water content. The higher the initial foam injection ratio $FIR_o$, the higher the void ratio of conditioned soil. The values of void ratio for most of the conditioned soils are greater than their $e_{\text{max}}$, except for soil 2 with $w = 20\%$ and $FIR_o = 30\%$. Figure 5.7d shows the results of $e/e_{\text{max}}$ for conditioned soils with $FIR_o = 30\%$ and $50\%$ with various water contents.
contents. It is found that the \( e/e_{max} \) values are relatively close for the three test soils with the same \( FIR_o \) and water content. The results indicate that \( FIR_o \) and molding water content \( w \) show more significant influences on void ratio \( e \) than the influence of soil types.

### 5.5.2 Influence of chamber pressure on foam-soil separation

To investigate the influence of chamber pressure on foam-soil separation, pressure cell tests were performed for the three test soils under applied air pressure of \( p = 0, 1, \) and 2 bar. Figure 5.8 shows the images of foam-conditioned soil samples with \( w_o = 17.5\% \), \( FIR_p = 50\% \), and \( FER_p = 10\% \). \( FIR_p \) and \( FER_p \) were kept constant to make sure the foam volume is the same at all pressures.

As shown in Figure 5.8a, there is 8 mm thick layer of separated foam at \( p = 0 \) bar, and the thickness of the separated foam increased to 10 mm at \( p = 1 \) bar and 11 mm at \( p = 2 \) bar. The increment in separated foam thickness is very slight. There is no apparent change in the thickness of replaced water. A similar trend regarding foam-soil separation was observed in soil 2 (Figure 5.8b) and soil 3 (Figure 5.8c) with increasing chamber pressure. Test results show that chamber pressure has very little influence on foam-soil separation. Another finding from the tests is that the height of the conditioned soil (not including the separated foam) in the pressure cell decreases as the chamber pressure increases, though the volume of foam is the same at all pressures. One possible reason could be that some bubbles burst when an air pressure is applied to the conditioned soil sample. The bubbles burst as the overlying soil particles and bubbles are suddenly compressed by the applied air pressure, and these bubbles may collapse due to the compression force from the overlying conditioned soil. Therefore, the volume of the conditioned soil at higher pressure is less than it at lower pressure.
Figure 5.8 Images of foam-conditioned soil with $w_o=17.5\%$ and $FIR_p=50\%$ for test soils at $p = 0, 1, \text{ and } 2 \text{ bar}$.

Figure 5.9a shows the results of the resulting $FIR$ for the conditioned soil samples at different pressures. In general, $FIR$ decreases slightly with increasing pressure for all the three test
soils. For example, $FIR$ is 43% at $p = 0$ bar for soil 1, and it decreases to 41% at 2 bar; for soil 2, $FIR$ decreases from 45% to 42% as the pressure increases from 0 to 2 bar. The values of the conditioned soils’ void ratio decrease as the pressure increases for all the three test soils, as shown in Figure 5.9b. One reason is that there is slightly more foam separated from the conditioned soil at higher pressure, so the void ratio is smaller. Another reason could be that some bubbles burst when an air pressure is applied to the conditioned soil sample. The bubbles burst as the overlying soil particles and bubbles are suddenly compressed by the applied air pressure. Therefore, the resulting void ratio of the conditioned soil is smaller at higher pressure.

![Graph showing results of $FIR$ and void ratio of conditioned soil under pressure](image)

Figure 5.9 (a) Results of $FIR$ in conditioned soils at different pressures, and (b) void ratio of conditioned soil under pressure with $w_o = 17.5\%$ and $FIR_p = 50\%$.

5.6 Foam Bubble Migration

The above section presents the test results of foam-soil separation at $t = 0$ through a series of pressure cell tests with different conditioning parameters. In this section, we investigate foam bubble migration with elapsed time under pressure and the mechanisms that cause bubble migration.
5.6.1 Time-dependent foam-soil separation under pressure

Time-dependent foam-soil separation for foam-conditioned soil was investigated by observing and recording the heights of migrated foam, replaced water, and conditioned soil with elapsed time (data was recorded every 5 min). To simulate the movement of conditioned soil in the mixing chamber, the pressure cell was rotated with a constant rotation rate of 20 rpm. The rotation direction is shown in Figure 5.1. Test duration for each test is 30 min.

