Rheological properties of sand-foam mixtures used in EPB tunnelling

A first-year report

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Abstract

The applications of ear-pressure balance tunnel-boring machines (EPB TBMs) have become increasingly popular in recent decades. Meanwhile, soil conditioning agents have been developed to modify the natural ground conditions, making them more readily excavated by EPB TBMs. In soft ground, effective soil conditioning significantly improves the abilities of soils to form a plastic paste flow in the machine. Although soil-conditioning agents are widely used in practice and many studies on conditioned soils have been carried out, the best conditioning treatments for specific soils are still not easy to determine because of the massive affecting factors involved. Apart from the traditional testing methods such as slump ~~tests~~ and shear box tests, a modified rheometer test might provide another effective approach to evaluate the effects of conditioning treatments on excavated soils by investigating the rheological properties of conditioned soils.

This report presents experimental investigations on the basic properties of foams and sand-foam mixtures. The pressure gaps in foam generators as well as ~~foam~~ the concentration and ~~compositions~~ composition of foams have been found to have great impacts on the ~~foam~~ expansion ratio and ~~foam~~ stability of the foams. In addition, the strengthening abilities of conditioned sands to form plastic pastes were observed during slump tests.

For the purpose of extending the application of rheometer tests to coarser soils, modifications on the geometry and technical parameters of the rheometer were proposed. This specially designed rheometer is expected to be used ~~on~~ in studies of the rheological properties of ~~the~~ both conditioned coarse ~~sands~~ and gravelly sands.

* Editor's Note: All keywords (or phrases) should appear in the Abstract. The phrase '*EPB tunnelling*' does not occur herein. You should either (1) revise the Abstract to include this phrase or (2) delete the phrase from your keywords list.

* *Keywords: EPB tunnelling, soil conditioning, sand-foam mixture, rheometer tests*

Table of contents

List of figures

List of tables

Nomenclature

α	coefficient ~~depends~~ dependent on ~~the~~ uniformity coefficient of ~~the~~ soil
A	~~the~~ percentage of soil passing 0.074 mm sieve
A_l	a coefficient of liquid
B	~~the~~ percentage of soil passing 0.25 mm sieve
B_l	another coefficient of liquid
C	~~the~~ percentage of soil passing 2.0 mm sieve
C_c	~~the~~ coefficient of curvature
C_u	~~the~~ uniformity coefficient of ~~the~~ soil
d_{10}, d_{30}, d_{60}	the particle diameter corresponding to 10%, 30%, 60% cumulative particle size distribution
D	vane diameter
d	~~the~~ vane shaft diameter
E	activation energy for flow
e	thickness of vane blade
FER	~~the~~ foam expansion ratio
FIR	~~the~~ foam injection ratio
G_s	~~the~~ specific gravity
h	~~the~~ distance between two parallel plates in viscometer
H	length of vane
K	~~the~~ consistency coefficient
n	flow property index
P	~~the~~ absolute pressure
P_α	~~the~~ atmospheric pressure
R	~~the~~ universal gas constant

S_u	undrained shear strength
T	temperature
T_m	measured torque on vane
t_{25}	time for drainage of 25% of foam liquid volume
t_{50}	time for drainage of 50% of foam liquid volume
V_A	vane area ratio
V_α	~~the~~ volume of foam agent
V_f	the volume of foam solution
V_s	~~the~~ volume of soils to be excavated
W_c	weight of foam
W_{cf}	weight of container and foam
X	concentration of bentonite slurry
σ	shear stress
σ_0	yield stress
μ	coefficient of viscosity
$\dot{\gamma}$	~~the~~ rate of shear deformation
η	apparent viscosity

CHAPTER ONE

1. Introduction

1.1 Motivation ~~of~~ for this study

~~As~~ With ~~the~~ a rapid worldwide increase ~~of~~ in national ~~economy~~ economies and urbanization ~~all over the world~~, the exploitation of urban underground space has ~~experienced~~ undergone great development. In particular, the development of underground transportation ~~could~~ can not only relieve the heavy traffic in major cities, but also save ~~many~~ much ground space~~s~~ for public infrastructure~~s~~. The EPB TBM has become the most popular tunnelling equipment for underground construction~~s~~ because of its efficient boring rate, the relatively small space~~s~~ required for installation and operation, and its limited disturbance to existing buildings on the ground.

One of the crucial factors ~~that~~ leading to satisfactory performance of EPB tunnelling is an ideal ground condition~~s~~, including high fine contents and great rheological properties to form a soft plastic paste with low permeability. Therefore, soil conditioning aiming to create the ideal properties manually has gained rapid development along with the increasing applications of the EPB TBM. With the help of conditioning agents such as foams, bentonite slurries and polymers, ~~the~~ applications of the EPB TBM ~~has~~ have been extended to coarser soils.

The benefits of successful soil conditioning have been summarised by many authors (Milligan, 2000 and Merritt, 2004), ~~including~~ to include better control of ~~the~~ pressure in the working chamber; ~~a more~~ smoother soil flow through the machine; effective control of groundwater inflows; lower torque and power consumption for the machine; reduced wear of the cutting head; and lower costs for essential maintenance and cleaning.

During an internship in a subway construction field in Chengdu, China, the author observed the significant effects of foams on the properties of gravelly sand ground. Satisfactory excavation rates ~~was~~ were achieved by injecting adequate foam agents ~~according to~~ in accordance with the real-time soil properties. However, the amount of foam and the settings of the operational parameters for foam generation are mainly ~~based on~~ determined by the experience of the driver, which may cause unexpected problems. For example, ~~the~~ one excavation had to be stopped because the wrong amount of foam resulted in clogging of the machine.

Although the importance as well as potential problems of soil conditioning are well known, ~~the massive~~ numerous variables such as geotechnical conditions, different effects of conditioners, and injection systems make it difficult to decide ~~right~~ appropriate conditioning treatments for specific soil. In the literature, ~~the~~ understanding of the effects of soil conditioners on the properties of excavated soils is limited. Moreover, the rheological properties of the excavated soils, as an important factor ~~of~~ in forming plastic soil flows through the EPB TBM, have usually been evaluated by simple slump tests. The ~~continuous~~ ongoing relationship between shear stress and ~~shear~~ rate under the pressure which exists in real tunnelling construction cannot be measured with this traditional method.

Recently, the successful application of a newly designed rheometer in investigating concrete workability (Koehler and Fowler, 2004) ~~provides~~ has provided a new approach to study the rheological properties of coarse materials. In studies of conditioned soils in tunnelling, the rheometer has also been used to determine the viscoplastic parameters of both conditioned sands and clays (Meng *et al.,* 2011 and Messerklinger *et al.,* 2011); ~~and~~ moreover, the data from rheometer tests of clays ~~were~~ have been verified by comparative measurements with a commercially available rheometer. In field constructions, these laboratory ~~experiments~~ experimental data would ~~be~~ serve as good references to decide the best conditioning treatments. Therefore, unnecessary delays and costs could be avoided.

All these reasons have motivated the author to proceed in more laboratory experiments with a rheometer specially developed for coarse soils to investigate the effects of conditioning treatments on the rheological properties of excavated soils. More specifically, sand-foam and gravelly sand-foam mixtures were chosen to be studied because of their popularity in EPB tunnelling.

1.2 Scope and objectives

The primary objective of this study is to investigate the influence of foam on the rheological properties of sand and gravelly sand under pressure with a specially designed rheometer. To achieve this goal, ~~efforts are~~ additional attention is required ~~in~~ regarding the following aspects:

- Index tests on foam and soil-foam mixture, aiming to create a systematic diagram of the effects of different conditioning treatments on specific soil;
- Microscopic study on the foam and soil-foam mixture ~~which helps~~ to facilitate an understanding of the underlying mechanism of using foam as a conditioner.
- Development of a soil rheometer that is able to investigate rheological properties of coarse soils (sands and gravelly sands).

1.3 Outline of report

This report presents the work~~s~~ that the author has done in the first year of PhD study. The contents of each chapter are briefly described below.

Chapter one introduces the original motivation of this study and the objectives determined by the author.

Chapter two provides a review ~~into~~ of the development of soil conditioning used in EPB tunnelling as well as the current laboratory testing methods for conditioned soils.

Chapter three presents the laboratory experiments that have been done by the author, including foam index tests and slump tests, ~~and~~ for which the results are discussed. In addition, the design of the soil rheometer is ~~showed~~ illustrated in this chapter.

Chapter four ~~gives~~ projects the future plan for the remaining time ~~of~~ devoted toward completion of the PhD, and Chapter five presents a conclusion for the work ~~of~~ accomplished in the first year.

CHAPTER TWO

2. Literature review

2.1 Introduction

The EPB TBM ~~could~~ can be considered the most commonly used ~~tunnelling~~ equipment for tunnelling in soils ranging from coarse sands and gravels to stiff clays, especially in urban areas. This increasing applications ~~if~~ of the EPB TBM ~~thank~~ can be attributed to not only ~~the~~ improvements ~~of~~ in mechanical technology but also ~~the widely~~ wider ~~used~~ use of soil conditioners. This chapter introduces the general background of ~~the~~ EPB tunnelling, the most used soil conditioners and their applications in tunnelling. ~~Furthermore~~ The importance of the rheological properties of ~~the~~ conditioned soils for achieving optimum EPB performance is also discussed. Laboratory ~~testing~~ methods for testing ~~of~~ conditioned soil properties are reviewed and some typical tests in recent years, as well as their results, are discussed.

2.2 Background of shield tunnelling

It is generally ~~realised~~ recognised that ~~there is~~ an increasing need for the utilisation of underground space ~~which~~ to provides new approaches to infrastructures such as public service networks (pipelines, cables and drainage systems) as well as roads and railways. However, difficulties ~~like~~ such as heavy traffic, existing buildings, complex ground conditions and high surface disruptions caused by underground construction in urban areas might make it unfavourable for conventional methods such as open excavation, ~~and~~ drilling and blasting (Psomas, 2001). Therefore, a rapid growth in the use of mechanised tunnelling has been ~~marked~~ observed as an important improvement in recent decades.

2.2.1 Development of shield tunnelling

Inspired ~~from~~ by the decay process caused by maggots ~~of boat's~~ in the hull of a boat ~~caused by maggots~~, the first idea ~~of~~ for a shield-tunnelling machine was developed by Marc Isambard Brunel in 1818, ~~and it was~~ being used to excavate the Thames Tunnel in 1825. Despite its successful application, the first shield machine was not actually a TBM in the true sense. ~~It~~ Brunel's machine was ~~only~~ invented only to create a groove space around the face of the tunnel; thus, ~~and~~ further standard excavation methods ~~like~~ such as explosives or wedges were still required to loosen the remaining core. In the 1960s, the introduction of the slurry TBM ~~brought~~ achieved a solution to the problem of an excessive groundwater level. The use of a bentonite-slurry ~~in the slurry~~ TBM ~~could~~ can not only support the face, but also ~~help~~ facilitate the removal process ~~of~~ for excavated soils. A few years later, difficulties occurred when the Japanese wanted to build tunnels in big cities. A method of tunnelling ~~which could~~ capable of being applied to soft ~~grounds~~ soil below the groundwater table, with minimum disturbance, was required. Therefore, the EPB TBM was developed to fulfill all ~~those~~ the aforementioned requirements. ~~Up to now~~ Thus far, various kinds of TBM have been improved in different ways. For example, the largest TBM in the world, called Bertha, has a diameter of 17.5 meters.

2.2.2 Slurry and EPB TBM

The slurry TBM is a specific ~~kind of TBM, which is~~ type usually used for digging in soft ~~ground~~ soil ~~with~~ containing a large amount of groundwater. ~~A brief~~ The structure of a slurry TBM is ~~shown~~ briefly illustrated in Figure 2.1. The front ~~part of it~~ portion is filled with excavated soils, with injections of bentonite slurry and air. ~~The~~ Pressure within ~~those~~ the air bubbles ~~are~~ is required to provide better control of the ~~pressure~~ fluctuation therein, and the addition of bentonite slurry leads to effective control of face stability ~~control~~ and waterproofing. One of the most important features ~~that make~~ differentiating the slurry TBM ~~different~~ from any other kind ~~of TBM~~ is the requirement of a large ~~slurry~~ separation system ~~required~~ on the ground surface, in order to separate spoils from the slurry in the extraction line so it ~~could~~ can be recycled back into the tunnel. Therefore, ~~it is noted by~~ Herrenknecht (2004) noted that the particle size must be considered before using a slurry TBM. The process of separating fine materials in ~~the~~ excavated soils from ~~the~~ bentonite slurry ~~could~~ can be extremely expensive.

The EPB TBM is normally suitable for excavations in unstable soft soils with a reasonably high fines content. ~~A brief~~ The structure of the EPB TBM is ~~shown~~ briefly illustrated in Figure 2.2. The cutter head consists of a rotating disc armed with massive cutting tools and several slits on cutter arms, ~~which~~ allowing the excavated materials to enter the working chamber, ~~The excavated materials~~ where they are collected, ~~and~~ compressed ~~in the working chamber~~ and removed by a screw conveyor. The EPB TBM aims to maintain a pressure in the working chamber equal to or greater than that of the groundwater and earth ~~pressures~~ at the cutting face. A stable pressure is sustained with the help of the screw conveyor, which extrudes a moderate volume of spoils to balance the amount of soils entering the working chamber. Compared with the slurry TBM, the EPB TBM mainly benefits from the simple process of the separation of the spoils. A large separation plant is not necessary since most of the additives are air and water, ~~This makes~~ thereby rendering the EPB TBM more suitable in urban areas because ~~it is often~~ of the frequent difficulty ~~to~~ in ~~decide~~ determining an appropriate plant layout. In addition, better overall production rates, lower capital cost, a smaller launch shaft and lower consumption of additives ~~could~~ can also be achieved by the EPB TBM. There has therefore been a continuous trend toward extending ~~the use of~~ EPB TEM usage to most types of soft ground. Editor's Note: What does the acronym 'TEM' designate? Identify here at its first occurrence in the main text. Or is this a typographical error?

2.2.3 Applications of EPB TBM [Compare with the 'Table of Contents' entry.]

Since the support medium of the EPB TBM is the excavated material itself, whether the balance between the pressure in the working chamber and the earth pressure ~~could~~ can be maintained depends mainly on the properties of the excavated soils. In order to achieve an optimum performance with the EPB TBM, the excavated soils must form a plastic mass ~~of~~ with appropriate flow characteristics, permeability, compressibility and low inner friction, which allow a well-controlled pressure dissipation from the working chamber to the ground surface through the screw conveyor. However, since natural soils do not often have all ~~those~~ these ideal properties, many difficulties might be encountered during excavations under complex geological conditions.

In clayey soils, the transformation process of ~~the~~ natural ground soils from a stiff to a soft consistency usually ~~could~~ cannot ~~prevent~~ occur without the addition of a large amount of water, which might ~~make~~ render the soils sticky and lead to serious clogging problems. For example, opening sections of the cutting head ~~being~~ could be plugged and steel surfaces ~~being~~ be covered by the excavated soils, resulting in a delay ~~of~~ in the advance rate and extra costs for essential ~~cleaning works~~ cleansing (Zumsteg *et al*, 2013).

In coarse sandy and gravelly soils, the main concern is whether the excavated soils ~~could~~ can be effectively impermeable and of great plastic consistency, properties which ~~help~~ facilitate ~~to remove~~ smooth removal of the spoils through the screw conveyor ~~smoothly~~ without groundwater inflow. The water pressure ~~could~~ cannot be resisted if the soil is too permeable. Milligan (2000) suggested that a coefficient of permeability of less than 10^{-6} to 10^{-5} m/s ~~was~~ is required for satisfactory performance of the EPB TBM.

However, in consideration of the many advantages of ~~the~~ EPB tunnelling, excavated soils are conditioned with additives such as foam, polymer and bentonite slurry to fit ~~EPB TBM~~ rather than limit the EPB TBM to natural soils. A ~~dramastic~~ dramatic extension of ~~use of the~~ EPB TBM usage ~~could be~~ is found ~~from~~ in the research results ~~of~~ reported in the Japanese Society of Civil ~~Enginners~~ Engineers Standard Specification for Tunnels (Kusakabe *et al*, 1999), ~~which is~~ simply reproduced in Table 2.1. Originally the EPB TBM ~~only~~ fits only in relatively soft and fine-grained soils, but it ~~could~~ can even work on gravel with boulders with the help of ~~the~~ additives.

2.3 Soil conditioning in EPB TBM

Soil conditioners are normally injected at the cutterhead, into the working chamber or along the screw conveyor. The aim of ~~adding them~~ their addition is to modify the properties of excavated soils to optimise the performance of the EPB TBM. Conditioners such as water, foams, polymers and bentonite slurries ~~could~~ can be used separately or in combination, ~~and~~ their performance~~s~~ with excavated soils being dependent on many factors.

One of the most important factors affecting the properties of the soil-soil conditioners mixture is the ground condition~~s~~, such as particle size distribution, water table level, permeability and plasticity (Merritt, 2004). ~~Those~~ These factors should be carefully considered before deciding which conditioner to use. Many commercial products are available as soil-conditioning agents, with detailed instructions ~~which suggests~~ suggesting the appropriate concentration, the injection ratio and, for foams, the expansion ratio for use in different ground conditions.

However, the same type of commercial products from two separate suppliers may have more or ~~less~~ fewer different effects on the excavated soils due to differences in components or ~~producing~~ production processes. Since the components of the conditioning agents are usually ~~kept~~ preserved as trade secrets, the choice of soil conditioners also becomes a factor affecting the ~~mixture's~~ properties of a mixture.

Another factor is the soil-conditioner injection system within the EPB TBM, This which includes a pressurised tank for storing soil-conditioning agents, ~~air~~ lines for applying compressed air, an adjusting device for controlling the flow rate of the soil conditioners and several ~~injecting~~ injection points in the machine. Both the air pressure ~~applying~~ applied to the conditioning agents and the flow rate of the soil conditioner have ~~great~~ remarkable impact on the properties of the soil conditioner, thus the properties of the soil-soil conditioner mixture as well.

