ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

SOIL CONDITIONING STUDIES FOR A WASTEWATER TUNNEL EXCAVATED BY AN EPB TBM

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

EPB TBM İLE KAZILAN BİR ATIKSU TÜNELİ İÇİN ZEMİN ŞARTLANDIRMA ÇALIŞMALARI

YÜKSEK LİSANS TEZİ

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Temmuz 2016

Sahand TOLOUEI, a **M.Sc.** student of ITU **Graduate School of Mining Engineering** student ID **505131013**, successfully defended the **thesis** entitled "**SOIL CONDITIONING STUDIES FOR A WASTEWATER TUNNEL EXCAVATED BY AN EPB TBM"** which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my parents and sister,

FOREWORD

The work described in this dissertation was conducted by the author in the Department of Mining Engineering at the Istanbul Technical University. I received great help from a lot of people during my time there, without whom I would not have completed my study. The first and most important one I would like to thank my supervisor, Prof. Dr. Hanifi Çopur who introduced me into the area of tunneling, and inspired, advised, and supported me from the beginning to the end. His broad knowledge in the area of tunneling, unique views to different problems, and sparkling imaginations benefited me enormously during every meeting with him. Financial support from The Scientific and Technological Research Council of Turkey (Tubitak Project No: 213M487) is gratefully acknowledged. My special appreciation also goes to the project researchers Prof.Dr. Nuh Bilgin, Prof.Dr. Cemal Balcı, the last but not least Assoc.Prof.Dr. Deniz Tumaç, who helped me both academically and in everyday life. I would also like to express my deep appreciation to my colleague, Res.Assist. Emre Avunduk who contributed in various ways to my thesis and life in Istanbul. I owe special thanks to my peer Eng. Shahabedin Hojjati for his help during writing my thesis and Eng. Aydin Shaterpour Mamaghani for his help during the laboratory tests.

It goes without saying that I would not be where I am today if it were not for the love and support of my parents and my dear sister.

June 2016 Sahand TOLOUEI

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ABBREVIATIONS

AR	: Advance rate of TBM
ASTM	: American Society For Testing And Materials
C_F	: Foam (anticlay) concentration
EPB	: Earth pressure balance
FER	: Foam expansion ratio
FIR	: Foam injection ratio
ICR	: Instantaneous cutting rate
IPR	: Instantaneous penetration rate
JSCE	: Japan society of civil engineering
M_c	: Mass of dry moisture can
M_{cds}	: Mass of moisture can containing dried soil
M_{cms}	: Mass of moisture can containing the moist soil
M_s	: Mass of soil
M_w	: Mass of water
BS	: British standards
MUT	: Machine utilization time
R^2	: Coefficient of determination
TBM	: Tunnel boring machine

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SOIL CONDITIONING STUDIES FOR A WASTEWATER TUNNEL EXCAVATED BY AN EPB TBM

SUMMARY

As a result of growing urbanization, subsurface space is developed and has to be expanded. Newer and bigger tunnels are required to meet the infrastructural needs.

Since most of the tunnel constructions in urban areas are in soft ground, study about tunneling in soft grounds is significant.

Earth pressure balance (EPB) tunnel boring machines (TBM) are commonly used in soft ground tunneling. These machines use the excavated soil in a pressurized head chamber to apply a support pressure to the tunnel face during excavation. How well an unstable face is supported in an EPB TBM depends on effectively maintaining a constant level of pressure from the support medium to the face. If the support pressure is not constant, the varying pressure inevitably leads to collapse of the face or heave on the surface ground. A machine may be designed to work in ideal ground conditions. However, natural soils rarely have ideal properties. Hence, conditioning of the soil is usually necessary to change its properties to suit the machine.

One of the main operational parameters in EPB TBMs is soil conditioning. Soil conditioning agents such as foam and polymer, are often injected through the cutterhead or into the cutting chamber to make the muck flowable, lower inner friction between the soil particles, control soil stickiness, prepare the excavated soil to be compressible during the tunneling operation, control the water inflow, reduce the torque on the cutterhead, and lower power and torque of the screw conveyor.