Figure 5.10 shows the images of conditioned soil 1 with $FIR_p = 50\%$, $FER_p = 10$ and water content of $w_o = 17.5\%$ under air pressure of $p = 0$ bar, 1 bar, and 2 bar. As shown in Figure 5.10a, there is about 12 mm separated foam and 4 mm replaced water on top of the conditioned soil, and after 30 min of agitation, there is about 30 mm foam and 5 mm replaced water on top. Also, the height of the conditioned soil decreased from 16.0 cm to 14.3 cm. The results suggest that the agitation process restructures the network of the conditioned soil, and thus foam bubbles in the upper part of the conditioned soil column migrated upwards. Similar results of foam separation with elapsed time were observed at $p = 1$ bar and 2 bar as shown in Figure 5.10b and c.

![Figure 5.10 Images of foam-conditioned soil 1 at $t = 0$ min and 30 min with agitating the sample at (a) $p = 0$ bar, (b) $p = 1$ bar, and (c) $p = 2$ bar.](image-url)
Figure 5.11 (a) \(\text{FIR}\) and (b) void ratio of the conditioned soil 1 under pressure with elapsed time (conditioning parameters: \(\text{FIR}_p = 50\%, \text{FER}_p = 10, w_o = 17.5\%\)).

Figure 5.11a shows the results of \(\text{FIR}\) of conditioned soil 1 with elapsed time at pressures. As shown, there is significant drop in \(\text{FIR}\) in the initial 5 min for the conditioned soil at all pressures. The decreases in \(\text{FIR}\) become stable after 10 min at \(p = 1\) bar and 2 bar, and it becomes less after 10 min at \(p = 0\) bar. Figure 5.11b shows the changes in void ratio of the conditioned soil at pressures. Void ratio becomes stable after 10 min at \(p = 1\) bar and 2 bar, and it continues decreasing until 25 min at \(p = 0\) bar. The maximum void ratio \(e_{\text{max}}\) for soil 1 is plotted in Figure 5.11b for reference. As shown, at \(t = 0\) min, the void ratio values are all above \(e_{\text{max}}\). As the agitation process is incorporated in the tests, void ratio decreases with elapsed time. The void ratio of conditioned soil at \(p = 2\) bar is below \(e_{\text{max}}\) after 5 min. The results show that the agitation induced foam-soil separation reduces the void ratio of conditioned soil. Also, the void ratio of conditioned soil at higher chamber pressure is less than it under atmospheric pressure, though \(\text{FIR}_p\) and \(\text{FER}_p\) are kept constant at all pressures. The reasons have been discussed in Section 5.5.2. In order to reach \(e > e_{\text{max}}\) for conditioned soil in the mixing chamber and avoid grain-grain stress, foam with a higher \(\text{FER}_p\) or more foam should be used at higher chamber pressure during EPB tunneling.
5.6.2 Influence of cyclic loading-unloading on foam-soil separation

In addition to the influence of chamber pressure on foam-soil separation, we also investigate the effects of cyclic loading-unloading pressure on foam separation from conditioned soils. The pressure cell tests were performed by applying (loading) and releasing (unloading) a 1 bar increment of air pressure ($\Delta p = 1$ bar) to the sample, and the separated foam height was recorded. Five loading-unloading cycles were performed for each sample.

Figure 5.12 shows the images for the conditioned soils (soil 1-3) before and after the 5 loading-unloading pressure cycles with conditioning parameters of $FIR_o = 50\%$ and $w_o = 17.5\%$. As shown, initially there are separated foam and replaced water on top for all the three conditioned soil samples. After 5 loading-unloading pressure cycles, the heights of foam and replaced water increase and the height of the conditioned soil decreases compared to the samples before loading. It reveals that part of the foam in the conditioned soil migrated upwards during the loading-unloading process.