2.3.1 Soil-conditioning agents

Because of the ~~great~~ remarkable affects of ~~the~~ soil conditioners on the properties of excavated soils, ~~there are a lot of~~ many commercially available products such as foam, polymer, bentonite slurry and dispersant exist. In order to limit the costs of ~~the~~ a project, new conditioning agents are also ~~made~~ formulated by the construction party according to the results from field experiments. In this ~~paper~~ report, the basic concepts and properties of bentonite slurry, polymers and foam are discussed below.

2.3.1.1 Bentonite slurry

As one of the most traditional soil conditioners used in EPB tunnelling, bentonite slurry has been widely employed ~~used wildly~~ in underground construction; ~~and~~ moreover, its properties have been discussed by many authors (Jefferis, 1992; Milligan, 2000; EFNARC, 2005). Bentonite is a processed form of a particular natural clay mineral, basically potassium, calcium and sodium montmorillonite. Because of the chemistry and structure of ~~the~~ montmorillonite clay particles, they are ~~able to~~ capable of holding up to ten times their dry volume after absorbing water. In particular, due to its smaller and thinner particle size and weaker bonding between clay sheets, sodium montmorillonite has a greater ability ~~of~~ to absorb water ~~absorption~~ than calcium montmorillonite ~~due to its smaller and thinner particle size and weaker bonding between clay sheets~~.

Bentonite slurries are ~~made~~ produced by dispersing montmorillonite in water. A high shear mixer is needed to ensure sufficient dispersion and hydration of clay particles. In granular soils, a low-permeability filter cake ~~could~~ can be formed at the cutting head of the EPB TBM by injecting bentonite slurries. The form of the ~~filter~~ cake ~~could~~ can not only help to improve the control of groundwater inflow and face support, but also reduce the torque of the cutting head and screw conveyor. In addition, foams or small quantities of polymers are often added to enhance the properties of bentonite slurries.

~~When~~ For ~~the~~ adding bentonite slurry ~~is added~~ to the working chamber of the EPB TBM to increase the plasticity of ~~the~~ granular soils, the ~~required~~ requisite amount ~~of bentonite slurry is suggested~~ has been formulated by Kusakabe *et al.* (1999):

$$X = a(30 - A)2.0 + (40 - B)0.5 + (60 - C)0.2 \qquad \text{Eqn 2.1}$$

where X is the concentration of the bentonite slurry; and *a,* ~~is~~ a coefficient ~~depends~~ dependent on the uniformity coefficient of the soil (C_u): *a* = 1.0 when C_u>4; ~~*a* =~~ 1.1 when 4>C_u>3; ~~*a* =~~ 1.2 when 3>C_u>1. *A* represents the percentage of soil passing through a 0.074mm sieve; *B,* ~~represents~~ the percentage ~~of soil passing~~ through a 0.25mm sieve; and *C,* ~~is~~ the percentage ~~of soil passing~~ through a 2.0mm sieve. The minimum values of the expressions within the brackets are zero.

2.3.1.2 Polymers

Polymers are macromolecules consisting of large ~~numbers~~ quantities of ~~repeating~~ recurring simple molecules linked by a non-covalent bond to a long chain. Homopolymers include only one single kind of monomer; whereas, at least two kinds ~~of monomer~~ are included in copolymers. The properties of polymer and its impact on excavated soils depend on their composition and structure. * Many kinds of polymers ~~have found applications in EPB tunnelling~~, such as starches, sugars, celluloses and proteins, which are all natural polymers, ~~and~~ as well as artificial polymers ~~like~~ such as polyacrylamides, polyacrylates and polyacrylamides (PA) have been applied in EPB tunnelling. Particularly, PA and their derivatives are among the most commonly used polymers in tunnelling.

*The highlighted sentence is problematic due to its ambiguity. Do you mean 'a polymer and **its** impact'? If so, then '**their** composition and structure' must refer to '**soils**'. However, I think you mean 'The properties of polymers and ~~its~~ their impact on excavated soils depend on their composition and structure'. The problem is one of agreement between a pronoun and its referent with regard to number, with '**their** composition and structure' [more likely] referring to 'polymers' [plural].

The most important factor determining the properties of polymers is molecular weight. PA polymers of high molecular weight (>10^7g/mol) act as flocculants, ~~helping~~ facilitating the separation process of solids from liquids. PA polymers of low molecular weight (<300,000g/mol) are used as dispersants, which are able to increase the negative surface charge on solid particles and reduce the tendency of particles to flocculate. As a result, solid particles ~~could~~ can maintain a dispersed structure of low viscosity (Milligan, 2000).

The influence of polymers as soil-conditioning agents used in tunnelling ~~have~~ has been reported in many studies (Lambe, 1953; Jefferis, 1995; Leinala *et al.,* 2002). It is believed that polymers ~~could~~ can help ~~to~~ form a plastic paste and coat the surface of clay particles. The improved plasticity and structure of excavated soils will lead to better control of the flow of soils through the working chamber and screw conveyor, ~~lower~~ decrease the torque at the cutting head and screw conveyor, and ~~lower~~ reduce the chance of clogging.

2.3.1.3 Foams

Foam is a mixture in a liquid phase, consisting of a water-based surfactant solution, compressed air (>90%), water and ~~some~~ certain additives. As illustrated in Figure 2.3, surfactant molecules include a hydrophobic chain and a hydrophilic end, which ~~could~~ can ~~have~~ possess anionic, cationic, non-ionic or amphoteric charge properties. Foams are created with the help of surfactants which adsorb at the air-water interface to reduce the surface tension and stabilise the liquid films between bubbles. The properties of foams are related to the solution chemistry, concentration, foam expansion ratio (FER), foam injection ratio (FIR), and the stability of foams.

Foam concentration represents the percentage of foaming agents in conditioning solutions, a higher concentration of which ~~could~~ can result in a higher FER and more stable foams. A concentration of only 1% to 3% is usually suggested by foam agent suppliers to achieve a satisfactory performance. Therefore, even concentrated foam agents are expensive, the costs of which might be quite modest compared with using more expensive polymers or a large amount of bentonite slurries. The concentration of foams strongly depends on the volume of water in the soils, to which further consideration~~s~~ should be given according to specific ground conditions.

~~The~~ Density ~~of foam~~ is an important parameter affecting the applications of foam. In soil conditioning, ~~it~~ density is measured in another ~~way~~ manner: the FER, which is calculated by

$$FER = \frac{V_a}{V_f} \times 100\% \qquad \text{Eqn 2.2}$$

where V_a is the volume of foam agent and V_f is the volume of foam solution. ~~It is noted by~~ EFNARC [the European Federation for Specialist Construction Chemicals and Concrete Systems] (2005) noted that the FER should be between 5 ~~to~~ and 30, which ~~will be~~ is suitable for EPB tunnelling. However, specific ground conditions ~~needs~~ require specific soil-conditioning treatments; e.g., the wetter a soil, the ~~higher~~ greater the requisite FER ~~is required~~. Since the foam generation process in the EPB TBM ~~is~~ occurs under pressurised conditions, the compressibility of the foam should be considered. By considering the fact that foam consists of more than 90% ~~of~~ air, an ideal gas law ~~could~~ can be applied to calculate ~~its volume~~ the change in volume ~~with~~ under pressure. Therefore, the FER at absolute pressure P is calculated by

$$FER_a = \frac{P_a}{P} \times (FER - 1) + 1 \qquad \text{Eqn 2.3}$$

where FER_a is the foam expansion ratio at atmospheric pressure P_a; and *FER*, ~~is~~ the foam expansion ratio at ~~the~~ absolute pressure P. As verified by a foam compression test (Quebaud et al., 1998), the ~~test~~ results ~~well~~ fitted this theoretical equation well.

The volume of foam required for conditioning is measured by the FIR, which is calculated by

$$FIR = \frac{V_f}{V_s} \times 100\% \qquad \text{Eqn 2.4}$$

where V_f is the volume of foam at working pressure and V_s, ~~is~~ the volume of soils to be excavated. An FIR around 30% - 60% is suggested in most cases (EFNARC, 2005). Laboratory tests or in situ tests are needed to determine the best value of the FIR during every project. In the literature, Kusakabe *et al.* (1999) proposed an empirical equation to ~~decide~~ determine the ~~required~~ requisite FIR:

$$FIR = \frac{a}{2}[(60 - 4.0A^{0.8}) + (80 - 3.3B^{0.8}) + (90 - 2.7C^{0.8})] \qquad \text{Eqn 2.5}$$

where *a* is a coefficient ~~depends~~ dependent on the uniformity coefficient of the soil (C_u): *a* = 1.0 when C_u>15; ~~*a* =~~ 1.2 when 15>C_u>4; ~~*a* =~~ 1.6 when 4>C_u. The terms *A, B* and *C* represent the same values as *A, B* and *C* in Equation 2.1.

Foams are expected to improve the properties of excavated soils during the ~~whole~~ entire process, from mixing in the working chamber to extruding by the screw conveyor. Rapid degradation or breakdown of the foam will lead to a loss of face support pressure. As a consequence, the stability of a foam-soil mixture is important for ~~persisting~~ maintaining the properties of conditioned soil over time. The ~~foam~~ stability of foam is evaluated by its half-life time. It ~~is~~ has been noted that when the foam is mixed with soils, the half-life time ~~of foam~~ is much ~~more~~ longer than that of the foam alone; ~~and~~ moreover, some foam-soil mixtures ~~could~~ can ~~keep~~ remain stable for even a couple of days (Babendererde, 1998). Foam stability is affected by many factors such as the size and uniformity of the bubbles, the confining pressure and temperature.

Recent research by Merritt (2004), Peña Duarte (2007), Zumsteg et al. (2013) and Gharahbagh et al. (2014) on foamed soils ~~showed~~ demonstrated that foam ~~could~~ can act as an effective conditioner with various types of soil. In clayey soils, foam is used to prevent excessive water absorption as well as reduce recompaction and ~~soil~~ stickiness therein, resulting in lower torques and fewer possibilities ~~of~~ for clogging problems. In granular soils, foam ~~could~~ can provide the excavated soils a proper plastic consistency, lower inner friction and greater compressibility. In addition, reduced permeability is also thought to be achieved with the help of ~~the~~ foams. In hard rock tunnelling, foam ~~acts~~ functions as a dust-suppressant agent and helps ~~with reducing~~ reduce machine wear.

The choice of foam types and polymer additives depends on the types of ~~the~~ soils to be excavated. A general guideline ~~is~~ has been provided by EFNARC (2005). As ~~shown~~ listed in Table 2.2, A is the foam ~~which has~~ exhibiting the greatest dispersing and coating abilities; B represents a general type of foam with medium stability; ~~and~~ whereas, ~~foam~~ type C should ~~has~~ have high stability and anti-segregation properties to sustain impermeability. It is ~~easy to notice~~ obvious that difficulties in forming satisfactory plastic paste increase when the soils become coarser.

2.3.2 Applications of conditioning agents

The efficiency of soil conditioning in the EPB TBM is influenced by comprehensive factors. However, investigations into ~~to~~ the effects of soil conditioners on the properties of soils in EPB tunnelling ~~are~~ have been limited. Most applications of soil conditioners are based on trial and error, which ~~could~~ can ~~cause~~ result in poor efficiency and extra costs. Applications of soil conditioning in granular soils and clayey soils are briefly discussed in this section.

2.3.2.1 ~~Soil conditioning~~ In clayey soils

Since most clayey soils have low permeability, which ~~could~~ can lead to better control of groundwater pressure, only a small amount of soil conditioning ~~are~~ is needed to achieve ideal soil properties. However, high plasticity might also cause serious problems during EPB tunnelling. Soils tend to adhere to the machine surface, ~~and~~ resulting in clogging the ~~openings~~ apertures of the working chamber. The best conditioning treatment suggested by Milligan (2000) is to use foam that ~~could~~ can coat the clay particles ~~in order~~ to form spoils ~~which could~~ capable of being extruded without recompaction. Using foam as the soil conditioner in clayey soils benefits from the small amount of water required to be injected into the soils, ~~also~~ as well as the great compressibility of the bubble-clay structure.

~~There are~~ Many factors ~~that~~ affect the efficiency of soil conditioning in clayey soils. Consideration~~s~~ should be given to the water content, liquidity index as well as soil compositions of the ~~soil~~ material to be excavated (Steiner, 1996). In addition, factors such as temperature and confining pressure might also have impacts on conditioned soils.

2.3.2.2 ~~Soil conditioning~~ In granular soils

The EPB TBM ~~could~~ can work quite efficiently in the excavation of soft soils including those with high fine contents and ~~proper~~ appropriate water pressures. However, problems ~~would~~ will be encountered when the ground conditions ~~is~~ are not ~~that~~ as ideal. The main objective ~~of~~ for adding ~~soil~~ conditioners to granular soils is to achieve satisfactory plasticity, low permeability as well as reduced wear.

~~The~~ Conditioning treatments for EPB TBMs with different soil gradings ~~are~~ have been suggested by Maidl *et al.* (1996), ~~which are~~ as ~~shown~~ graphed in Figure 2.4. For ~~the~~ soils ~~of~~ having grading curves above line 1, a small amount of water, bentonite, polymers or foams could help the ~~forming~~ formation of plastic paste; for ~~the~~ soils ~~of~~ with gradings between lines 1 and 2, the choice of conditioning treatment should mainly depend~~s~~ on the permeability and groundwater level; for ~~the~~ soils with gradings between lines 2 and 3, high-density bentonite slurry or foam-polymer conditioning treatments are ~~suggested~~ advised; and for those with gradings below line 3, EPB machines are not recommended unless special conditioners are used, ~~and~~ with obligatory essential in-situ experiments ~~are required~~.

Recommendations for ~~the~~ applications of ~~the~~ commercially available agents are provided by suppliers. Different foam agents as well as various stabilisers are available for conditioning in different ground conditions. For example, MasterRoc SLF 30 from BASF is generally suggested ~~to~~ for use in soft-ground tunneling; ~~while~~ whereas, polymer-reinforced MasterRoc SLF 41 is specially designed for silt-to-sand soils with high water content, and the MasterRoc SLP polymer series are used to enhance the performance of MasterRoc SLF foam products in difficult ground conditions (BASF, 2013).

2.4 Rheology

Rheology is defined as the study of the flow properties and deformation of materials. The flow properties of liquids play an important role in ~~our~~ daily life, from the viscosity of the blood flowing in ~~our bodies~~ the vascular system, to the ~~patrol~~ petrol pouring into ~~care~~ automotive engines. In EPB tunnelling, the soil flow in EPB TBMs exhibits the properties of viscoplastic fluids (Day and Holmgren, 1952; Ghavami *et al.,* 1974; Ghezzehei and Or*,* 2001); ~~and~~ moreover, the application of soil conditioners is significantly influenced by the flow properties of the excavated soils (Millgan, 2000). Therefore, ~~to~~ qualifying the plastic-flow characteristic of the conditioned soils could become an alternative approach for investigating the efficiency of soil conditioners.

2.4.1 ~~Rheology~~ Rheological theories

Rheology is well established as the behavioural science ~~of the behaviour~~ in which materials respond to applied stress or strain. ~~Basically~~ Essentially, all materials have rheological properties, including those in the fields of geology and mining (Cristescu, 1989), concrete technology (Tattersall and Banfill, 1983) and soil mechanics (Haghighi *et al.,* 1987).

2.4.1.1 Viscosity

Viscosity is a measure of ~~it's~~ a fluid's resistance to deformation, which ~~could~~ can be simply understood as the relationship between shear stress and ~~shear~~ rate. As ~~shown~~ illustrated in Figure 2.5, an idealised situation is assumed ~~that~~ wherein a layer of fluid ~~is~~ lies between two parallel plates. The bottom plate is fixed, while the top one is moving towards x_1 direction at a constant speed *u*. The shear stress σ is calculated by

$$\sigma = \mu u / h \qquad \text{Eqn 2.6}$$

where μ is the coefficient of viscosity; and *h*, ~~is~~ the distance between the two plates. The ratio μ/h is called the rate of shear deformation or simply shear rate and is often ~~used~~ expressed as $\dot{\gamma}$.

The viscosity of most simple liquids decreases with an increase in temperature due to the increased Brownian motion of ~~their~~ the constituent molecules. One of the most widely-adapted mathematical expressions of the effects of temperature on viscosity ~~is given~~ was formulated by Andrade (1934):

$$\log_{10} \mu = A_l + B_l / T \qquad \text{Eqn 2.7}$$

where *T* is the temperature (°C + 273.15); A_l, is a the coefficient of a liquid; ~~and~~ moreover, B_l ~~could~~ can be replaced by *E/R*, where *E* is the activation energy for flow and *R*, ~~is~~ the universal gas constant.

Furthermore, the viscosity increases when the applied pressure increases. The two

~~main~~ principal features of the viscosity of most single-phase liquids with an increase in pressure ~~are~~ were summarised by Barnes (2000). The viscosity approximately doubles when the pressure increases from atmospheric pressure to 1000 bar. However, ~~the~~ this increase ~~in viscosity~~ becomes much faster when the pressure exceeds 1000 bar, the viscosity ~~might~~ perhaps ~~increase~~ increasing tenfold at ~~around~~ approximately 2000 bar and 100-fold at 4000 bar ~~might be 100-fold~~. In EPB tunneling, the pressure in the working chamber is in the range of 100-400 kPa, ~~and~~ where the viscosity of the excavated materials is believed to increase linearly with increasing pressure.

2.4.1.2 Newtonian ~~fluid~~ and Non-Newtonian fluids

Newtonian fluids are those ~~for~~ in which the viscosity is independent of the shear rate; and whereas, all fluids ~~do~~ not exhibiting this behaviour are called Non-Newtonian ~~fluid~~. In order to investigate the flow behaviours of different fluids, ~~flow~~ curves which ~~show~~ graph the relationship between shear stress and ~~shear~~ rate are drawn and analysed.