However, for the common soil conditioning methods, the effects of different conditioning treatments on soil properties and the machine performance are not clearly understood, and therefore problems with EPB operations related to the soil properties are often encountered.

The effect of soil conditioning on performance of EPB TBM used to excavate Zeytinburnu- Ayvali 2 Wastewater Tunnel in Istanbul is investigated in the present study which is supported financially by The Scientific and Technological Research Council of Turkey (Tubitak Project No: 213M487). Basic soil characterization via laboratory tests such as grain size distribution, natural water content, cone penetrometer (liquid limit) and plastic limit have been carried out paralleled with foam characterization. Moreover, foam and soil mixture characterization tests are performed by mixing test with power measurements, cone penetration test and flow table test.

The natural water content of the soil sample is determined as being 33%. Using the grain size distribution, liquid and plastic limit tests the place of soil sample in plasticity and clogging risk chart is located and high clogging potential for the sample is detected. Foam characterization were carried out via half-life and density for 2 different types of foam produced by different companies (Exfoam 2 and ACP 143). Soil+water and soil+foam tests are performed with different water amounts, FER of

16 and C_F of 3% and varying FIR amounts in order to observe the effect of water, foam on power requirement, sticking amount and consistency of the sample. Conditioning with adding just water between the range of 35-54 % were resulted in reduction of power requirement and sticking amount from 92 W to 35 W and 2042 g to 295 g and rising the penetration value from 8.4 mm to 22.6 mm respectively. Even though conditioning with Exfoam 2 reduced the power requirement from 81 to 44 W and sticking amount from1958 to 1570 g, ACP 143 had better results than Exfoam 2 where the FIR value ranged from 50 to 300 % and power requirement decreased from 67.5 to 42 W, sticking amount decreased from 1800 g to 1600 g and the penetration value increased from 7.5 to 13.1 mm. However, it was considered that there was still possibility to improve the conditioning so that 12% of additional water was added to the natural water content of the soil and conditioning tests performed using ACP 143 which had better results. The power requirement and sticking amount decreased significantly and the superior conditioning results were achieved where FIR was around 250 %, cone penetration was around 19 mm, sticking amount was 900 g and the net power requirement was around 37 W.

The optimized soil conditioning parameters and suggested conditioning method were tried on the field to validate the experimental results. Performance of the EPB TBM was improved by means of increasing penetration rate and decreasing cutterhead torque. The changings on penetration rates, torque and Thrust before and after improvement is compared and presented where the average cutter head torque decreased from 1072 kNm to 930 kNm and the penetration rate increased from 24.3 to 32.1 mm/rev and thrust force decreased slightly from 3932 to 3539 kN.

A new soil conditioning method was used in this study: To increase the reliability of soil conditioning parameters, it is suggested applying different types of experiments with enough number of tests, instead of using only one type of conditioning test.

EPB TBM İLE KAZILAN BİR ATIKSU TÜNELİ İÇİN ZEMİN ŞARTLANDIRMA ÇALIŞMALARI

ÖZET

Büyüyen kentleşme sonucunda, yeraltı yapılarının kullanımı giderek artmaktadır. Altyapı ihtiyaçlarını karşılamak için yeni ve daha büyük tünellere ihtiyaç her geçen gün artmaktadır.