![Figure 5.12 Influence of cyclic loading-unloading pressure on bubble migration for foam-conditioned (a) soil 1, (b) soil 2, and (c) soil 3.](image)

(a) Soil 1, $w_o=17.5\%, ~FIR_o=50\%$:  
(b) Soil 2, $w_o=17.5\%, ~FIR_o=50\%$:  
(c) Soil 3, $w_o=17.5\%, ~FIR_o=50\%$:  

Figure 5.12 Influence of cyclic loading-unloading pressure on bubble migration for foam-conditioned (a) soil 1, (b) soil 2, and (c) soil 3.
Figure 5.13 (a) $FIR$ and (b) void ratio for the foam-conditioned soils (soil 1-3) with loading-unloading cycles with conditioning parameters of $FIR_o = 50\%$ and $w_o = 17.5\%$.

Figure 5.13a shows the results of $FIR$ with loading-unloading cycles for the three test soils. In general $FIR$ decreases with the loading-unloading cycles. Foam bubbles in the conditioned soil migrated upwards as the loading-unloading of pressure restructures the network of foam-soil mixture. Soil 3 shows the highest $FIR$ over the loading cycle compared to soil 1 and 2 since there are more fines in soil 3. Figure 5.13b shows the void ratio of the conditioned soils with loading-unloading cycles. As shown, void ratio decreases almost linearly with the loading-unloading cycles for all the three soils. The reduction in void ratio is due to the bubble migration caused by the pressure changes in the chamber. After 5 loading-unloading cycles, the void ratio values of the conditioned soils are still larger than their $e_{max}$ values.

**5.7 Conclusions**

This paper investigates the foam-soil separation and bubble migration in foam-conditioned soil through a series of pressure cell tests with different soil conditioning parameters and soils. Parameters including capacity for foam $FIR$, retained water content $w$, replaced water fraction $\alpha$, and void ratio $e$ are used to characterize foam-soil separation. Time-dependent bubble migration
is investigated through sample agitation and loading-unloading of air pressure. The main findings from this study can be summarized as follows:

- Test results show that soil with more fines shows less separated foam and replaced water, i.e., higher resulting $FIR$ and retained water content $w$. This suggests that fines content increases the soil’s capacity for foam and water.

- The initial foam injection ratio $FIR_o$ and molding water content $w$ exhibit significant influence on capacity for foam. There is more separated foam for a conditioned soil with higher water content and higher $FIR_o$.

- Test results show that $FIR$ decreases as water replacement $\alpha$ increases. $FIR = FIR_o$ when $\alpha = 0$ and $FIR < FIR_o$ when $\alpha > 0$. This suggests that foam-soil separation occurs along with water replacement. Since foam bubbles are much lighter than water, the replaced pore water from a conditioned soil serves as a carrier for bubbles to travel upwards with the driven of buoyancy force. Therefore, the expelled foam increases with increasing in replaced water. In other words, the resulting conditioned soil $FIR$ decreases with increasing in replaced water.

- Test results show that $FIR$ decreases slightly with increasing chamber pressure as more bubbles migrated from the conditioned soil under higher pressure.

- Regarding foam-soil separation for conditioned soil with elapsed time under pressure, there is significant drop in $FIR$ in the initial 5 min for the conditioned soil at all pressures. The decreases in $FIR$ become relatively stable after 10 min. Test results show that the agitation process in a conditioned soil induce foam-soil separation, it reduces the void ratio of conditioned soil and capacity for foam of a soil.
• Cyclic loading-unloading of air pressure induces further foam-soil separation since the changes in pressure restructures the network of foam-soil mixture. Void ratio decreases nearly linearly with the loading-unloading cycles for the test soils.

5.8 References


CHAPTER 6
CONCLUSIONS AND OUTLOOK

The research in this thesis seeks to advance the understanding of the fundamentals of foam and foam-conditioned soil in the EPB mixing chamber through series of soil conditioning experiments. This chapter discusses specific conclusions from each portion of the research, presents a general summary and discussion of the findings from this study, and proposes some recommendations for future work.