The flow curves of four typical time-independent fluids as well as Newtonian fluids are ~~shown~~ graphed in Figure 2.6. Newtonian fluids have a linear relationship between the shear stress and ~~the shear~~ rate. For Non-Newtonian fluids, the Herschel-Bulkley model is used to describe all their behaviours in general:

$$\sigma = K(\dot{\gamma})^n + \sigma_0 \qquad \text{Eqn 2.8}$$

where K is the consistency coefficient; n, ~~is~~ the flow property index and σ_0, ~~is~~ the yield stress. The values of n and σ_0 for different fluids are listed in Table 2.3. An important feature of the Herschel-Bulkley and Bingham plastic model is the yield stress ~~which is~~ associated with the force required to initiate flow. The phenomenon of yield stress is often observed in multiphase fluids such as excavated soils in EPB tunnelling. Particularly, the interaction between sand particles in a sand-foam mixture ~~could~~ can form a three-dimensional network structure to resist flow at low stress.

Apparent viscosity (η) is defined as shear stress divided by shear rate, ~~it is~~ being a measurement for the flow behaviours of ~~the~~ Non-Newtonian fluids. For the general Herschel-Bulkley model, the apparent viscosity is determined by

$$\eta = f(\dot{\gamma}) = \frac{K(\dot{\gamma}) + \sigma_0}{\dot{\gamma}} = K(\dot{\gamma})^{n-1} + \frac{\sigma_0}{\dot{\gamma}} \qquad \text{Eqn 2.9}$$

2.4.2 Testing methods for viscosity

The viscosity of a material is often measured by a viscometer or a rheometer in laboratory research. The viscometer is capable of measuring rheological properties ~~of~~ under simple flow conditions; whereas, the rheometer ~~could~~ can provide a greater characterisation of flow and deformation behaviours.

2.4.2.1 Viscometers

Tube ~~viscometer~~ and rotational viscometers are the most used types ~~of viscometer~~. Both ~~of Them could~~ offer the advantages of ~~the~~ simplicity of use. One of the basic tube viscometers is the glass capillary (Figure 2.7), usually called the U-tube viscometer. The flow in the U-tube ~~is~~ occurs because of gravity, ~~and~~ wherein the viscosity is calculated from the time that a certain volume of fluid flows from the upper ~~etched line~~ to the lower of the etched lines. There is also a pressure-driven type viscometer in which a pump or gas system is used to create the driving force. Tube viscometers are used for research on time-independent fluids; ~~while~~ whereas, rotational viscometers focus on time-dependent fluids. Rotational viscometers are designed ~~based~~ on the basis of the idea that the torque required to rotate a disk or bob in a fluid is a function of viscosity. Traditional rotational viscometers include parallel plates as well as cone-and-plate and concentric-cylinder types, ~~and~~ all of ~~them~~ which ~~could~~ can measure the viscosity over ~~a period of~~ time.

2.4.2.2 Rheometers

Rheometers are used for ~~investigations on those~~ investigating fluids that ~~could~~ cannot be defined by a single value of viscosity ~~and~~ but ~~need~~ require consideration of ~~more~~ additional parameters ~~to be considered~~. Various commercial products are available, ~~and~~ one of ~~them~~ which is ~~shown~~ exemplified in Figure 2.8 ~~as an example~~. This Brookfield RST rheometer ~~could~~ can control the applied shear stress or ~~shear~~ rate and record the responding torques. ~~A lot of~~ Many accessories such as cone-and-plate ~~spindle~~, parallel-plate~~s~~ ~~spindle~~, coaxial ~~cylinder~~ and vane spindles, ~~and~~ as well as water jackets for temperature control, are available according to ~~the~~ specific research needs ~~of study~~, ~~and~~ for which the measurable max shear stress varies from 177Pa to 69.6kPa. Commercially available rheometers are designed ~~to do~~ in accordance with most comprehensive rheological testing capabilities for single-point viscosity as well as flow-curve analysis. However, in the case of tunnelling, most laboratory rheometers cannot be used without modification due to the large particle size~~d~~ of the conditioned soils in EPB tunnelling and the complex conditions in the machines.

Many efforts have been ~~made~~ undertaken to develop a new device for investigating the rheological properties of materials with large particle sizes. As the yield stress and workability of concrete are also of great practical interest~~s~~ ~~in practice~~ for pumping, mixing, casting and transportation, the ICAR portable concrete rheometer ~~is~~ was developed by Koehler and Fowler (2014). This ~~rheometer~~ device is a controlled-shear rate rheometer ~~that could~~ capable of ~~be applied to provide~~ providing flow curves or conducting stress growth tests. A four-blade vane impeller is chosen after comparing ~~6~~ six potential impeller types, including vanes, eggbeaters, half-eggbeaters, offset-eggbeaters, joint compound paddles and spirals. ~~It is indicated that~~ Reportedly, the vane impeller ~~could~~ can not only engage the flow of surrounding materials with favourable flow patterns, but also minimise the wall effect.

Inspired ~~from~~ by the successful application of the rheometer ~~in~~ to concrete workability, researchers (Meng *et al.*, 2011, and Messerklinger *et al.*, 2011, respectively) have developed modified rheometers used for investigating the effects of foam on sands and clays under pressurised conditions ~~have been developed by Meng *et al.* (2011) and Messerklinger *et al.* (2011) respectively~~. Details of their designs and testing results will be discussed in section 2.5.2.4.

2.5 Laboratory tests ~~for conditioned soils~~

~~As a result of those~~ Due to the advantages of using foams as conditioning agents in EPB tunnelling, various testing methods have been developed to assess the properties of foamed-soil mixtures. However, ~~due to~~ because of the ~~massive~~ numerous commercially available foam agents and many influencing factors involved, it is difficult to specify the particular conditioning treatment for a specific soil; ~~and~~ furthermore, none of those testing methods has yet been standardised ~~yet~~. Some of the popular testing methods for foamed soils as well as foam are discussed below.

2.5.1 Foam-index ~~tests~~ testing

Index tests of foam agents ~~could~~ can not only help ~~to~~ compare the basic properties of different foam solutions but also provide the ~~first~~ initial criteria for determining soil conditioning treatments. Some standard testing methods have been proposed by EFNARC (2005).

2.5.1.1 FER and stability

The expansion ratio ~~of foam~~ and stability of foam are generally tested ~~based~~ on the basis of methods described in the Ministry of Defence Standard (1998). A cylindrical steel container of 1600ml volume ~~is used,~~ with a drainage hole of 1.6mm in diameter at its conical base, as ~~shown~~ illustrated in Figure 2.9, is used. Freshly produced foams are collected to ~~fulfill~~ fill the container before measuring ~~and~~ the weight ~~of foam and container is measured~~. By weighing the empty container, the weight of foam ~~could~~ can subsequently be measured. When assuming that the density of the foam solution is $1.0\mathrm{g/cm^3}$, the initial volume of the foam agents ~~could~~ can be calculated by

$$FER = \frac{V_f}{W_{cf} - W_c} \qquad \text{Eqn 2.10}$$

where V_f is the volume of the foam, ~~it~~ which is 1600ml in this case. The term W_{cf} ~~is~~ designates the weight of the container ~~and~~ plus foam; ~~and~~ W_c, ~~is~~ the weight of the empty container. A container with calibrations is placed beneath the outlet of the foam-filled container. The volume of the liquid draining ~~form~~ from the full container is recorded over time; ~~and~~ moreover, the drainage time for 25% (t_{25}) and 50% (t_{50}) of the volume of the original foam solution ~~volume~~ ~~are~~ is used to evaluate the stability of the foam. Note: 'Ministry of Defence' of WHAT country? You need to specify: '(Name of Country) Ministry of Defence' here and in the Reference list.

Various commercial products ~~were~~ have been tested at different concentrations by ~~many authors~~ several researchers (Psomas, 2001; Merritt, 2004; Peña Duarte, 2007). ~~and~~ The FER and stability for ~~7~~ seven foam agents are ~~shown~~ listed in Table 2.4. It ~~is~~ has been found that the basic properties of different foam agents vary ~~a lot~~ considerably; ~~but~~ however, ~~there are~~ several underlying principles ~~that could~~ can be applied to all types of foam. The flow rate of air mixed with foam agents has an influence on the FER and drainage time. A higher flow rate means that a higher volume of air is injected into the foam agents, thus leading to a higher FER and a longer drainage time. However, there should be a maximum volume of air that ~~could~~ can be sustained within the air bubbles. Once the maximum value is exceeded, the foam might become unstable. ~~On the other hand~~ Contrariwise, the FER and drainage time are also significantly affected by ~~foam~~ the concentration of the foam ~~significantly~~. Both the FER and the drainage time increase with the increase in foam concentration. It should be remembered that the increase in FER is not linear with the increase ~~of~~ in foam concentration; thus, whether to increase this ~~foam~~ concentration or to increase the foam injection ratio should be considered to limit project costs.

As mentioned ~~before~~ earlier, a foam ~~could~~ can maintain its structure much ~~more~~ longer when mixed with soils than ~~that of~~ an unmixed ~~foam~~ one alone; therefore, a testing method for the stability of a sand-foam mixture ~~is~~ has been proposed by EFNARC (2005). A certain volume of fresh sand-foam mixture is collected in a perforated glass/plastic cylinder, and the volume of the mixture is recorded on a daily or half-daily basis for up to ~~3~~ three days. Since the ~~whole~~ entire testing process is not under pressurised conditions, the results should ~~only~~ be used for comparative purposes only.

2.5.1.2 Bubble sizes and images

One of the factors ~~that~~ affecting the stability of foam is ~~the~~ bubble size, ~~it~~ which ~~could~~ can ~~act as~~ perform an important role in the behaviour of a sand-foam mixture under shear stress (Peña Duarte, 2007). ~~It is~~ Langmaack (2000) ~~suggested~~ concluded that uniformly sized bubbles with diameters less than 1mm are suitable for stability ~~(Langmaack, 2000)~~. Foams of diameters ranging from 0.5mm to 2mm are often produced in the EPB TBM; moreover, in ~~laboratory~~ laboratories, ~~different~~ various attempts have been made to observe the sizes of foams [Citation?].

Bubble images of foams, both without external pressure and under constant pressure, ~~have~~ been were ~~taken~~ obtained by Peña Duarte (2007), ~~The foam~~ who used ~~is~~ Versa foam, ~~which is~~ a commercially available product. The first image, ~~which is~~ shown in Figure 2.10, ~~is~~ was taken by a Nikon D1X digital camera, ~~with~~ the foam being exposed to free air. As ~~shown~~ depicted in Figure 2.11, another attempt was made to ~~take~~ capture an image ~~on~~ of the pressurised foam between two acrylic platens ~~with~~ by using a Sony DKC-ID1 digital camera. It ~~is observed~~ should be noted that the max diameter of the bubbles is 0.5 mm in the first attempt, but 1 mm in the second attempt ~~and the max diameter in the second attempt is 1 mm~~ due to the ~~compressing effects~~ compression ~~of~~ resulting from applied pressure. ~~Picture~~ A photograph of a sand-foam mixture ~~have~~ was also ~~been~~ taken, ~~which is~~ as shown in Figure 2.12; however, the boundaries between foams and sands ~~could~~ are not ~~be~~ clearly ~~identified~~ identifiable therein.

With the application of a more advanced BT-1600 image particle analysis system, Liu (2012) and Yang and Wang (2012) ~~have~~ obtained more detailed and clear images of another type of foam as well as the size distribution of the bubbles. As ~~shown~~ depicted in Figure 2.13, ~~this~~ their system consists of an optical microscope, a digital CCD camera, a computer with image processing software and a printer. According to Table 2.5, the diameters of most bubbles are in the range of 68.3 μm to 115 μm.

2.5.2 Tests for conditioned soils

Many laboratory testing methods ~~could~~ can be ~~carried out~~ implemented to investigate the properties of conditioned soils. Milligan (2000) has discussed the advantages of the most commonly applied methods, such as mixing ~~tests~~, cone-penetration ~~tests~~, slump ~~tests~~, shear-box ~~tests~~ and vane-shear tests. For the purpose of simulating the ~~real~~ actual working conditions of the EPB TBM, large-scale screw-conveyor model tests ~~has~~ have also been developed and used in several studies. ~~As~~ Since ~~this~~ the present research focuses on the rheological properties of sand-foam mixtures, only those methods for investigating the flow abilities of ~~the sand-foam~~ such mixtures are discussed below.

2.5.2.1 Slump ~~tests~~ testing

Slump tests ~~are~~ were originally developed for measuring the workability of fresh concrete, ~~and it has been~~ being predominately used for more than 80 years. Because of ~~its~~ their simplicity and economy, most recent studies on the flow properties of ~~the~~

conditioned soils ~~are~~ have been based on slump tests (Quebaud *et al.,* 1998; Peila *et al.,* 2009; Thewes and Budach, 2010), ~~following~~ in accordance with the Standard Test Method for Slump in ASTM 143C.* ~~In~~ For EPB tunnelling, Quebaud *et al.* (1998) ~~suggest~~ found that a minimum slump value of 12 cm is needed to form an ~~proper~~ appropriate plastic flow through the EPB TBM. * Citation & Reference? Check title for missing word(s).

Soil behaviours with different FIRs and water contents were ~~summarised~~ analysed by Peila *et al.* (2009), as ~~shown~~ depicted in Figure 2.14. According to ~~Peila *et al.*~~ their findings, suitable conditioned soil should have a slump value within the 15-20cm range, with a water content from 3% to 18% and a FIR within the range of 20%-50%. Their results are quite close to the suitable slump values (>12cm) ~~mentioned~~ obtained by Milligan (2000) as well as the optimum FIR values (20%-40%) ~~suggested~~ specified by EFNARC (2005). In addition, because ~~of~~ the excavation process often lasts hours ~~under~~ at different temperatures, the influences of time and temperature on conditioned soils are also investigated with slump tests. It ~~is found~~ has been discovered that high temperatures and longer processing times ~~could~~ can reduce the slump value, possibly due to the faster breakdown process ~~of~~ in the sand-foam matrix.

Slump testing ~~could~~ can provide a good indicator of the overall properties of ~~the~~ conditioned soils; thus, it is preferable ~~to use it at~~ for field usage to ~~keep~~ maintain continuous quality control. However, slump testing is ~~viewed as~~ considered incapable of providing adequate information ~~of~~ on the flow properties of ~~the~~ conditioned soils in laboratory research.

2.5.2.2 Shear-box ~~tests~~ testing

In EPB tunnelling, ~~the~~ a reduction ~~of~~ in the shear strength of ~~the~~ excavated soils ~~could~~ can lead to a decrease in the torque required to rotate the cutting tools. Thus, the shear strength is of great importance in investigating the effects of soil conditioners on excavated soils.

~~The~~ Shear-box ~~tests~~ testing is one of the most fundamental methods ~~to investigate~~ for investigating the relationship ~~of~~ between shear stress and ~~shear~~ rate as well as ~~determine~~ determining the angle of shearing resistance. Shear-box tests on conditioned sands were ~~presented~~ conducted by Psomas (2001) and Peña (2007). The results ~~showed~~ indicated that the application of foam reduced the shear strength of ~~the~~ a sand-foam mixture, and ~~the~~ an increase ~~of~~ in the FIR resulted in reduced shear strength.

However, the ~~continuous~~ continuing relationships between shear strength and ~~shear~~ rate ~~could~~ cannot be investigated. Therefore, the at-large residual strength ~~at large~~ strains strength-and-rate relationships such as those existing in the EPB TBM.

2.5.2.3 Model ~~tests~~ testing

In order to simulate the pressurised conditions in the EPB TBM, model tests with a screw conveyor in the EPB machine ~~are~~ were developed by Merritt *et al.* (2004), Vinai *et al.* (2006), and Peña (2007). The screw conveyor is one of the most important parts in the EPB TBM, controlling the flow rate of the excavated soils and sustaining the pressure balance within the working chamber. ~~A better~~ An enhanced understanding of the screw conveyor ~~could~~ can provide guidance for conditioning treatments to optimise EBP performance.

The 1:10 scale of a normal EPB screw conveyor system model developed in ~~the~~ research ~~of~~ conducted by Merritt (2004) and Peña (2007) is ~~shown~~ illustrated in Figure 2.15. This system ~~mainly~~ consists mainly of a container filled with ~~testing~~ soils for testing, a horizontally assembled screw conveyor and a variable-speed electric motor. In addition, some extensive instrumentations ~~are~~ were applied to investigate the performance of the ~~screw~~ conveyor. Two Cambridge-type load cells and ~~one~~ a single-pore water-pressure transducer ~~are~~ were installed along the ~~screw~~ conveyor in order to study the normal stresses--~~and~~ both shear ~~stresses~~ and others--acting on the conveyor casing as well as the pressure fluctuations within the casing. The torque required to rotate the screw conveyor is measured by a ~~torque~~ sensor on the screw shaft. With the help of this novel system, both conditioned clays and sands were tested ~~with~~ at variable pressures, flow rates, and different screw geometries. The results from their tests ~~showed~~ demonstrated that the undrained shear strengths of the conditioned soils have great effects on the pressure gradient in the screw conveyor, and the use of conditioning agents ~~could~~ can reduce the required torque.

Model tests have confirmed that ~~the~~ investigation of the shear strength of excavated soils at different strain rates and pressures is essential for improving EPB performance as well as ~~saving~~ controlling operation costs. However, ~~the~~ application of ~~the~~ model tests is limited due to ~~its~~ the complex testing process and the extremely ~~huge demand~~ large quantity of testing materials (soils and conditioning agents) required.

2.5.2.4 Rheometer ~~tests~~ testing

As a consequence of the limitations of ~~these~~ the aforementioned existing testing methods ~~mentioned before~~, there ~~is~~ had been no standard test for investigating the shear strength and ~~its~~ the ancillary rate dependency of the conditioned soils. In order to determine the optimum conditioning treatments in EPB tunnelling, a pressurised soil rheometer ~~is~~ was developed by Meng *et al.* (2011).