Kentsel alanlardaki tünel inşaatlarının çoğunlukla alüvyal ortamlarda olması sebebiyle, yumuşak zeminlerde tünel açma çalışmaları büyük önem taşımaktadır. Pasa basınçlı (EPB) tünel açma makineleri (TBM) yaygın olarak yumuşak zemin tünel kazılarında kullanılmaktadır. Bu makineler kazı sırasında basınçlı kafa haznesi içerisindeki kazılmış zemini, tünel aynasına destek uygulamak için kullanır. Sağlam olmayan bir tünel aynasının EPB TBM'de ne kadar desteklendiği, sabit basıncın destek ortamından tünel aynasına etkili bir şekilde transferine bağlıdır. Destek basıncı sabit değil de değişken ise, değişken basınç aynanın çökmesine ve yeryüzü oturmalarına yol açabilir. Bur tür makineler belirli ve ideal zemin koşullarında çalışmak üzere tasarlanmışlardır. Ancak, doğal zemin nadiren bu özelliklere sahiptir ve genellikle zemin koşullarının makineye uyacak şekilde değiştirilmesi gereklidir. Yüzyıllar boyunca insanlar zeminlerin özelliklerini değiştirmeye veya kontrol altına almaya çalışmışlardır. Gelişen medeniyetle birlikte özellikle modern ulaşım sistemlerinin gelişmesiyle mühendisler açısından zeminin karakteristiklerinin değiştirilmesi veya değişen zemin suyu şartları altında optimum zemin özelliklerine ulaşılması önem kazanmıştır.

EPB TBM'lerdeki pasa basıncı dengesinin ana çalışma parametrelerinden biri zemin şartlandırmadır. Zemin şartlandırma terimi mekanize tünel kazılarında kazılan zeminin özelliklerini çeşitli oranlarda uygun katkı maddeleri (şartlandırma katkıları) kullanılarak iyileştirilmesi anlamına gelir. Şartlandırma katkıları yıllardır tünelcilik uygulamalarında yaygın olarak kullanılmaktadır. Uygun zemin şartlandırma sonrasında tünel açma makinelerinin performansının önemli ölçüde arttığı bilinmektedir. Köpük ve polimer gibi zemin şartlandırıcı maddeler, genellikle kesici kafa ya da kazı odası içine pasanın akışkan, zemin taneciklerinin arasında daha düşük içsel sürtünmeli olmasını sağlamak, zeminin yapışkan kıvamını kontrol etmek, zeminin tünel yapımı sırasında basınçlandırılabilir olmasını sağlamak, su oranını kontrol etmek, kesici kafadaki torku azaltmak ve burgu konveyörün tork ve gücünü düşürmek için enjekte edilir. Ancak, zeminin şartlandırılmasının, EPB TBM performansları üzerindeki etkileri açık bir şekilde anlaşılabilir değildir ve EPB TBM'lerin kullanıldığı projelerde sık sık problemlerle karşılaşılmaktadır.

Bu çalışmada, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (Tübitak Proje No: 213M487) tarafından finansal olarak desteklenen bir proje kapsamında İstanbul Zeytinburnu-Ayvalı 2 Atıksu Tüneli kazısında kullanılan EPB TBM'in performansına zemin şartlandırmanın etkileri araştırılmıştır. Bu amaçla sahadan alınan zemin numunesi üzerinde tane boyut dağılımı, doğal nem içeriği, konik penetrometre (likit

limit ve plastik limit) ve özgül ağırlık deneyleri yapılarak temel zemin karakteristiği ortaya konulmuştur. Daha sonra, iki farklı köpük (antikil) (Exfoam 2 ve ACP 143) örnekleri üzerinde köpük kararlılığı (yarı ömrü) ve köpük yoğunluğu deneyleri yapılarak köpüklerin karakteristikleri ortaya konulmuştur. En son olarak, suyun ve köpüğün şartlandırmadaki etkilerini belirlemek amacıyla, zemin+su ve zemin+köpük örnekleri üzerinde güç ve yapışma ölçümlü mikser, konik penetrometre ve yayılma tablası deneyleri farklı su içeriklerinde, değişen FIR miktarlarında, sabit FER= 16 ve C_F= %3 değerlerinde gerçekleştirilmiştir.

Zemin numunesinin doğal nem içeriği %33 olarak belirlenmiştir. Yapılan elek analizi ve hidrometre deney sonuçları değerlendirildiğinde numunenin %80 killi siltli (yaklaşık eşit oranda) ve geri kalan yüzdesinin kum ve çakıl olduğu tespit edilmiştir. Ayrıca numune içindeki kil+silt kısım kullanılarak likit limit ve plastik limit deneyleri yapılarak zemin numunesinin plastisite ve tıkanma riski grafiğindeki yeri bulunmuştur. Numunenin likit limit değeri %56,2, plastik limit değeri %29,7, plastisite indeksi 26,5 ve kıvam indeksi 0,87 olarak bulunmuştur. Numune plastik özellik göstermekte ve yüksek tıkama (yapışma) potansiyeli saptanmıştır.