6.1 Specific Conclusions from Each Paper Chapter

6.1.1 Foam stability under pressure

This paper examines foam stability under pressure through a novel foam generation – pressure chamber – foam capture testing system. The pressure chamber was used to measure liquid and foam loss with elapsed time under pressure. The foam capture device was used to assess foam bubble size distribution with elapsed time. The combination of these two test methods was utilized to investigate time-dependent foam behaviors under pressure.

Test results reveal that liquid loss is significantly retarded at higher chamber pressures. The bubble size analysis shows that foam bubbles are smaller and more uniform at higher pressures. The smaller and more uniform bubbles lead to less gas diffusion between bubbles, as well as a longer, more tortuous liquid drainage path. Therefore, liquid drainage is significantly slowed at higher pressures. Liquid loss half-life is used in the tunneling industry as a measure of foam stability, and it is measured at atmospheric pressure as EFNARC (2005) recommended. Because most EPB soil conditioning occurs under pressures greater than atmospheric pressure, the liquid drainage half-life of foam in-situ is much greater than the EFNARC atmospheric pressure
test indicates. As liquid drainage is used in the design of EPB soil conditioning, it should be adjusted to the excavation chamber pressures anticipated along the tunnel project alignment.

Test results suggest that the influence of $FER$ on bubble size is negligible. The bubble image analysis shows that drier $FER_p = 20$ bubbles degrade more slowly over time compared to $FER_p = 10$ foam bubbles. Because drier foam has less liquid to drain and the gravity-driven liquid drainage plays a dominant role in the initial phase of foam aging. For similar reasons, drier foam accumulates less liquid loss than wet foam. This study suggests that there is excess unnecessary liquid in wetter $FER_p = 10$ foam.

Test results also show that foam volume loss is minimal (less than 10% over 60 min) with elapsed time compared to significant liquid volume loss, and air loss is negligible (less than 2% over 60 min) in all tests. This finding was made through a series of unload-reload tests over time in an attempt to agitate the foam and test its desired properties. Test results in this study suggest that foam volume loss is a more appropriate measure of foam stability compared to the measure of liquid drainage as EFNARC (2005) recommended. Because the persistence of the desired engineering properties, i.e., the definition of stability, is directly controlled by the persistence of foam volume and not the liquid drainage.

### 6.1.2 Foam-soil stability under pressure

This chapter investigates the stability of foam-conditioned soil through a series of soil conditioning tests. Bubble size analysis was conducted to obtain bubble size distributions for bubbles in the conditioned soil with elapsed time. Bubble sizes were compared with the estimated pore sizes of the conditioned soil. In addition, engineering properties were assessed with elapsed time using the pressurized testing chamber (PTC) to examine the stability of the engineering properties of foam-conditioned soil.
Results of the foam-soil interaction image analysis show that pore sizes are larger than bubble sizes of foam-conditioned soil. This suggests that bubbles would have little resistance to migration. However, foam bubbles would remain trapped in the conditioned soil if there are no continuous pathways in the pore space to enable migration.

In addition, the bubble size analysis results show that foam is more stable when it is mixed with soil than foam itself in terms of less changes in bubble sizes. This means that soil particles help stabilizing foam bubbles. The general mechanism of particles stabilizing foams is that soil particles create a steric barrier to bubble coalescence and coarsening. This study also discusses the detailed bubble-grain interaction mechanisms including the particle detachment energy ($\Delta G$) and the maximum capillary pressure ($P_{c}^{max}$).

The PTC test results suggest that the engineering properties of conditioned soil are relatively stable over time. Changes in the compressibility and void ratio of the conditioned soil are negligible in 60 min at all total pressures. The vane shear strength of foam-conditioned soil is very low (2.8 - 4.6 kPa) at all pressures and it shows negligible changes with elapsed time. The pore fluid pressure presents little changes in 60 min. The effective stress of the foam-conditioned soil ranges between 0-15 kPa at all pressures with elapsed time. The effective stress does not build-up significantly with increasing total pressure.