~~It is shown in~~ Figure 2.16 indicates that the main body of this rheometer ~~is made up~~ consists of a pressurised tank with a loading system, a torque sensor and a motor with two reducers. A vane-type impeller ~~is~~ was chosen in consideration of the shearing gap, the wall-slip effect and the disturbance to the soil samples occurring when the impeller is inserted into the soils. The form of the soil failure ~~would~~ will be a cylinder which depends on the geometric size of the vane impeller. ~~and~~ Furthermore, it is assumed that the shear stress is distributed on the top, bottom and lateral surface of the cylinder homogeneously. In addition, compressed air is applied through a gasbag at the bottom of the tank, aiming to provide a comparable pressure in the working chamber of the EPB TBM. This device is capable of measuring the torque on the vane ~~with~~ at various controlled shear-strain rates. Sand samples were conditioned with foams and bentonite slurries and tested with confining pressures ranging from 0-500kPa. ~~It was found from~~ The testing results indicated that the conditioned sands followed the Bingham fluid model, ~~and showed~~ exhibiting shear-thinning properties of Non-Newtonian fluids, ~~which meant~~ meaning that the viscosity ~~would~~ will decrease with an increasing shear rate. Furthermore, the apparent viscosity and yield stress of the conditioned soils increased with the increase ~~of~~ in confining pressure. More specifically, the shear strength of the conditioned sands ~~increases~~ increased from 1.5kPa to 10.2kPa, and the apparent viscosity ~~increases~~ increased from 210kPa.s to 1250kPa.s when the confining pressure ~~grows~~ was increasing from 0kPa to 400kPa.

A similar vane-shear test apparatus ~~is~~ was developed by Messerklinger *et al.* (2012) in order to investigate the shear strength of conditioned clays at different pressures and shear velocities. The most significant difference between these two devices is the torque sensor ~~is~~ placed inside the soil container for the purpose of offering more accurate ~~torque~~ measurement by minimising ~~machine~~ the friction inside the machine. A series of tests on conditioned kaolinite and illite clays ~~were~~ was performed, ~~and~~ the results of which were compared to those from a commercially available rheometer to ensure their applicability.

Overall, these studies have provided good references for further research on the rheological properties of ~~the~~ conditioned soils under pressurised conditions.

2.6 Summary

A review of the literature relevant to the objectives of this study ~~is~~ has been presented in this chapter. Among the most widely used soil conditioners, such as the bentonite slurry, polymers and foams ~~which are~~ introduced in section 2.3, it ~~seems~~

appears that foam would be a solution to most difficulties encountered during EPB tunneling. Since the main objective of conditioning treatments is to form a plastic soil flow in the EPB TBM, the rheological properties might be a remarkable factor affecting ~~the~~ EPB performance. Several testing methods for investigating the influence of soil conditioners on the properties of excavated soils ~~are~~ were reviewed in section 2.5. However, most of the existing approaches do not allow continuous observations ~~on~~ of the shear strength and ~~its~~ the ancillary shear rate dependency of the specimen. ~~Inspired from~~ Motivated by ~~the~~ successful applications of the rheometer ~~on~~ to the study~~ing~~ of concrete workability, researchers have developed newly designed soil rheometers ~~are developed and used to~~ for use in testing the rheological properties of both conditioned sands and clays under pressurised conditions. This new ~~kind of new~~ type of device ~~could~~ can provide ~~a new~~ an innovative method ~~to evaluate~~ for more comprehensively evaluating the efficiency of conditioning treatments ~~more comprehensively~~. Further efforts might be required to establish relationships between the results from traditional testing methods and the ~~results from~~ findings obtained by rheometers, as well as ~~to~~ extend the applications of the new device to soils with coarser particles.

CHAPTER THREE

3. Index ~~tests~~ testing and apparatus design

3.1 Introduction

Due to ~~so many~~ the numerous factors affecting the performance of conditioning treatments, it ~~would be~~ is difficult to specify the best conditioning treatment for a particular soil. Proper conditioning agents and a suitable range of parameters for different kinds of soil are normally suggested according to practical experience. In the laboratory, index tests for both conditioning agents and conditioned soils are always required to determine satisfactory conditioning treatments.

A foam generator ~~which was~~ used for foamed concrete ~~is~~ was commissioned ~~for generating~~ to generate a foam solution ~~in~~ for EPB tunnelling. The effects of the operational parameters of ~~the foam~~ this generator on the basic properties of foams are discussed in this chapter. In addition, the results ~~of~~ from a few ~~numbers of~~ slump tests are ~~performed~~ examined to compare the overall behaviour of a sand-foam mixture. ~~On the other hand~~ In addition, a modified soil rheometer is proposed to investigate the rheological properties of ~~sand-foam~~ the same mixture.

3.2 Index tests

The index tests performed in this study included FER ~~tests~~, foam stability ~~tests~~ and slump tests. Details of the materials, laboratory apparatuses, testing methods and results are described in this section.

3.2.1 Soils

Leighton Buzzard sands have been used by Psomas (2001) and Peña (2007) to study the behaviour of conditioned sands in shear-box ~~tests~~, compression ~~tests~~, permeability ~~tests~~ and screw-conveyor model tests. Because of ~~these~~ the ~~good~~ favorable references provided by previous studies, ~~Leighton Buzzard~~ the same type of sands ~~are used~~ were chosen for use in this research as well.

Generally, ~~L.B.~~ Leighton Buzzard (LB) sands ~~has~~ have more than 90% silica content, ~~and has a~~ are light brown in colour and have a sub-angular-to-rounded shape. Three different kinds of ~~Leighton Buzzard~~ LB sands ~~have been bought~~, ~~named~~ designated L1, L2 and L3, were purchased ~~and all of them are supplied by~~ from Aggregate Industries. The grading curves of L1, L2 and L3 are ~~shown~~ plotted in Figures 3.1, 3.2 and 3.3, respectively. The product name of the L1 sand is fine sharp ~~Leighton Buzzard sand~~ LB, ~~and~~ the sizes of most ~~of its~~ particles of which (98.1%) are between 0.06mm and 2.00mm. Further treatments ~~might~~ can sometimes be required to sieve out the unexpected oversize particles (>2.00mm). L2 is a kind of coarse sand, originally named Garside 8/16 ~~sand~~ by the supplier. The size range of the L2 is 1.00mm to 2.00mm. Garside 16/30 is the original product name of the L3 sand, which has particle sizes between 0.5mm to 2.00mm. Table 3.1 ~~shows~~ lists the characteristic sizes of these three kinds of sand (d_{10}, d_{30} and d_{60}), the uniformity coefficients ($C_u = d_{60} / d_{10}$), the coefficients of curvature ($C_c = \dfrac{(d_{30})^2}{d_{10} \times d_{60}}$) and the specific gravity (G_s).

3.2.2 Soil conditioners

In the trial stage of this study, two kinds of foam agents and two polymers designed for EPB tunnelling ~~are~~ were ordered from the BASF chemical company. However, due to time limitations, only two ~~foam~~ agents ~~have been~~ were actually used in the foam-index tests and mixed with the sands.

3.2.2.1 Foam agents

MasterRoc SLF30 and MasterRoc SLF41 ~~are~~ were selected for this research, both of ~~them~~ which are especially designed for soil conditioning in shield-tunnelling boring machines. ~~They~~ Both agents are ~~all~~ liquid solutions based on anionic surfactants or glycols with polymer additives. Full details of the properties of these two agents provided by the supplier are ~~shown~~ listed in Table 3.2, where F30 ~~represents~~ designates SLF30 and F41 ~~represents~~ signifies SLF41. Both agents ~~could~~ can be expanded with air to produce stable foams for ~~injecting~~ injection onto the face, into the working chamber or along the screw conveyor. The ~~foam~~ expansion ratio and the ~~foam~~ injection rate of the foam ~~depends~~ depend on the soil conditions encountered.

3.2.2.2 Polymer additives

As ~~suggested~~ recommended by the supplier, MasterRoc SLP 1 or MasterRoc SLP 2 polymers ~~could~~ can be used jointly ~~used~~ with F30 and F40 to enhance the stabilities of ~~the~~ foams or to ~~adjust~~ modify the properties of excavated soils. Table 3.3 ~~shows~~ lists the properties of the polymers, wherein P1 ~~represents~~ designates MasterRoc SLP 1 and P2 ~~means~~ signifies MasterRoc SLP 2. Both polymers are based on polyalkylene oxides, which have ~~similar~~ properties similar to PHPA polymers, and are used in liquid form. P1 is a lubricating polymer ~~which is suggested~~ recommended ~~to~~ for use ~~under~~ in ~~difficult~~ extenuating ~~ground conditions~~ situations with soils containing fine sand, silt or clay with high water content, ~~where~~ in which foam ~~along~~ alone is not adequate to modify the ~~soil~~ properties (BASF, 2013). In contrast, the soil-structuring polymer P2 is more suitable in coarse sands due to its good anti-segregation properties (BASF, 2013).

3.2.3 Foam generator

A laboratory foam generator (Figure 3.4) ~~is~~ was used to produce foam ~~of proper qualities as~~ having properties comparable to those generated in the EPB TBM. The product name of this ~~foam generator~~ machine is the Portafoam TM2 portable foaming generator, supplied by ~~Malaysian company,~~ the UEM Group (Kuala Lumpur, Malaysia). This device was designed to provide aqueous stable foam for foamed concrete and was previously used by another PhD student to investigate the indentation behaviour of fibre-reinforced foamed concrete. However, it ~~is~~ was found that foams used in EPB tunnelling ~~could~~ can also be produced by adjusting ~~some~~ certain initial setups.

The foam generator consists of ~~4~~ four main parts: ~~which are~~ an air compressor, a pressure tank, a control box and a foam lancer, the detailed schematic of which is ~~shown~~ diagramed in Figure 3.5. The arrows on the lines ~~show~~ indicate the flow directions. It is mentioned in the instruction manual that the air flow and recharge rate ~~from air~~ of the compressor should ~~be higher than~~ exceed 450 liters/min to sustain proper operation of the ~~foam~~ generator. The flow of compressed air is controlled by V1. The compressed air is then mixed with a foam agent of certain concentration and water in the pressure tank, which has a volume of 50 liters ~~volume~~ and a maximum pressure capacity of 120 psi. V2 and R2 ~~could~~ adjust the pressure in the ~~pressure~~ tank, and V3 is opened when the foam solution is mixed sufficiently. The foam solution and compressed air are mixed before reaching the foam lancer with the help of the T-shaped inverter system, which has already been described in a previous study (Psomas, 2001). Finally, the foam solution is conditioned in the ~~foam~~ lancer to generate stable foams of relatively homogeneous bubble sizes.

One of the most important factors affecting the final properties of foams is the pressure within the ~~pressure~~ tank, which ~~has to~~ must be less than that ~~of~~ in the air line so that satisfactory mixing of liquid and air ~~could~~ can be achieved. Adjustment of the regulators, R1 and R2, ~~could~~ can result in a lower or higher ~~pressure~~ difference in pressure between ~~pressure~~ the tank and the air line. ~~In~~ Generally, a ~~higher~~ greater ~~pressure~~ difference in pressure ~~would~~ leads to a lower foam density, thus a ~~higher~~ larger FER.

3.2.4 Soil mixer

The ~~mixing~~ process of mixing sand and foam ~~is achieved~~ was accomplished by using a standard Mortar* mixer (Figure 3.6) supplied by the Controls Group. This robust mixer is capable of mixing 5 liters of sand-foam mixture ~~and provide~~ at two beater speeds: 140 and 285 r.p.m. Whether the mixing is sufficient ~~or not~~ is simply ~~observed~~ determined by ~~eyes~~ visual observation. Generally, a one-minute mixing at 140 r.p.m.

is adequate for producing a homogeneous mixture. In order to form enough volume of the sand-foam mixture for both slump ~~tests~~ and further rheometer ~~tests~~ testing, two ~~same~~ identical Mortar* mixers ~~are~~ were prepared. In addition, a concrete mixer of much ~~more~~ greater capacity ~~would be~~ [was/should be]** available if difficulties [are/had been]** encountered ~~when~~ during the concurrent usage of two Mortar* mixers ~~are used at the same time~~. * [See Editor's Note @ Fig 3.6]

**Choose one pair: 'was' followed by 'had been' or 'should be' followed by 'are', depending on whether you are offering a suggestion or describing part of your own procedure.

3.2.5 Foam index testing

In order to investigate the effects of generation parameters on foam properties as well as measure the properties of foams of different agents and concentrations, foam index tests ~~are~~ were performed with simple measuring methods.

3.2.5.1 Testing methods

~~According to the basic idea of~~ In general accordance with the testing methods described in the Ministry of Defence Standard (1998), the FER and foam stability ~~are~~ were measured ~~in~~ by an easier ~~way~~ procedure in this study. A plastic container ~~of~~ having an exact volume of 1 liter ~~is~~ was used to collect fresh foam produced by ~~foam~~ the generator; ~~and~~ then, the ~~weight of the~~ container with foam ~~is~~ was subsequently ~~measured~~ weighed. ~~Therefore~~ Thus, the FER ~~is~~ was calculated ~~from~~ by Eqn 2.10.

The equipment used to measure the foam drainage time, ~~is shown~~ pictured in Figure 3.7, ~~which is~~ simply ~~made up~~ consisted of a plastic bucket with a hole ~~at its~~ in the bottom, a sieve ~~of~~ with 150 μm ~~opening~~ apertures ~~size~~ and a glass~~ware~~ beaker with calibrations. The fresh foam ~~is~~ was collected in the bucket ~~which is~~ placed on the sieve. Then, the liquid weight of the foam could be calculated from the volume (5.9 liters) and weight of the foams in the bucket. A filter paper ~~is added~~ was inserted between the bucket and the sieve because the foam diameter reported in previous studies ~~is~~ was smaller than the ~~opening size~~ apertures of the sieve used in the present study. The time required for collecting 25% and 50% of the total weight of the foam solution in the glassware ~~is~~ was recorded as t_{25} and t_{50}, respectively.

3.2.5.2 Testing results

Since the laboratory foam generator was not designed for soil conditioning in EPB tunnelling, a series of tests ~~were~~ was performed to ~~find out~~ determine the best operational settings for producing a sand-foam mixture. The FER and stability of the F30 foam agents were measured under different tank pressures and ~~pressure~~ gaps between the ~~pressure~~ tank and air line. At least eight tests were ~~done~~ conducted for each tank- ~~pressure~~ and air-line pressure combination in order to ~~provide~~ obtain reliable information. The ~~results~~ data listed in Table 3.4 clearly ~~show~~ indicate that both the FER and drainage time increase with an increase in the pressure gap, but the increase ~~slow down~~ decelerates when the pressure is ~~higher~~ greater than 20 psi. More obvious increasing trends ~~of~~ in the FER and drainage time ~~could~~ can be observed in Figures 3.8 and ~~Figure~~ 3.9, wherein the FER becomes quite stable between 23 and 27 when the pressure difference reaches 20 psi; ~~and~~ moreover, the half-life time of the foams is ~~higher~~ greater than 400 seconds when a 15 psi pressure gap is set. ~~Moreover~~ Furthermore, the influence of the pressures in the tank ~~could~~ can also be observed from these results. Generally, a higher pressure in the tank ~~would~~ results in a greater value of the FER and a longer drainage time, and this difference tends to be eliminated with ~~the~~ an increase in the pressure gap. Therefore, it might be concluded that the pressure gap is the most important operational parameter affecting the foam properties.

~~On the other hand~~ However, the influences of concentration and type of foam were also investigated in this study. As the data ~~shown~~ listed in Table 3.5 indicate, an increase in foam concentration ~~would~~ leads to increased FER and greater stability. By comparing the foam properties of F30 and F41, it is ~~noticed~~ observed that F30 ~~could~~

can produce a foam ~~of~~ with a higher FER. This ~~is~~ occurs mainly because of the different types of surfactants and the polymer additives used in the foam agents.

The suitability of ~~the~~ foam as a soil conditioner is basically determined from FER and stability. According to previous studies (Quebaud *et al.,* 1998; EFNARC, 2005), an FER of 5 to 30 and stability of longer than 5 minutes are commonly considered adequate for tunnelling applications. The specific requirements of foam properties depend on in-situ ground conditions. For example, ~~a~~ high stability ~~of foam~~ is needed in foams when the cutting circles are delayed in order to sustain continuous conditioning on excavated soils.

3.2.6 Slump tests

The sand-foam mixture of F41 and L1 ~~is~~ was tested to evaluate the overall behaviour of conditioned sand as well as to compare its plastic fluidity with ~~those~~ the results ~~from~~ obtained in previous research. Because ~~there was~~ no standard slump-testing apparatus was currently available ~~at that moment~~, ~~a~~ the Vee Bee consistometer pictured in Figure 3.10 ~~is~~ was commissioned for the trials, ~~This apparatus is used for~~ consisting of concrete slump tests and vibration tests. ~~and a picture of it is shown in Figure 3.10.~~ ~~The~~ This consistometer ~~comprises~~ consisted of a slump cone with a hopper, a plastic plate attached to a graduated rod, a specimen container fixed on a vibrating table ~~which has~~ having a fixed amplitude and frequency of vibration. Only the upper parts, including the slump cone, cylindrical container and graduated rod, ~~are~~ were used in this study. A freshly produced sand-foam mixture ~~were~~ was poured into the slump cone ~~that is~~ placed in the container. After ~~compacting~~ the mixture was compacted by a tamping rod, the slump cone was raised the vertical distance between the original and the displaced positions of the top surface of the sand-foam. The mixture was then measured and recorded as the slump value.