Numunenin alındığı sahada kullanılan antikil ajanı Exfoam 2 ve daha sonra zemin şartlandırma deneyleri ile Exfoam 2'nin numune yapışmasını yeterince önlememesi nedeniyle ikinci bir antikil ajanı ACP 143 üzerinde yaygın olarak bilinen köpük karakterizasyon (köpük kararlılığı (yarı ömrü) ve köpük yoğunluğu) deneyleri yapılmıştır. Exfoam 2 köpük yoğunluğunun artan C_F oranı ile arttığı ve artan FER ile ise azaldığı tespit edilmiştir. ACP 143'de ise C_F'nin köpük yoğunluğuna etkisinin olmadığı ve artan FER ile ise köpük yoğunluğunun azaldığı görülmüştür. Exfoam 2'de köpük yarı ömür süresinin artan C_F değeri ile düştüğü ve artan FER ile arttığı bulunmuştur; en yüksek yarı ömür süresi %3 C_F ve 16 FER değerlerinde 792 saniye olarak ve en düşük yarı ömür süresi ise %5 C_F ve 8,5 FER değerinde 493 saniye olarak ölçülmüştür. ACP 143'de köpük yarı ömür süresinin artan C_F değeri ile düştüğü ve artan FER değeri ile arttığı bulunmuştur. En yüksek yarı ömür süresi %3 C_F ve 16 FER değerlerinde 761 saniye olarak ve en düşük yarı ömür suresi ise % 4 C_F ve 8,5 FER değerinde 464 saniye olarak ölçülmüştür. Dolayısı ile iki antikil arasındaki en belirgin farklılık yoğunluk karakteristikleridir.

Sadece su eklenerek yapılan şartlandırma deneylerinde %35 ve %54 oranları arasında su içeriği değiştirilmiştir. Buna göre yapılan mikser deneylerinde, artan su içeriğiyle birlikte güç ihtiyacının 92 W'tan 35 W'a düştüğü, mikser bıçağına zemin yapışma miktarının 2024 g'dan 295 g'a düştüğü, penetrasyon değerinin 8,4 mm'den 22,6 mm'ye yükseldiği görülmüştür. İstenen şartlandırma kıvamına numunenin likit limit değerine yakın su içeriğinde ulaşılmıştır. Ancak, suyun nakliye esnasında kuruyup numuneye plastiklik kazandırması ve dolayısı ile döküm sahasına nakliye esnasında kamyonlara yapışma problemleri veya tünel aynasındaki pasanın istenen kıvama getirilmesinde cıvıklık problemleri ile karşılaşılabileceği nedenlerle, antikil kimyasalı kullanılmasının daha doğru olacağına karar verilmiştir. Exfoam 2 ile şartlandırmada güç ihtiyacı ve yapışma miktarı azalmasına rağmen, ACP 143, %50'den %300'e değişen FIR değerlerinde, 67,5 W'tan 42 W'a kadar azalan güç gereksinimi, 1800 g'dan 1600 g'a azalan yapışma miktarı ve 7,5 mm'den 13,1 mm'ye artan penetrasyon değeri ile Exfoam 2'den daha iyi sonuç vermiştir. Ancak şartlandırmanın daha da geliştirilmesinde hala bir ihtimal olduğu düşünülmüştür; bu nedenle %12 ilave su, zeminin su içeriğine eklenmiştir ve şartlandırma testleri daha iyi sonuçlara sahip ACP 143 kullanılarak yapılmıştır. Güç ihtiyacı ve yapışma miktarı önemli ölçüde azalmıştır.