In summary, this study reveal that foam bubbles are relatively stable when mixed with soil with elapsed time. It may not be appropriate using foam liquid loss (i.e., the EFNARC (2005) recommended foam half-life) to assess/predict the stability of foam-conditioned soil in the EPB chamber. Further, test results reveal that the phenomenon of air bubble on top of the EPB mixing chamber is not resulted from the instability of foam in conditioned soil. Soil conditioning parameters (i.e., $FIR$ and $FER$), soil types and properties (i.e., water content, particle size
distribution), and chamber pressure could be the reasons resulting in an air bubble in the mixing chamber.

6.1.3 Foam-soil separation

This chapter investigates the foam-soil separation and bubble migration in foam-conditioned soil through a series of pressure cell tests with different soil conditioning parameters and fines content. Parameters including capacity for foam $FIR$, retained water content $w$, replaced water fraction $\alpha$, and void ratio $e$ are used to characterize foam-soil separation. Time-dependent bubble migration is investigated through sample agitation and loading-unloading of air pressure.

Test results show that soil with more fines shows less separated foam and replaced water, i.e., higher resulting $FIR$ and retained water content $w$. This suggests that fines content increases the soil’s capacity for foam and water. The initial foam injection ratio $FIR_0$ and molding water content $w_o$ exhibit significant influence on capacity for foam. There is more separated foam for a conditioned soil with higher water content and higher $FIR_0$.

Test results present that $FIR$ decreases as water replacement $\alpha$ increases. $FIR = FIR_0$ when $\alpha = 0$ and $FIR < FIR_0$ when $\alpha > 0$. This suggests that foam-soil separation occurs along with water replacement. Since foam bubbles are much lighter than water, the replaced pore water from a conditioned soil serves as a carrier for bubbles to travel upwards with the driven of buoyancy force. Therefore, the expelled foam increases with increasing in replaced water. In other words, the resulting conditioned soil $FIR$ decreases with increasing in replaced water.

Regarding time-dependent foam-soil separation under pressure, test results show that there is significant drop in $FIR$ in the initial 5 min for the conditioned soil at all pressures. The decreases in $FIR$ become relatively stable after 10 min. Test results show that the agitation process in a
conditioned soil induce further foam-soil separation, it reduces the void ratio of conditioned soil and capacity for foam of a soil.

6.2 General Conclusions

This thesis mainly focuses on the fundamentals of foam stability and foam-soil interaction behaviors under pressure in EPB mixing chamber. The research about foam seeks to advance the state of understanding foam stability under pressure in tunneling perspective. The research about foam-conditioned soil stability intends to improve understanding the mechanisms of bubble-grain interaction as well as the stability of engineering properties of foam-conditioned soil. Moreover, this thesis also investigates capacity for foam of a soil and mechanisms that cause foam-soil separation and bubble migration. The foam-soil separation and bubble migration induced air bubble at the crown of the EPB chamber is a significant issue in EPB soil conditioning.

The research in this thesis has developed several novel experimental methods to test foam and foam-conditioned soil properties. The self-developed testing devices include foam capture device for bubble size analysis, pressure chamber for measuring liquid and foam loss, foam-soil capture device for determining bubble stability in conditioned soil, and pressure cell for evaluating foam-soil separation and bubble migration. All these devices are portable and easy to operate, so they can be utilized in a specific tunneling project to perform in-situ soil conditioning tests.

The findings of this thesis provide a reference in the design of soil conditioning for an EPB tunneling project. The results of this study help contractors consider the influence of chamber pressure on foam properties, as well as the stability of foam-conditioned soil in the mixing chamber. The results of capacity for foam of a soil and bubble migration help contractors use proper soil conditioning parameters via conducting some laboratory tests in advance of tunnel
excavation. Results of the influence of each parameter on capacity for foam and bubble migration provide a reference for contractors to choose proper conditioning parameters.

6.3 Recommendations for Future Work

The research on foam-soil stability has addressed bubble-grain interaction mechanisms in foam-conditioned sand. Broader soil types such as silt or clay are recommended to be mixed with foam bubbles to assess the stability of bubbles in finer soil particles.

The study about capacity for foam and bubble migration has investigated the influences of water content, $FIR$, and soil types on foam-conditioned soil. It should be beneficial to consider the influence of $FER$ on capacity for foam issue as well.