A foam injection ratio (FIR) ~~is~~ was used to determine the volume of foam required to condition the soils, ~~and it is~~ being calculated by

$$FIR = 100\% \times V_f / V_s \qquad \text{Eqn 3.1}$$

where V_f is the volume of foam, and V_s, ~~is~~ the volume of excavated soils. The guidelines published by EFNARC (2005) ~~It is suggested in the guideline of EFNARC (2005)~~ recommend that the FIR ~~should~~ be around 30% to 60 %. In this study, F41 foams were produced at 40 psi tank pressure and 60 psi air-line pressure and ~~were~~ mixed with L1 at a FIR of 50%. Four tests were conducted, ~~one of~~ the ~~typical test~~ result~~s~~ from a typical one of which is ~~shown~~ pictured in Figure 3.11. All mixtures tested had slump values ~~higher~~ greater than 150mm and exhibited behaviours characteristic of plastic fluids. However, the exact slump value could not be measured because the casing of the specimen container ~~stopped~~ restrained the sand-foam mixture from free movement. ~~As a result~~ Consequently, a standard slump cone apparatus will be used in further studies.

3.3 Design of ~~a~~ proposed soil rheometer

Inspired ~~from~~ by the ~~newly developed~~ soil rheometers recently developed by Meng et al. (2011) and Messerklinger et al. (2011), a ~~soil~~ rheometer which ~~could~~ can be applied to ~~more~~ coarser soils is proposed in this study (Figure 3.12). This apparatus is basically composed of a specimen container where the soil samples are pressurised and rotated by an impeller, a torque sensor which is able to measure the torque required to spin the impeller, and a stepper motor providing various constant speeds.

3.3.1 Vane geometry

First~~ly~~, a vane-type impeller ~~is~~ was selected ~~according to~~ in accordance with previous research (Koehler and Fowler, 2004; Meng *et al.*, 2011; Estelle and Lanos, 2012). It is believed that ~~vane~~ this type ~~impeller~~ has two major advantages: (1) the structure of the soil sample ~~would~~ will be less distributed by the vane entry, which is important for structured and granular suspensions; and (2) the wall slippage ~~would~~ will be reduced. However, ~~there is~~ since no standard design criteria exist for vanes used in testing the rheological properties of sands, the geometric size of the proposed vane was determined ~~according to~~ in accordance with the standard ~~tests~~ methods for vane shear field-testing ~~vane shear test~~ in cohesive soil (ASTM D2573).

~~Some~~ The basic requirements for vane geometry include~~s~~ the following:

~~The~~ Vane diameter D: 35 to 100 mm;

~~The vane~~ Shaft diameter d: 12.5 to 16.5 mm;

Vane height H: $D \le H \le 2.5D$;

The maximum blade thickness e should be less than 3 mm.

In addition, the vane area ratio V_A must be less than 12% to ensure a minimised soil disturbance during insertion. The V_A is calculated by

$$V_A = \frac{8(D-d)e + \pi d^2}{\pi D^2} \qquad \text{Eqn 3.2}$$

The final vane geometry, ~~which is shown~~ enumerated in Table 3.6, ~~is~~ represents a compromise between the maximum size of the sand particles and the range of torque measurements, which increases with an increasing vane diameter.

3.3.2 Specimen container

A sand-foam mixture should be tested in a sealed container which allows for an undrained condition. Soil rheology presents several unique challenges due to the large particle size of coarse aggregates.

One of the main problems ~~relating~~ related to the specimen container ~~of~~ on the soil rheometer is the ~~gap~~ size of the gap between the vane and the casing of the container. A sufficient gap size ~~would~~ will lead to a steady particle-packing density near the container wall. In general rules for a rheometer, ~~it is suggested by~~ Ferraris (1999) recommended that the gap size ~~should~~ be at least ten times the maximum particle size. For sand samples with a maximum particle size of 2mm, a 20mm gap would be required; therefore, the diameter of the soil container ~~would~~ should be at least 90mm.

Two spare consolidation cells from ELE International were stacked and used for the specimen container (Figure 3.13), the product name ~~for the cell~~ of which is an EL25-0705 Rowe-type consolidation cell, with a sample diameter of 151.4mm and a sample height of 50mm. A hole was cut at the bottom of the cell for the shaft of the vane impeller. ~~The~~ Undrained conditions for soil samples are ~~available~~ achievable with proper sealing at the hole, ~~and~~ the required pressure ~~required is~~ being readily applied to the samples when the laboratory-compressed air system is connected to the top of the cell. The working pressure of the EPB TBM varies from case to case, ~~but is~~ generally being around 200 kPa. These cells have a maximum working pressure of 1000 kPa ~~and~~ although the working pressure in this study might ~~go up~~ rise to only 500 kPa.

3.3.3 Torque sensor and stepper motor

In order to select ~~proper~~ an appropriate torque sensor which is ~~able to~~ capable of accurately ~~measure~~ measuring ~~the accurate~~ torque under pressurised conditions, the measuring range of ~~torque~~ the sensor was first considered ~~at first~~. According to Meng *et al.* (2011), the peak undrained shear strength of conditioned sands is about 34 kPa with a confining pressure of 400 kPa and vane speed of 1/3.4 rpm. ~~On the other hand~~ However, ~~it is noted in~~ ASTM D2573 has reported that the value of measured torque T_m corrected for apparatus and rod friction is calculated by

$$T_m = \frac{7\pi D^2 H S_u}{12} \qquad \text{Eqn 3.3}$$

where S_u is the undrained shear strength from the vane. By applying S_u = 34 kPa, D = 50 mm and H = 50 mm to Eqn 3.3, a maximum T of 7.8 Nm is required for the torque sensor.

Considering that this device might be used for further research on soils with larger particle sizes, the present researcher purchased a 4520 A100 torque sensor from the KISTLER company ~~was bought~~. The measuring range of this torque sensor is 100 Nm, and the linearity error is within ±0.5%, ~~which results in~~ delivering an accuracy of ±0.5 Nm.

It is believed that, in laboratory research, the stepper motor ~~could~~ can provide better control of the ~~rotating~~ rotation rate ~~in laboratory research~~. The rotational speed ~~of the stepper motor rotation~~ is directly related to the frequency of the input pulse, ~~and~~ the degree of rotation ~~is~~ being directly related to the number of ~~input~~ pulses applied. Therefore, a wide range of rotational speeds ~~could~~ can be achieved and controlled. In this study, an AR911ACD-PLE80-20 type, purchased from the Oriental Motor company, ~~is~~ was selected. This type of motor ~~could~~ can provide a maximum speed of 7000 rpm and a nominal maximum output torque of 120 Nm in correspondence with the maximum measuring capabilities ~~torque~~ of the selected torque sensor. In addition, a data acquisition system ~~would~~ should be connected to both the torque sensor and the stepper motor to conduct ~~data collecting~~ collection and analysis.

3.3.4 Overall design

The design of the soil rheometer was ~~done~~ prepared by SolidWorks, ~~a picture of the overall design is shown~~ as illustrated in Figure 3.14. Parts of the rheometer ~~could~~ can be simply connected by ~~connecting~~ joining the couplings from shaft to shaft. ~~and~~ A supporting base is also needed to provide stable working conditions. Extensive apparatuses, ~~like~~ such as those for data acquisition and voltage supply ~~and~~ as well as a PC, ~~are~~ were available in the laboratory.

3.4 Summary

In this chapter, the materials and laboratory apparatuses used ~~are~~ have been introduced. The methods for investigating the index properties of foams and sand-foam mixtures and the design of a new soil rheometer ~~are~~ have been described. Some results of the trials are summarised below.

The foam-index tests ~~showed~~ indicated that the pressure gap between ~~pressure~~ the tank and the air line had great effects on the expansion ratio and stability. The properties of foam ~~could~~ can also ~~be varies~~ vary ~~from~~ due to different types of agents and ~~the foam~~ concentrations. Generally, an FER of 20-30 and a drainage time of at least 5 minutes ~~is~~ are recommended.

The results from the slump tests ~~illustrated~~ demonstrated that the sand-foam mixture had ~~great~~ favourable plastic-flow properties with slump values ~~over~~ exceeding 150 mm, although ~~a wrong~~ an incorrect device was used, which in turn probably resulted in lower slump values. ~~More~~ Additional ~~slump~~ tests with a standard slump cone would be required to verify the results.

~~At last~~ Finally, a new soil rheometer ~~was~~ has been proposed and details of the main parts thereof ~~of the rheometer were given~~ presented. It is expected that ~~to use~~ this device can be used to determine the rheological parameters of sand-foam mixtures, ~~which works~~ functioning on the principle of measuring the undrained shear stress on a vane impeller with a controlled strain rate.

CHAPTER FOUR

4. Plan for future ~~work~~ research

The proposed plan ~~of work~~ for research during the ~~remaining duration~~ remainder of this PhD ~~study~~ program is ~~given~~ outlined in Table 4.1, consisting of ~~There are mainly 6 works~~ six main projects which ~~needed to~~ should be ~~done~~ completed within ~~3~~ three years.

The first ~~one~~ step is to use a standard slump cone to evaluate the plastic behaviour of a sand-foam mixture in order to create a systematic diagram of the effects of sand ~~types~~ and agent types as well as the FER and FIR on the rheological properties of the ~~sand-foam~~ mixture. Meanwhile, a microscopic study on the ~~foam and sand-foam~~ mixture will be started at the beginning of the next ~~period of study~~ term. It is believed that ~~the~~ this investigation on the microstructure of a sand-foam mixture and the decay process of the foam in the mixture can provide a better understanding ~~on~~ of the fundamental mechanism ~~of~~ as to how the foam ~~is affecting~~ affects the properties of excavated soils. Since the new rheometer is expected to be available before the middle of next year, a study on the rheological properties of a sand-foam mixture will be ~~started~~ initiated in June and ~~last~~ continue for approximately ~~8~~ eight months. By the end of next year, a relationship between the results from both the rheometer ~~tests~~ and ~~those from~~ the slump tests will be ~~developed~~ analysed so that the intuitive behaviour (slump value) can be related to the abstract one (viscosity). However, the reliability of the results from the rheometer tests ~~need to~~ must be verified by some comparative tests. A modified pipe viscometer used for measuring the viscosity of ice cream is ~~supposed to be~~ reportedly capable of ~~applying on~~ being applied to a sand-foam mixture; ~~and~~ therefore, the comparative tests will be conducted with the help of ~~it~~ this device. Once the validation of the rheometer is successful, it will be modified ~~to~~ for ~~adapt to~~ measuring coarser soils (gravelly sands) in order to extend the application of the rheometer test as well as to investigate the influences of foam on gravelly sands. ~~At last~~ Finally, writing of the PhD thesis ~~writing~~

will be ~~started~~ undertaken after ~~finishing~~ all laboratory work has been finished. ~~and~~ Completion of the final draft is expected ~~to be finished in~~ within the following ~~9~~ nine to 12 months.

CHAPTER FIVE

5. Conclusion

This report has presented the ~~works~~ research that the author has done ~~in~~ during the first year of PhD study, including a comprehensive literature review on the background of EPB tunnelling and ~~the~~ current research ~~of~~ on conditioned soils, the methods and results of ~~the~~ index tests on foams and sand-foam mixtures, and a simple description of ~~the~~ a specially designed soil rheometer.

The ~~great~~ remarkable influences of ~~the~~ soil conditioners on ~~the~~ soil properties are well known by researchers, ~~and~~ some of whom have proffered general guidelines for conditioning ~~treatments for different~~ various soils ~~are provided~~. However, problems are still encountered during tunnelling because the testing methods for determining conditioning treatments cannot be easily applied in practice, for example, ~~the~~ screw-conveyor model tests. Slump ~~tests~~ testing ~~are~~ is the most used in situ ~~testing~~ method because of its simplicity and rapid testing process; ~~but~~ however, only control parameters ~~could~~ can be ~~gained~~ obtained from slump tests, which might mislead ~~the~~ decisions ~~of~~ concerning conditioning treatments.

In order to investigate the detailed rheological properties of conditioned soils, a modified rheometer might be more efficient than slump tests. In recent years ~~the~~ rheometer tests have already been applied to concrete, clays conditioned with foams and polymers, ~~and~~ as well as sands conditioned with foams and bentonite slurries. Thus, it is believed that the application of the rheometer ~~could~~ can be extended to gravelly sand-foam mixtures.

Foam index tests were first conducted ~~at first~~ by using a laboratory foam generator. From the results ~~shown~~ presented in Chapter 3, several factors ~~that~~ affecting the FER and stability of foams ~~could~~ can be noticed: Increased tank pressure, ~~pressure~~ the gap between tank ~~pressure~~ and air-line pressure and foam concentration ~~would~~ will all lead to increasing FER and stability. Furthermore, the different properties of the foams generated from F30 and F41 ~~implied~~ imply that the composition of foam agents also affects the performance of ~~coil~~ soil conditioning, even if ~~they were~~ supplied ~~from~~ by only one company. A few slump tests were ~~presented~~ conducted, in which ~~good~~ favorable properties of a sand-foam mixture for forming a plastic flow were observed. Although the apparatus used for slump tests prevented the mixture from free slump, the slump value was still ~~higher~~ greater than 150 mm, which was considered ~~to be~~ suitable for EPB tunnelling.

A torque sensor and a stepper motor, along with two spare Rowe cells, were used to ~~build~~ construct a soil rheometer for investigating the rheological properties of a sand-foam mixture. A vane-type impeller was selected, ~~and~~ the geometry of ~~it~~ which was determined ~~according to~~ in accordance with previous research and relevant standards ~~in~~ prescribed by ASTM D2573. Furthermore, the measuring range of the torque sensor and the technical parameters of the stepper motor were chosen in accordance with the vane geometry, with an aim~~ing~~ to provide reliable measurements ~~on~~ of the sand-foam and gravelly sand-foam mixtures.

~~Up to now~~ To date, the new soil rheometer is still ~~under assembling process~~ being assembled in a laboratory workshop. Upon completion, further research will be conducted with the help of this ~~new soil rheometer~~ apparatus, and essential comparative tests will be required to validate the reliability of the data ~~from~~ obtained with ~~this~~ the device.

References

Andrade, E.N.daC. (1943) 'Theory of viscosity of liquids', *Philosophical ~~Magazing~~ Magazine,* 17, pp. 698-732.

Barnes, 2000. *A handbook of elementary rheology*. University of Wales, Aberystwyth, Wales.

Babendererde, L.H. (1998) 'Developments in polymer application for soil conditioning in EPB-TEMs', in Negro Jr, A. and Ferreira, A.A. (eds.) *Tunnels and Metropolises*. Balkema, Rotterdam, Vol.2, pp. 691-695.

BASF, (2013) *Technologies - TBM.* Available at: www.master-builders-solutions.basf.com/en-basf/products/masterroc/tbm (Accessed: 28 November 2014).

Cristescu, N. (1989) *Rock Rheology.* Kluwer Academic Publications, Boston.

Day, P.R. and Holmgren, G. (1952) 'Microscopic change in soil structure during compression', *Soil Science Society of America Proceedings*. 16(1), pp. 73-77.

EFNARC, (2005) *Specifications and guidelines for the use of specialist products for mechanised tunnelling*. European Federation for Specialist Construction Chemicals and Concrete Systems.

Ghavami, M., Keller, J. and Dunn, I.S. (1974) 'Predicting soil density following irrigation', *Trans. ASAE,* 17, pp. 166-171.

Ghezzehei, T.A. and Or. D. (2001) 'Rheological properties of wet soils and clays under steady and oscillatory stresses', *Soil Science Society of America Journal,* 65, pp. 624-637.

Haghighi, K., Srivastava, A.K. and Steffe, J.F. (1987) 'The rheological approach to soil modeling', *Trans. ASAE*, 30, pp. 1661-1672.

Herrenknecht, M. (2004) ‘EPB or Slurry machine: The choice’, *Tunnels & Tunnelling,* June, pp. 35-36.

James, F.S. (1996) *Rheological Methods in Food Process Engineering.* Freeman Press, USA.

Jefferis, S.A. (1992) 'Grouts and Slurries', in Doran, D. and Cather, B. (eds.) *Construction Materials Reference Book.* Butterworth-Heinemann, Oxford, pp. 166-194.

Jefferis, S.A. (1995) 'Water-soluble polymers in tunnelling and slurry supported excavations', In Kennedy, J.F., Phillips, G.O. and William, P.A. (eds) *Cellulose and Cellulose Derivatives: Physico-chemical aspects and industrial applications.* Woodhead Publishing Ltd, Camberdge.

Koehler, E.P. and Fowler, D.W. (2004) *Development of a portable rheometer for fresh Portland cement concrete*. International Center for Aggregates Research, Texas.

Kusakabe, O., Nomoto, T., and Imamura, S. (1999) 'Geotechnical criteria for selecting a mechanized tunnel system and DMM for tunnelling', *Proceedings of 14th International Conference on Soil Mechanics and Foundation Engineering.* Balkema, Rotterdam. Vol.4, pp. 2439-2440.

Langmaack, L. (2000) 'Advanced technology of soil conditioning in EPB shield tunnelling', *Proceedings of 3rd International Conference on Soil Mechanics and Foundation Engineering*. Balkema, Rotterdam, pp. 525-542.

Langmaack, L. and Zamecnik, M. (2009) 'Advanced technology of soil conditioning for a tunnel boring machine (TBM)' *Tunnel,* 18, 28-33.

Lambe, T.W. (1953) 'The effect of polymers on soil properties', *Proceedings of 3rd International Conference on Soil Mechanics and Foundation Engineering.* Engng., Zurich. Vol.1, pp. 253-257.

Leinala, T., Delmar, R., Collins, J.R., Pennington, B.N. and Grabinsky, M. (1999) 'Soil conditioning for enhanced TBM performance in differing ground conditions'. *52nd Canadian Geotechnical Conference.* Regina. pp. 537-544.

Liu, D. (2012) *The appraisal of improving the soil condition of EPBS with new foam*. Master’s Thesis, China University of Geosciences.

Maidl, U., Herrenknecht, M. and Anheuser, L. (1996) *Mechanised shield tunnelling.* Ernst and Sohn, Berlin.

Meng, Q., Qu, F. and Li, S. (2011) 'Experimental investigation on viscoplastic parameters of conditioned sands in earth pressure balance shield tunnelling', *Journal of Mechanical Science and Technology,* 25(9), PP. 2259-2266.