Optimum şartlandırma koşulu yaklaşık % 250 FIR değerinde, konik penetrometre değeri 19 mm, yapışma miktarı 900 g ve güç ihtiyacı 37 W olarak sonuç vermiştir.

Önerilen optimum zemin şartlandırma parametrelerini doğrulamak için, Zeytinburnu Ayvalı 2 Atıksu Tüneli'nin kazısında çalışan 3,96 m kazı çapındaki EPB TBM üzerinde ölçüm ve gözlemler yapılmıştır. Sahada önceleri %1 C_F oranında ve 15-16 FER değerinde Exfoam 2 kullanılırken ve zeminde yaklaşık %45 toplam su içeriği sağlanırken, yüklenici firma ile yapılan görüşmeler sonucunda maliyetler de göz önüne alınarak %1-1,5 C_F, 15-16 FER ve %50 toplam su içeriğinde bir şartlandırma için karar alınmıştır. Ayrıca, yüklenici firma kesici kafada bulunan grizzly barları da sökmeye karar vermiştir. Bu koşullarda, EPB TBM'in kesici kafa torkunun 1072 kNm'den 930 kNm'ye (yaklaşık %13 düşüş), itme kuvvetinin 3932 kN'dan 3539 kN'a (yaklaşık %10) düştüğü ve net kazı hızının 24,3 mm/dev'den 32,1 mm/dev'e çıktığı (%32 artış) görülmüştür. Kazı aynası stabil olduğundan ve ayna basıncı verilmediğinden dolayı, tork ve baskı kuvvetindeki düşüşün daha çok grizzly barların sökülmesinden kaynaklandığı düşünülmektedir. Net kazı hızındaki %30'un üzerindeki artışın ise şartlandırmada yapılan iyileşme sonucunda yapışkan malzemenin keskilere yapışmamasından ve dolayısı ile keskilerin temiz kalarak daha iyi penetrasyon yapmasından dolayı olduğu düşünülmektedir.

Bu çalışmada zemin şartlandırma parametrelerinin güvenilirliğini arttırmak amacıyla yeni bir şartlandırma metodu geliştirilmiştir. Literatürdekinin aksine tek bir şartlandırma deneyi yapmak yerine çeşitli deneyler yapılarak ortalama bir optimum şartlandırma koşulu belirlenmiştir. Değişik deneylerin değişik kıvamlar oluşturması ve değişik optimum FER değerleri ile sonuçlanması, bu yaklaşımın doğruluğunu göstermiştir.

1. INTRODUCTION

1.1 General

The ever growing urban population is fueling the demand for expanding cities and infrastructures. This issue is addressed with the help of knowledge improvements and newly developed technologies especially in mining and civil industries.

Underground excavation has been implemented mostly for construction of transport routes, however there are also other applications such as waste water, energy extraction, storage and refuge spaces, utility tunnels as well as underground urban development (Maidl et al., 2012).

The majority of large tunneling projects are now carried out by mechanical excavation rather than conventional drilling and blasting method. However, mechanical excavation has its own advantages and disadvantages compared to drilling and blasting method (Bilgin et al., 2014). Basic advantages of mechanical excavation include:

- More environmental friendly and safer operation
- Minimum ground disturbance
- Uniform muck size
- Selective mining
- Continuous operation
- Higher excavation rate in favorable ground conditions
- Automation opportunities

On the other hand, basic disadvantages of mechanical excavation are:

- Higher initial cost
- Less flexibility on working conditions
- Lack of mobility
- Inability to cut very hard and abrasive rocks

It is a fact that most of the tunnels in urban areas are located in soft ground and most of the infrastructures are constructed under shallow overburden, loose ground and

under water table. For this reason, studying about the operation and challenges of tunneling in soft ground has significantly drawn attention in the recent years.