In this study, foam and soil are first mixed at atmospheric pressure and then compressed to the desired chamber pressure. However, in tunneling practice, foam is injected and mixed under pressure. It would be more realistic if foam is directly injected and mixed in a testing device to simulate the real condition.
APPENDIX A

INFLUENCE OF FOAM HEIGHT ON LIQUID DRAINAGE

The EFNARC (2005) recommends method to characterize foam stability analysis via liquid drainage involves a 80 g foam sample placed in a filtered funnel. The time required for 40 ml of liquid to drain from the foam is the so-called half-life. Previous research has shown that foam half-life is proportional to the height of foam column. The taller the foam column, the longer the half-life (Rand and Kraynik, 1983; Saint-Jalmes and Langevin, 2002). To investigate if foam height dominates half-life comparing to the influence of foam mass, a filtered funnel, a glass cylinder, and an acrylic pressure chamber with different dimensions (Figure A.1) were used to measure foam liquid drainage and half-life.

In accordance with EFNARC (2005), a 80 g foam sample with $FER = 15$ was prepared and placed into the filtered funnel ($D = 13$ cm). The measured initial foam height is 9 cm. The liquid drainage from the foam was measured with time. For comparison, an additional 80 g foam with the same concentration and $FER$ was placed into the $D = 6$ cm cylinder. The resulting foam height

Figure A.1 Devices for foam liquid drainage testing.
is 42 cm. The test results are shown in Figure A.2. The liquid drainage rate of the 42 cm tall, 6 cm diameter foam sample is much slower than that of the 9 cm tall, 13 cm diameter foam sample in the funnel, even though they have the same mass of foam. This is due to the difference in liquid drainage distance. Liquid drains due to gravity, so naturally the drainage time increases with foam height.

An additional 42 cm tall test was performed in the $D = 18$ cm cylinder. The measured liquid drainage data are very close to the test with the $D = 6$ cm cylinder. The results reveal that foam liquid drainage is not influenced by the mass of foam or the diameter of the sample. It is mainly affected by the foam column height for foam with the same properties. To further verify this conclusion, liquid drainage from $D = 6$ and 18 cm foam samples each with $H = 9$ and 20 cm was recorded as a function of time. The responses obtained from these tests clearly show that liquid drainage is dependent on sample height and independent of sample diameter. Foam samples with the same height but different diameters show similar liquid drainage curves. Therefore, it can be concluded that time dependent foam liquid drainage, including the so-called foam liquid half-life is influenced by the foam column height, not the mass of foam or the sample diameter.

Five additional foam liquid drainage tests with different foam heights ($H = 5, 15, 25, 30, 35$ cm) were conducted using the $D = 6$ cm cylinder to determine $T_{50}$ (half-life) and $T_{25}$ (quarter drain time). Combining with the previous testing results of $H = 9, 20,$ and 42 cm, the total eight sets of $T_{50}$ and $T_{25}$ data with different foam heights are shown in Figure A.3. It presents that $T_{50}$ increases with the increasing of initial foam height. As $H$ changes from 5 to 42 cm, $T_{50}$ increases from 16.8 to 37.5 min. It is obvious that the $T_{50}$ and $H$ have a non-linear relationship. Similar to $T_{50}$, $T_{25}$ data also exhibit non-linear trend with $H$. The results confirm the findings from previous study (Rand and Kraynik, 1983; Saint-Jalmes and Langevin, 2002) that liquid drainage time
increases with the increasing of foam column height. Based upon the above testing results, it can be concluded that the initial foam height is an important factor that influences foam liquid drainage. It should be considered in designing the laboratory testing for foam stability.

Figure A.2 Liquid drainage curves for foam with $FER = 15$ measured by a funnel with $D = 13$ cm, a cylinder with $D = 6$ cm and a cylinder with $D = 18$ cm.

Figure A.3 The influence of foam column height on foam half-life ($FER = 15$).
References

EFNARC, 2005, Specification and guidelines for the use of specialist products for mechanised tunnelling (TBM) in soft ground and hard rock.