Merritt, A.S. (2004) *Conditioning of clay soil for tunnelling machine screw conveyors.* PhD Thesis, University of Cambridge.

Messerklinger, S., Zumsteg, R. and Puzrin, A.M. (2011) 'A new pressurized vane shear apparatus', *Geotechnical Testing Journal,* 34(2), pp. 1-9.

Milligan, G. (2000) *Lubrication and Soil conditioning in tunnelling, pipe jacking and microtunnelling*. Geotechnical Consulting Group.

Ministry of Defence Standard 42-40, (1998) *Foam liquids, fire extinguishing*. Issue 1.

NFM Technologies, (2007) *Soft ground machines.* Available at: www.nfm-technologies.com/-Soft-ground-machines-.html (Accessed: 19 November 2014).

Psomas, S.(2001) *Properties of foam/sand mixtures for tunnelling applications*. Master's Dissertation, University of Oxford.

Peila, D., Oggeri, C. and Borio, C. (2009) 'Using the slump test to assess the behaviour of conditioned soil for EPB tunnelling', *Environmental & Engineering Geoscience*, 15, pp. 167-174.

Quebaud, S., Sibai, M. and Henry, J. P. (1998) ' Use of chemical foam for improvements in drilling by an Earth-Pressure Balanced Shield in granular soils', *Tunnelling and Underground Space Technology*, 13, pp. 173-180.

Steiner, W. (1996) 'Criteria for selecting mechanized tunnelling systems in soft ground'. *Proceedings of the North American Tunnelling 96*. Balkema, Rotterdam, pp. 483-491. [Is there a missing word which should follow '*Tunnelling*'?]

Tattersall, G.H. and Banfill, P.F.G. (1983) *The Rheology of Fresh Concrete.* Pitman Publishing Inc., Boston.

Thewes, M. and Budach, C. (2010) 'Soil conditioning with foam during EPB tunnelling', *Geomechanics and Tunelling*, 3, pp. 256-267.

Zumsteg, R., Plötze, M. and Puzrin, A. (2013) 'Reduction of the clogging potential of clays: New chemical applications and novel quantification approaches', *Géotechnique,* 63(4), pp. 274-286.

Tables

Soil type		EPBM without additives	EPBM with additives
Alluvial cohesive soil	Silt and clay	Y	Y
	Sandy silt, sandy clay	Y	Y
Pleistocene cohesive soil	Loam and clay	Y	Y
	Sandy loam, sandy clay	N	Y
Sandy soil	Sand with silty clay	N	Y
	Loose sandy soil	N	Y
	Consolidated sand	N	Y
Gravel with boulders	Loose gravel	N	Y
	Consolidated gravel	N	Y
	Gravel with boulders	N	Y
	Boulder gravel,	N	N

Table 2.1 Geotechnical selection table for EPB TEM (from Kusakabe *et al,* 1999).

Soil types	Foam types			FIR	Polymer additives
	A	B	C		
Clay	+			30-80	Anti-clogging polymer
Sandy clay – silt	+	+		40-60	Anti-clogging polymer
Sandy clayey silt		+		20-40	Polymer for consistency
Sand		+	+	30-40	Polymer for cohesiveness and consistency control
Clayey gravels			+	25-50	Polymer for cohesiveness and consistency control
Sandy gravels			+	30-60	Polymer for cohesiveness and consistency control

Table 2.2 Choice of foam types according to soil types (EFNARC, 2005).

Fluid model	*n*	σ_0
Herschel-Bulkley	$0 < n < \infty$	> 0
Newtonian	1	0
shear-thinning	$0 < n < 1$	0
shear-thickening	$1 < n < \infty$	0
Binghan plastic	1	> 0

Table 2.3 Newtonian, Power Law and Bingham Plastic fluids as special cases of the Herschel-Bulkley Model

Foam agent	Concentration (%)	Air flow rate (Nm^3/h)	FER	t_{25} (h:m:s)	t_{50} (h:m:s)
F4	1.5	2.1	17.9	0:14:44	0:29:20
		3.5	26.3	0:20:30	0:38:15
	2.0	2.1	21.1	0:21:10	0:42:00
		3.5	27.2	0:24:12	0:44:30
	5.0	2.1	27.7	0:33:30	1:02:00
F4 TM	2.5	2.1	7.7	0:04:45	0:11:30
		5.2	10.8	0:12:30	0:25:30
	5.0	2.1	9.5	0:13:10	0:26:30
		3.5	12.9	0:17:45	0:33:54
		5.2	15.6	0:16:48	0:31:55
F4 L	5.0	2.1	6.5	-	-
		5.2	9.0	0:07:10	0:14:50
SLF30	3.0	2.1	13.9	0:04:32	0:06:45
		5.2	21.3	0:05:48	0:08:05
TR	1.0	2.1	12.8	0:04:04	0:06:10
		3.5	16.8	0:05:54	0:08:36
	1.5	2.1	16.4	0:05:38	0:08:06
	3.5	2.1	15.6	0:05:38	0:07:59
		3.5	23.7	0:07:00	0:09:35
EC	2.5	2.1	9.9	0:03:01	0:05:04
		3.5	11.0	0:04:10	0:06:27
	4.0	2.1	13.8	0:04:55	0:07:10
T-7	1.0	2.1	16.4	0:05:10	0:07:55
	2.0	1.5	15.5	0:04:06	0:06:05
		2.1	22.9	0:04:55	0:07:10

Table 2.4 Foam index tests (Merritt, 2004)

Size range (μm)	Interval distribution (%)	Cumulative distribution (%)
10.00 – 21.67	0.02	0.02
21.67 – 33.33	0.15	0.17
33.33 – 45.00	0.31	0.48
45.00 – 56.67	0.91	1.4
56.67 – 68.33	3.11	4.51
68.33 – 80.00	15.74	20.25
80.00 – 91.67	24.24	44.48
91.67 – 103.33	29.27	73.75
103.33 – 115.00	17.42	91.17
115.00 – 126.67	5.53	96.7
126.67 – 138.33	2.41	99.1
138.33 – 150.00	0.9	100

Table 2.5 Size distribution of ~~the~~ foam (Yang & Wang, 2012)

Sand	d_{10}(mm)	d_{30}(mm)	d_{60}(mm)	U_C	C_c	G_s
L1	0.26	0.4	0.55	2.12	1.12	2.65
L2	1.2	1.4	1.6	1.33	1.02	
L3	0.6	0.67	0.78	1.30	0.96	

Table 3.1 ~~Sand~~ Characteristic parameters of sands

Foam agents	F30	F41
Field of application	Soft ground	Silt to sand soils which may contain a high ~~amount~~ concentration of water
Features and benefits	1. Improved soil behaviour 2. Easier mucking 3. Reduced permeability and increased sealing at face 4. Creation of plastic deformation properties in ~~the~~ soil 5. Lower inner friction and lower abrasiveness 6. Reduced stickiness in certain soils	
Density(kg/m^3;20°C)	1035 - 1045	1035 - 1045
pH (3% solution; 20°C)	6.5 - 7.5	6.5 - 7.5
Recommended concentration	1.5% - 4%	2% - 6%

Table 3.2 Properties of F30 and F40 agents

Polymers	P1	P2
Field of application	Fine sand, silt or clay with high water content	High ground water pressures, poorly graded or ground containing low amounts of fine particles, and bentonite slurry modification
Features and benefits	1. Reduced permeability and increased sealing at ~~the~~ face 2. Increases cohesion of coarse, clean sands and gravels 3. Strengthens viscosifying effect 4. Helps the formation of the plug	1. Structuring ~~the~~ soil, particularly in coarse, clean sands and gravels 2. Reducing soil permeability 3. Creation of plastic deformation properties 4. Lowering ~~the~~ inner friction and abrasiveness of ~~the~~ soil 5. Water soaking and swelling effect 6. Improves ~~the~~ yield and filter cake properties of bentonite slurries
Density(kg/m3;20°C)	1000	900 - 950
pH (3% solution; 20°C)	6.5 - 7.5	8.5 - 10.5
Recommended concentration	0.3% - 3%	0.3% - 3%

Table 3.3 Properties of P1 and P2 polymers

Editor's Note, applicable to all table and figure captions and contents, as well as sectional headers: It is both permissible and desirable, for the sake of brevity, to use headline grammar in such contexts. Headline grammar omits the definite article [*the*] which would be required when the same wording is used in the main text of the document.

Foam agent	Concen-tration (%)	Volume of solution (L)	Pressure in tank (psi)	Pressure in air line (psi)	Average FER	Average t_{25} (s)	Average t_{50} (s)
F30	2	10	30	30	8.4	172	305
			30	35	13.2	202	339
			30	40	16.1	212	345
			30	45	20	258	385
			30	50	23.6	294	427
			30	60	27.6	316	453
			40	40	16.7	229	326
			40	45	22.1	249	336
			40	50	24.0	283	363
			40	55	26.6	294	422
			40	60	27.9	314	439
			40	70	28.5	330	443
			50	50	20.7	257	382
			50	55	22.9	264	398
			50	60	25.2	279	410
			50	65	27.0	293	428
			50	70	27.8	302	438
			50	80	28.5	319	440

Table 3.4 ~~The~~ Effects of pressure differences on foam properties

Foam agent	Concen-tration (%)	Volume of solution (L)	Pressure in tank (psi)	Pressure in air line (psi)	Average FER	Average t_{25} (s)	Average t_{50} (s)
F30	2	10	40	40	16.7	229	326
			40	45	22.1	249	336
			40	50	24.0	283	363
			40	55	26.6	294	422
			40	60	27.9	314	439
			40	70	28.5	330	443
F41	2		40	40	9.2	204	290
			40	45	11.8	230	329
			40	50	16.3	253	350
			40	60	18.6	269	404
			40	70	19.6	281	415
	3		40	60	24.6	267	420

Table 3.5 ~~The~~ Effects of concentration and foam types on foam properties

Type	D(mm)	d(mm)	e(mm)	H(mm)	V_A(%)
Rectangular	50	12.5	1	50	10.1

Table 3.6 ~~The~~ Geometry of vane

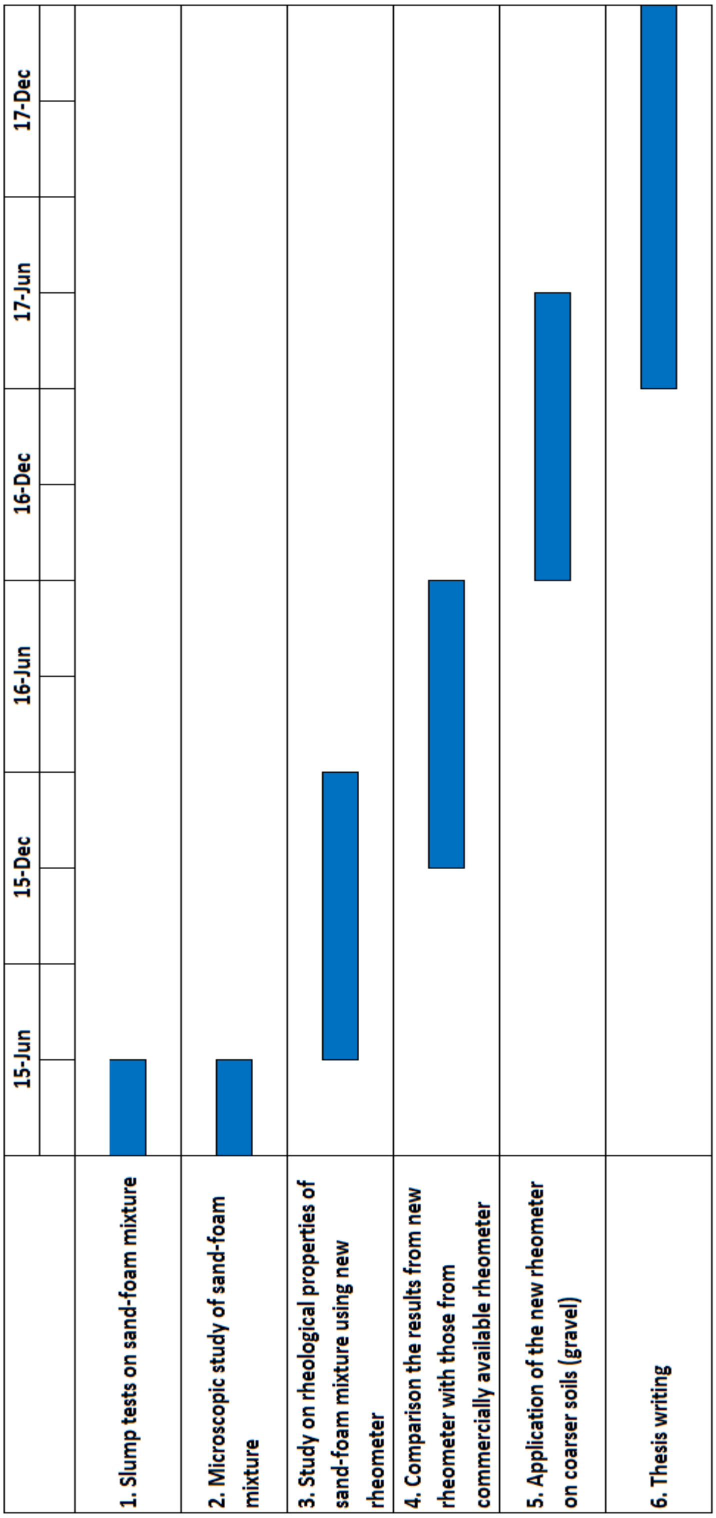

Table 4.1 ~~Working~~ Projected research plan

Revise Table 4.1 as follows:

4. Comparison of results from new rheometer with those from commercially available device

5. Application of new rheometer to coarser soils (gravel)

Figures

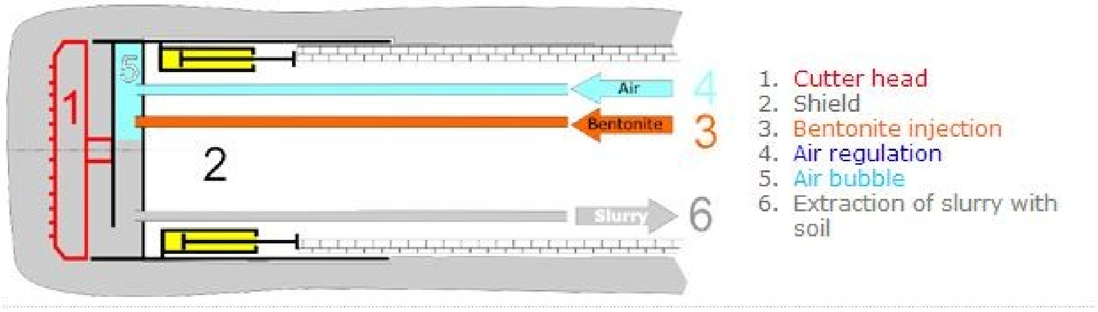

Figure 2.1 Brief structure of slurry TBM (NFM Technologies, 2007)

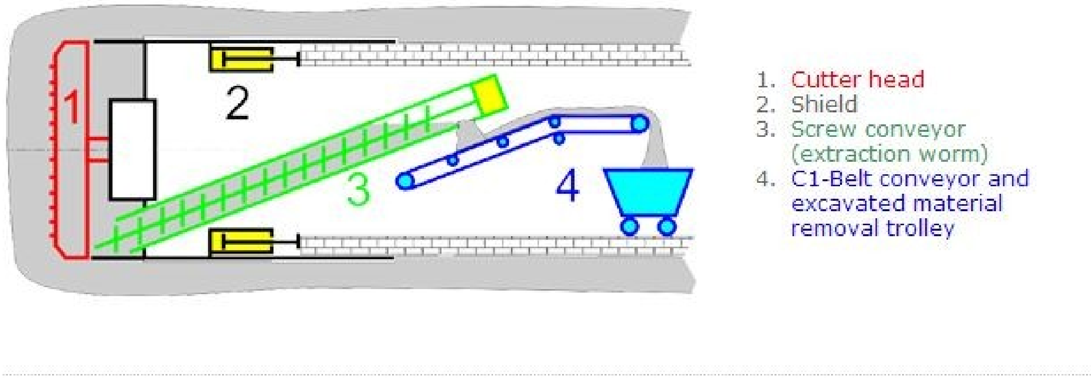

Figure 2.2 Brief structure of EPB TBM (NFM Technologies, 2007)