1.2 Problem Definition

Recently, by development of new technologies, urbanization, and mechanical excavation, TBMs are widely used in urban tunneling where there is a high risk of excavation due to difficult ground conditions. Underground excavation in the mentioned conditions is challenging and hence considering safety, construction cost, period of construction, reducing the construction risks come to a great importance. It is a fact that, in a tunneling project it is desired to complete the project as fast as possible, with low cost and minimum damage to the environment. Although the emerging technology makes it possible, especially in urban tunneling regarding complicated structures of ground and high potential of risk, several problems such as decreasing performance of tunneling progress, increasing costs, surface settlements, which will result in damages to the surface buildings, could arise. Therefore, in order to deal with the mentioned problems, it is necessary to develop new technologies and improve the knowledge about the soft ground tunneling and soil conditioning.

Soil conditioning in EPB TBM operations is particularly important for increasing excavation performance as well as applying an effective face support pressure to the tunnel face resulting in reduced damages to the environment.

1.2 Objective of the Thesis

This thesis presents experimental laboratory investigations and field studies on soil conditioning in soft ground tunneling and its effect on EPB TBM performance during the excavation of Zeytinburnu-Ayvali 2 waste water tunnel project.

The main purpose of this thesis is to advance understanding the effect of soil conditioning in EPB TBM performance via laboratory tests in parallel to field observations and records. Furthermore, in the light of those investigations, an optimum foam design and recommendations are provided in order to optimize the TBMs performance.

1.3 Scope of the Thesis

This research is performed as a part of Zeytinburnu-Ayvali 2 waste water tunnel project in Istanbul. The thesis starts with literature review and introducing the waste water tunnel project (chapters 2 and 3). Then proceeds with chapters 4, 5 and 6 dealing with laboratory tests on soil conditioning and validating the laboratory results with field observations and records. The contents of each chapter maybe outlined as follows:

- **Chapter 2** reviews literature relevant to EPB TBMs and soil conditioning. EPB TBMs and the history of their development from the beginning to the present is summarized. Furthermore, soil conditioning definition as well as terminology and the past researches on tunneling in soft ground and soil conditioning are covered.
- **Chapter 3** introduces the Zeytinburnu-Ayvali 2 waste water tunnel project which is investigated during this study. This chapter contains detailed information about purpose of the project as well as project route, general geology, specifications of EPB TBM used in the project and other relevant information about the project.
- **Chapter 4** Details of the experimental tests carried out in the soil conditioning laboratory of the Istanbul Technical University are brought in this chapter. These tests contain basic soil characterization tests including determination of natural water content, grain size distribution, liquid limit and plastic limit tests, foam characterization tests including half-life, density and tests on soil+foam and soil+water mixtures.
- **Chapter 5** presents the results of laboratory tests described in chapter 4 and their analysis in detail by presenting graphs and figures.
- **Chapter 6** includes explanations about validation of the laboratory tests results in the field. Furthermore, this chapter explains The effect of soil conditioning and suggested foam design on the TBMs performance (torque, penetration and thrust).

2. LITERATURE REVIEW

2.1 Introduction

People have tried to change or control the properties of ground throughout the centuries. Recently, with developing new technologies and civilization as well as improvement of modern transportation systems, researchers are in purpose of changing the characteristics of ground in a desirable condition. For the first time, Lambe (1953) provided that, by using polymer, it was possible to change the behavior of soil by means of changing the plasticity, permeability, strength and density.

The first EPB tunnel boring machine was developed in 1974 in Japan and the first soil conditioning practice was carried out in 1976 by pumping high density mud to the excavation chamber in order to increase the fluidity of muck.

2.2 EPB TBMs

Shield machines with an earth pressure support are described as earth pressure balance (EPB) shield. As it is mentioned before, the development of EPB TBMs started in 1974 (Figure 2.1). It is one of the most used TBMs especially in urban tunneling. The largest TBM ever, was manufactured by Hitachi Zosen in 2012 with a cutterhead diameter of 17.48 m and was used in USA (Figure 2.2).