APPENDIX B

TESTING PROCEDURES FOR FOAM GENERATION-PRESSURE CHAMBER-FOAM CAPTURE DEVICE

The testing procedures for foam generation – pressure chamber – foam capture device introduced in Chapter 3 are as follows:

1. Assemble the pressure chamber and set the scale: tighten the bolts and nuts of the chamber; place the chamber onto the scale, and then zero the scale.

2. Pressurize the chamber to the desired pressure: Open the valve that connects to the air supply line and pressurize the chamber to the desired pressure, use the back pressure regulator to control the chamber pressure. When the chamber pressure is stable, close the air supply valve.

3. Start generating foam: Input the desired air and liquid flow rates and start the foam generation program (LabVIEW) on the computer, open the bleeding off valve to flow foam into a bucket, and make sure the valve that connects to the pressure chamber is closed. Monitoring the pressures along the foam generation system (air-line pressure, pressure before the foam generator, and pressure after the foam generator).

4. Bleed off foam: When the pressures are stable, partially close the bleeding off valve and watch the pressure gauge (next to the bleeding off valve) until the pressure reaches to the same pressure in the chamber. Adjust the liquid flow rate to keep it constant if it drops due to back pressure. Then fully close the bleeding off valve and open the valve which connects to the pressure chamber simultaneously.

5. Inject foam into the chamber: Foam flows into the pressure chamber after switching the valves. Watch the foam column height in the chamber and stop injecting foam when the
height reaches 40 cm (here we propose 40 cm as the foam column height considering the height of the chamber-45 cm, and the safety of the back pressure regulator on the chamber).

Start timing when the foam injection process is completed.

(6) Inject foam into the foam capture device: when foam is flowing into the pressure chamber, partially close the back pressure regulator (2-3 rotations) that is connected to the foam capture device to provide similar pressurized environment. Then open the valve that connects to the foam capture device to let foam flow through it. Adjust the pressure in the capture device the same as the chamber pressure. When there is steady foam flow through the capture device, stop the foam flow by closing both the upstream valve and the downstream back pressure regulator. Use the microscope to take foam bubble pictures automatically with elapsed time (i.e., \( t = 0, 5, 10, \ldots, 60 \) min). The bubble images will be processed using a commercial image analysis software (AmScope) to obtain bubble sizes and bubble size distribution curves.

(7) Calculate \( FER_p \), volume of liquid \( (V_l) \) and height of liquid \( (H_l) \) for the foam sample in the pressure chamber: Record the mass of the foam in the chamber from the scale and calculate \( FER_p \) (at that certain pressure, \( p \)), \( V_l \) and \( H_l \) as follows:

\[
FER_p = \frac{V_f}{V_l} = \frac{V_l}{M_l} = \frac{V_f}{M_f} \quad (B.1)
\]

\[
V_l = \frac{V_f}{FER_p} \quad (B.2)
\]

\[
H_l = \frac{V_l}{A} \quad (B.3)
\]

where \( V_f \) is the initial volume of foam in the chamber, and \( M_f \) is the mass of foam read from the scale, \( A \) is the cross-sectional area of the pressure chamber.
(8) Record the height of foam and liquid with time: Record the height of foam, height of liquid accumulated at the bottom of the chamber with certain time intervals (i.e., 5 min). Determine liquid loss, foam loss, and air loss using Eq. 3.1-3.3 as shown in Chapter 3.

(9) Test foam compressibility: Apply 1 bar extra air pressure to the foam sample to test its compressibility every 5 min, and then unload the air pressure to the original chamber pressure. Figure B.1 shows an example of compressibility test for foam at $p = 0$ bar chamber pressure. Record the changes of foam height. Repeat this step for 60 min duration. Foam compressibility at time $t$ can be calculated as shown in Eq. 3.4 in Chapter 3.

Discharge foam: When the test is completed, discharge the foam sample through the port at the bottom of the chamber. Release air pressure and get rid of the rest of foam in the chamber.

Figure B.1 Pictures of compressibility test for foam at $p = 0$ bar pressure: (a) before applying 1 bar extra air pressure, (b) during applying 1 bar extra air pressure, and (c) after unloading the air pressure.