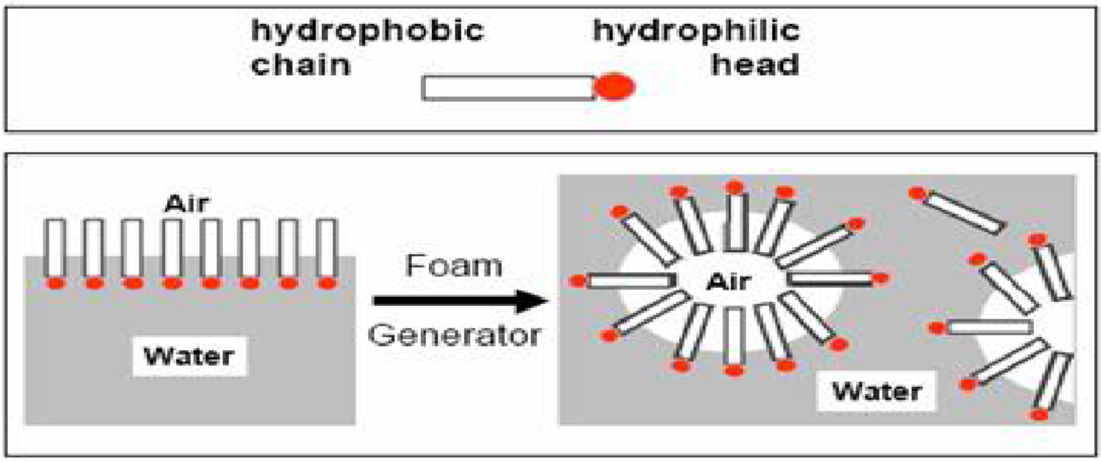

Figure 2.3 Structure and mechanism of surfactant

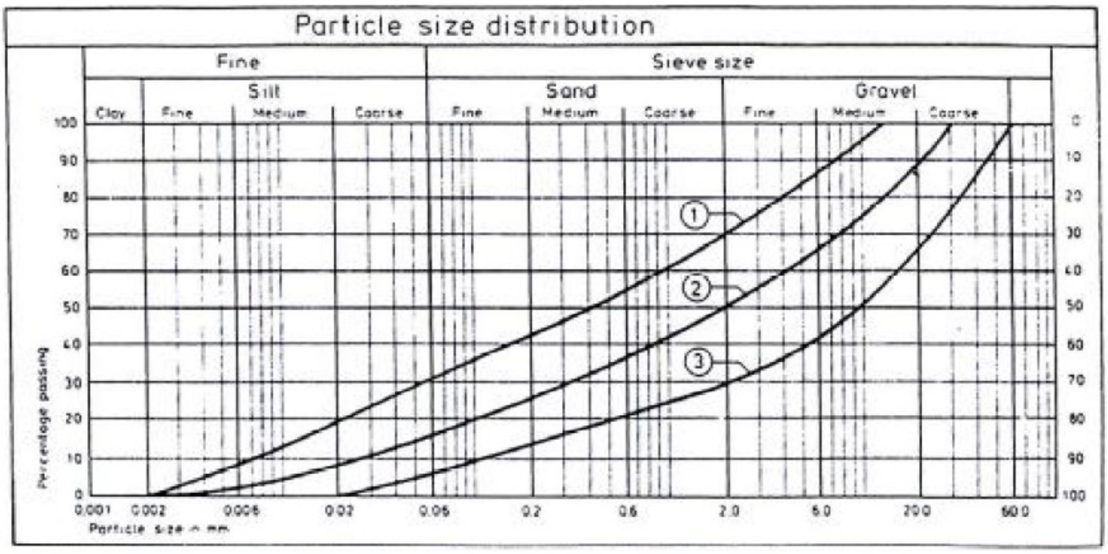

Figure 2.4 Applications of soil conditioning according to particle size distribution (Maidl *et al.,* 1996)

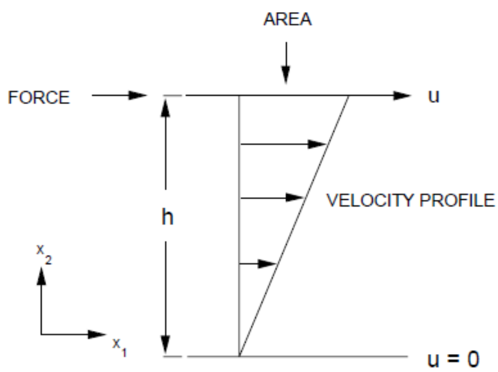

Figure 2.5 Fluid between parallel plates

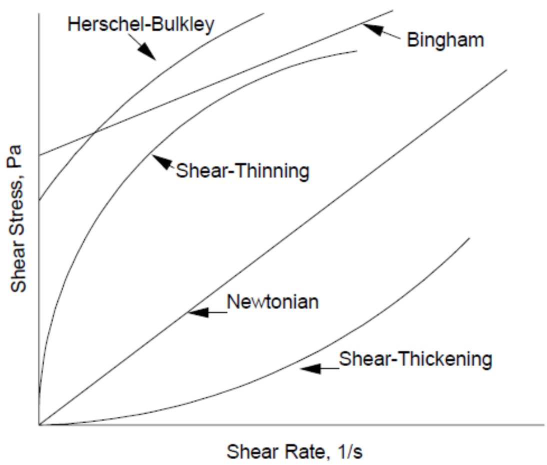

Figure 2.6 Flow curves for typical fluids

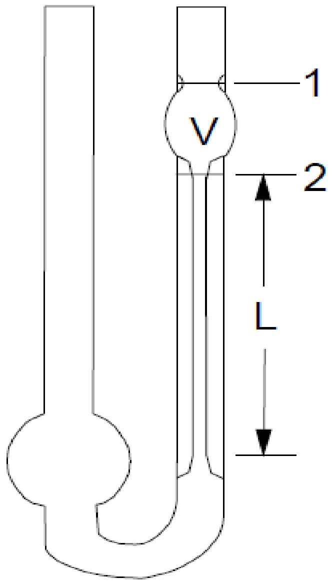

Figure 2.7 Glass capillary

Figure 2.8 Brookfield RST rheometer

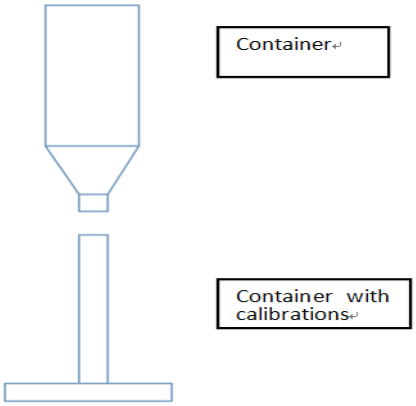

Figure 2.9 Apparatus for measuring expansion ratio and stability

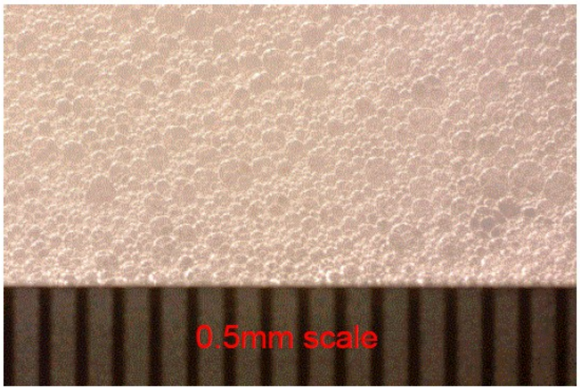

Figure 2.10 ~~Image of~~ Foam bubbles without external pressure (Peña Duarte, 2007)

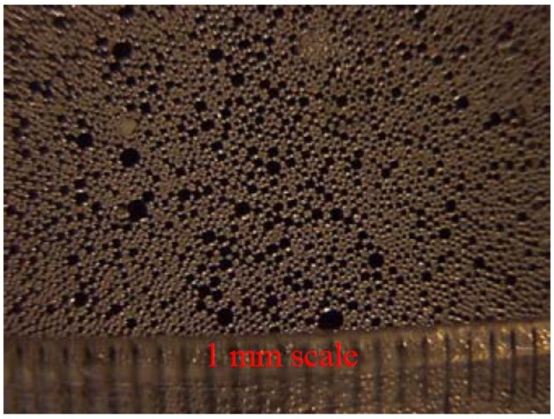

Figure 2.11 ~~Image of~~ Foam bubbles with constant pressure (Peña Duarte, 2007)

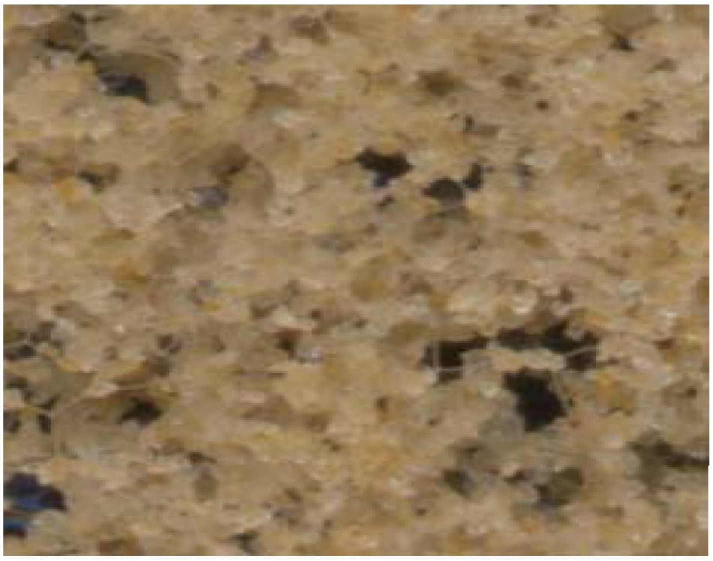

Figure 2.12 ~~Image of~~ Sand-foam mixture (Peña Duarte, 2007)

Figure 2.13 BT-1600 image particle size ~~analysis~~ analytical system (Liu, 2012)

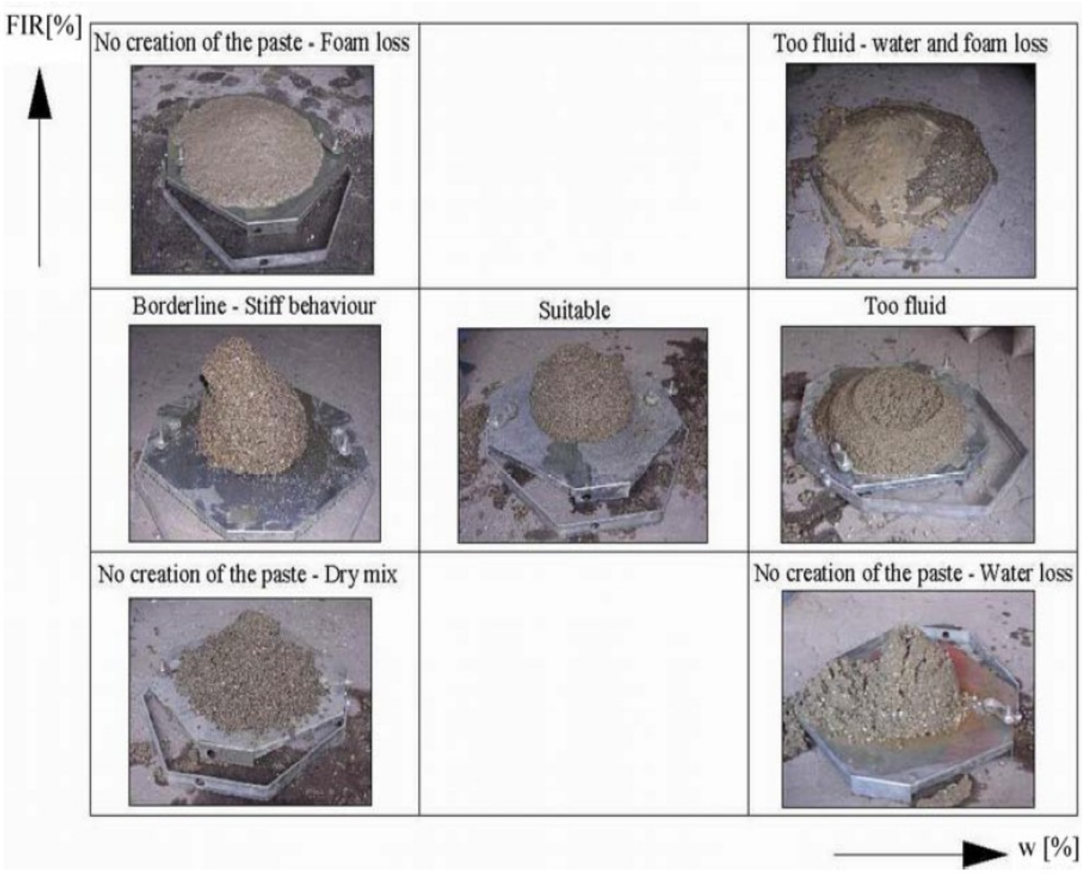

Figure 2.14 Behaviours of conditioned soils in slump tests (Peila et al., 2009) Revise: “No creation of ~~the~~ paste” 3 times. (Delete the definite article.)

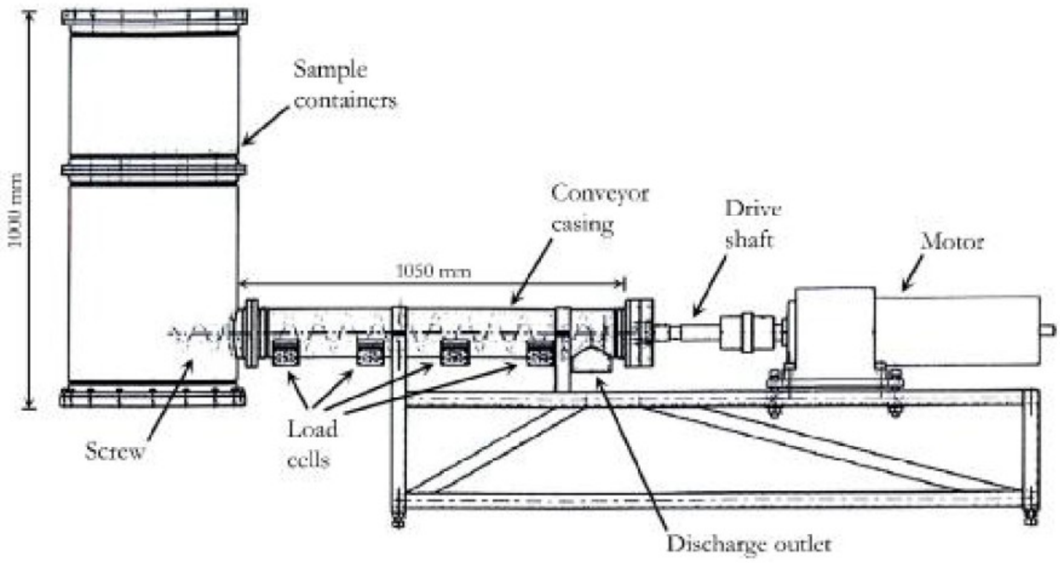

Figure 2.15 Model of EPB screw conveyor system ~~model~~ (Merritt, 2004)

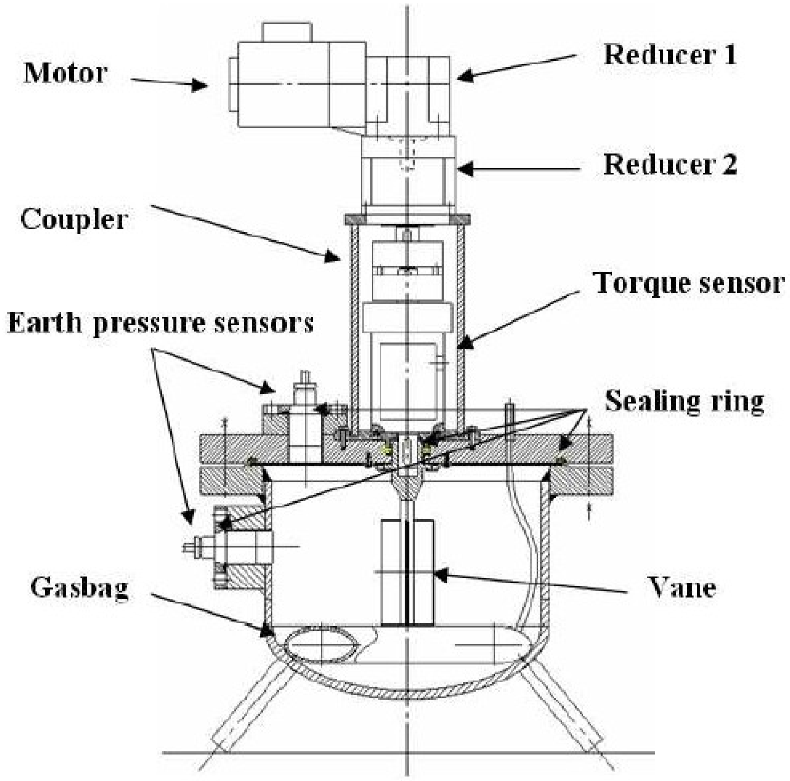

Figure 2.16 Structure of soil rheometer (Meng *et al.*, 2011)

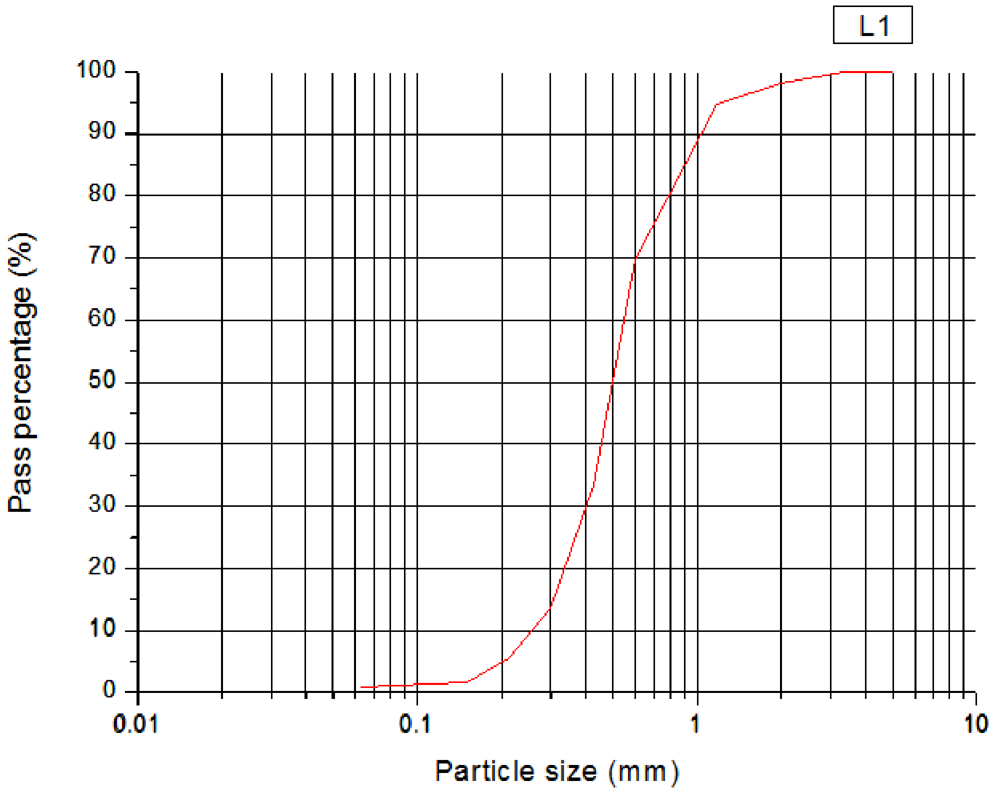

Figure 3.1 Grading curve for L1 sands [Revise 'Pass' to 'Passing'.]

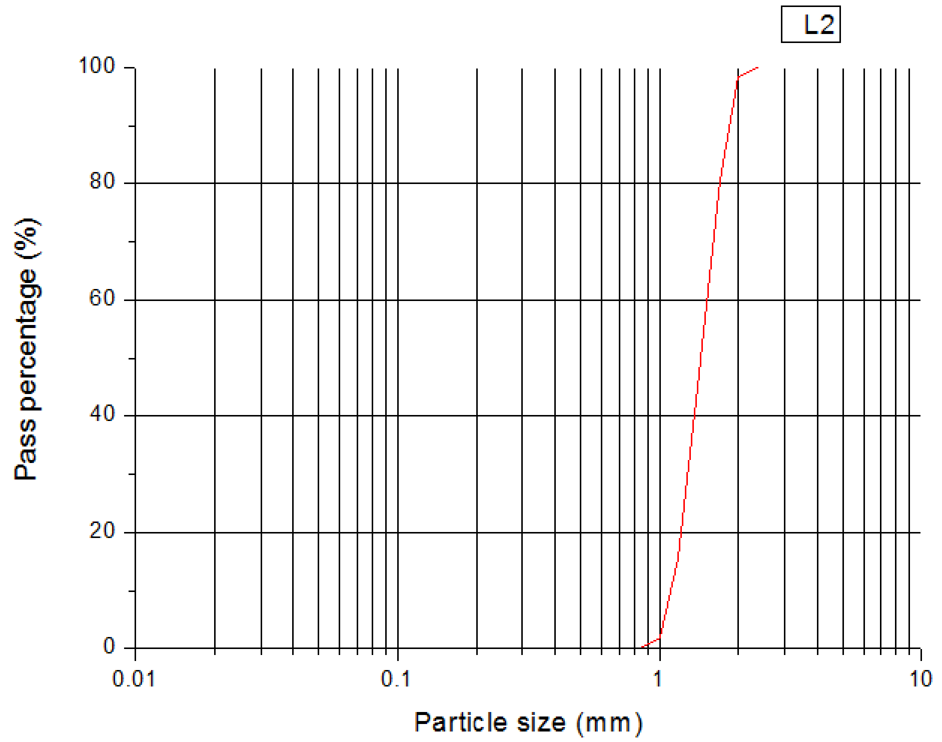

Figure 3.2 Grading curve for L2 sands [Revise 'Pass' to 'Passing'.]

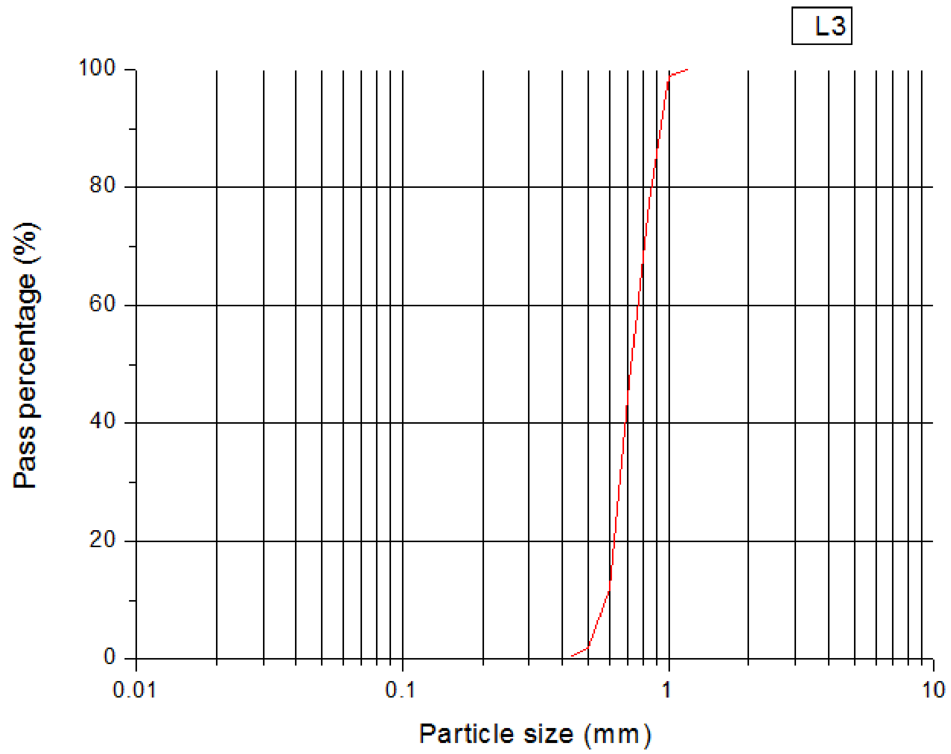

Figure 3.3 Grading curve for L3 sands [Revise 'Pass' to 'Passing'.]

Figure 3.4 Laboratory foam generator

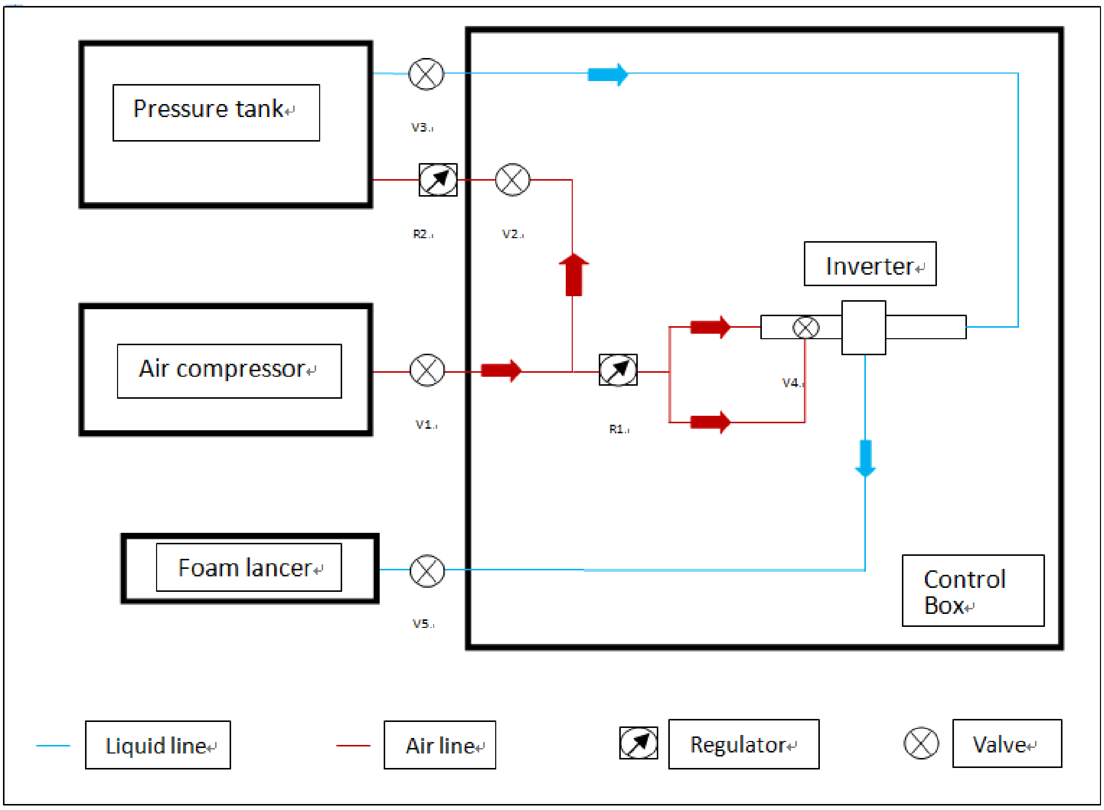

Figure 3.5 Schematic of Portafoam TM2

Figure 3.6 Standard Mortar mixer

Editor's Note: Do not capitalize 'Mortar' unless this word is a brand name.

Figure 3.7 Simple equipment for testing foam stability

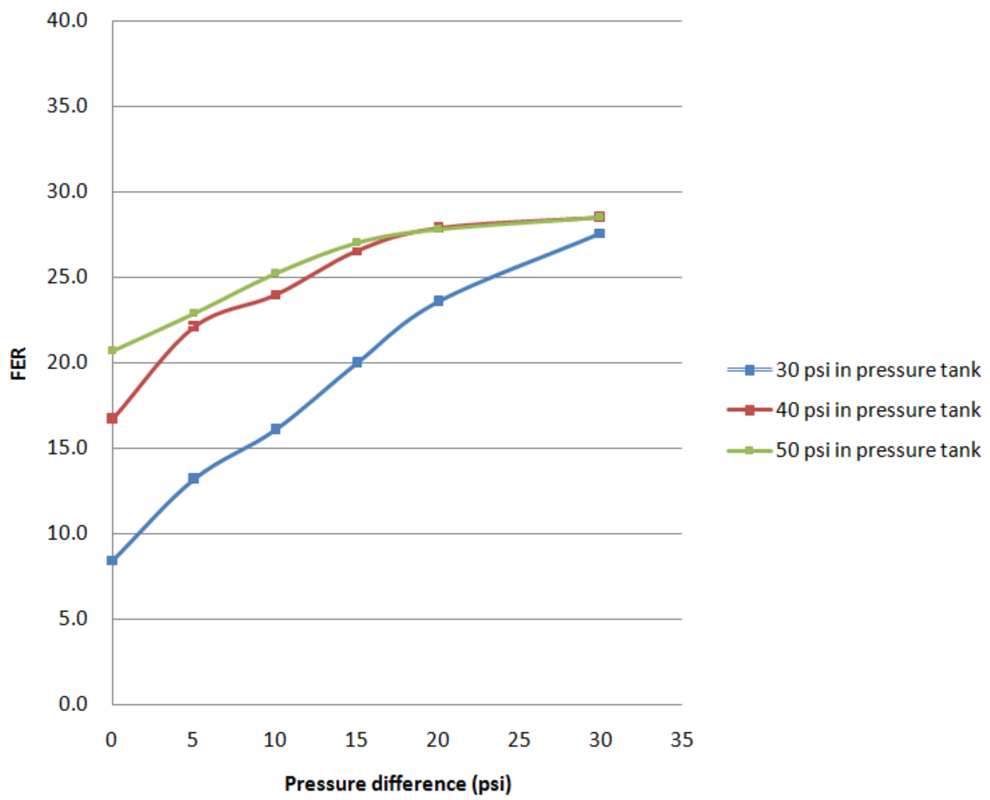

Figure 3.8 ~~The~~ Influence of pressure differences on FER

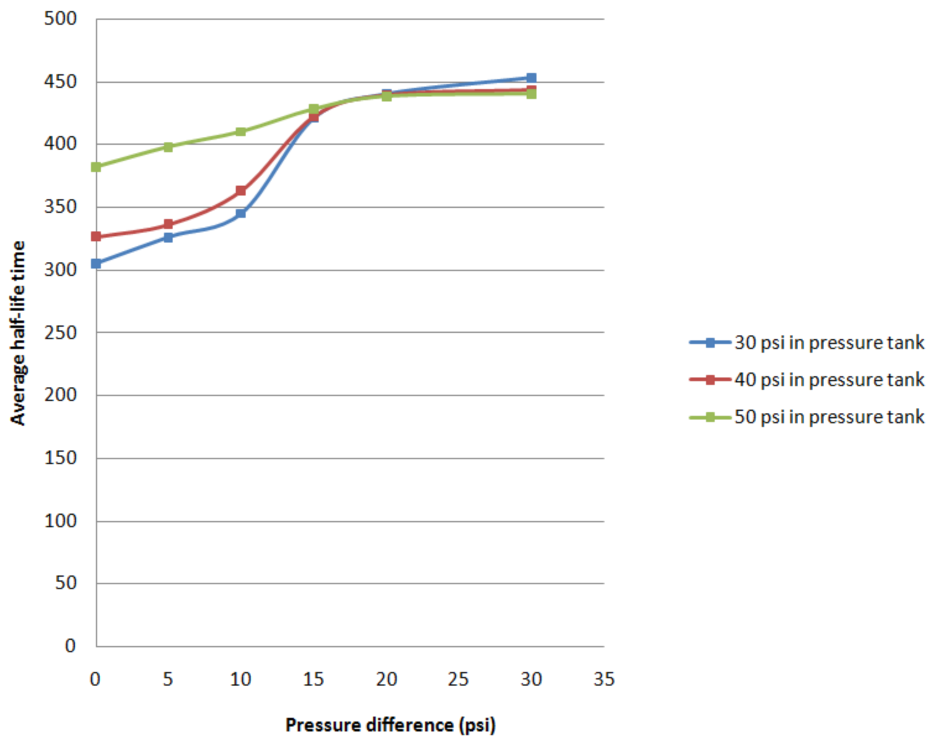

Figure 3.9 ~~The~~ Influence of pressure differences on foam stability

Figure 3.10 Vee Bee consistometer

Figure 3.11 Typical slump test result for sand-foam mixture

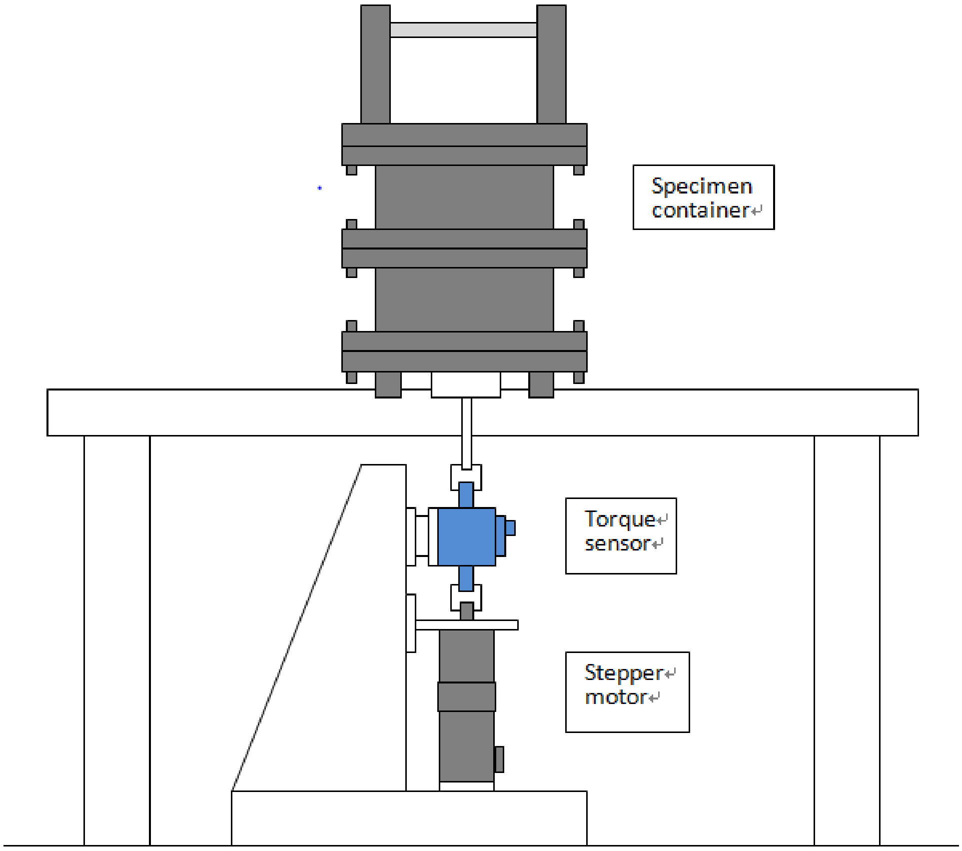

Figure 3.12 Brief structure of proposed soil rheometer

Figure 3.13 ELE Rowe-type consolidation cell

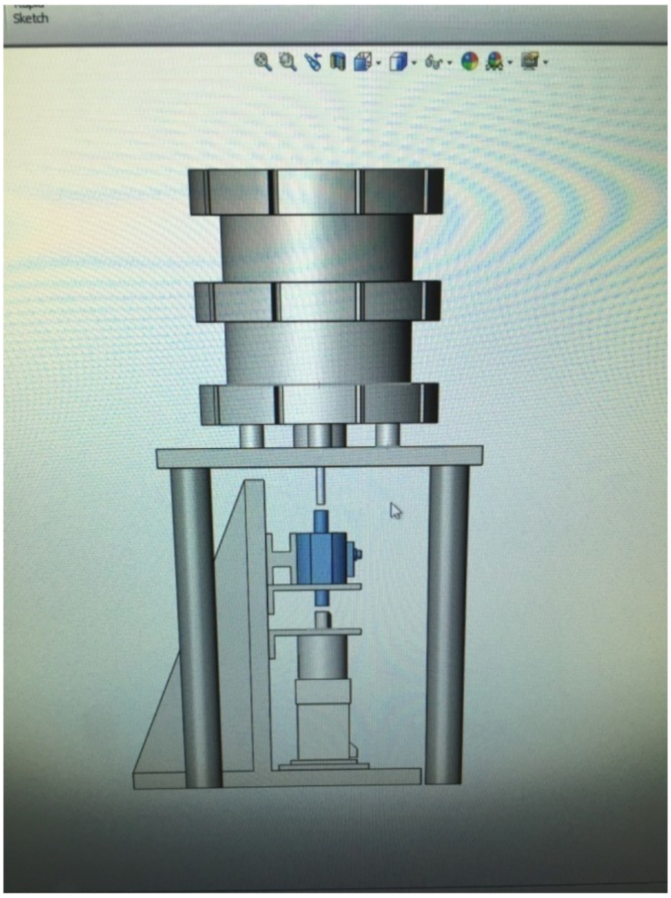

Figure 3.14 Soil rheometer designed by SolidWorks ~~design of soil rheometer~~