Figure 2.1: World's first EPB TBM used in 1974. (Herrenknecht et al., 2011)

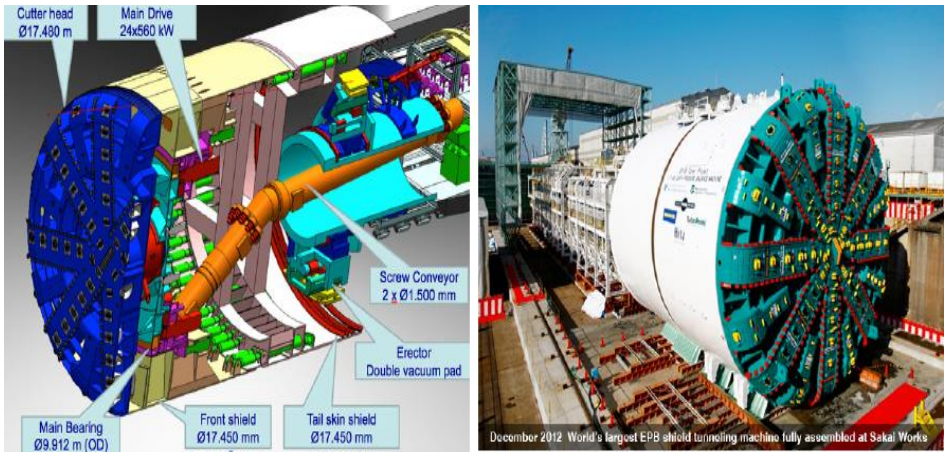

Figure 2.2: World's largest EPB TBM produced by Hitachi Zosen in 2012. (Tunneltalk, 2012)

In order to prevent the ground being excavated from entering the excavation chamber to an uncontrolled fashion, the face is supported by an already excavated muck which is under pressure in excavation chamber of EPB shield and is then transported by a screw conveyor out of the excavation chamber in to an atmospheric pressure. It should be mentioned that, in order to counterbalance the pressure difference between the support pressure at the face and the atmospheric pressure at the tunnel, an appropriate pressure gradient has to be dissipated along the length of the screw conveyor (Herreknecht et al., 2011). The functions of an EPB shield are shown in Figure 2.3.

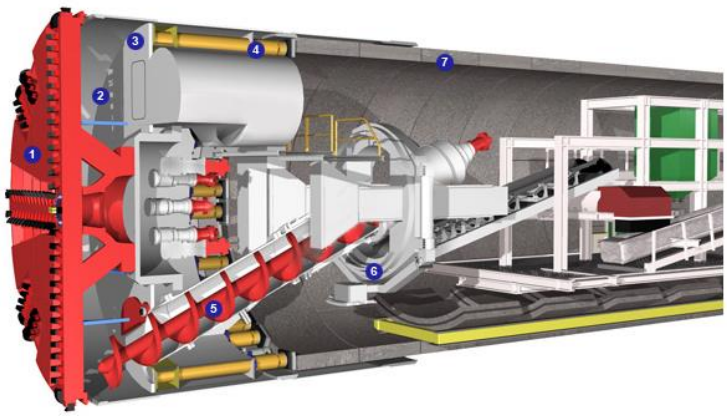

Figure 2.3: Functions of an EPB TBM (Herreknecht et al., 2011).

The functions of different parts (Figure 2.3) of an EPB TBM may be summarized as follows:

1) **Cutterhead** excavates the ground.

2) **Excavation chamber** receives the excavated ground by the cutterhead.

3) **Pressure bulkhead** is located at the back of excavation chamber.

4) **Thrust cylinders** regulates the support pressure of excavation chamber through the control of supply advance rate of the thrust presses.

5) **Screw conveyor** transports the excavated material out.

6) **Erector** is used to install the segments.

7) **Segments** are used to support the excavated tunnel.

EPB technology is generally based on the use of excavated ground as supporting medium in excavation chamber. This requires a cohesive soil with stiff to soft consistency which extrudes through the openings of the cutterhead towards the screw conveyor and closes the connection between pressurized excavation chamber, the conveyor and atmospheric conveyor during the stand still of the machine.

Depending on geological conditions, 6 different modes can be applied with an EPB shield (Figure 2.4).

- Closed mode
- Closed mode with piston pumps
- Closed mode with slurry transportation
- Half open mode
- Transition mode
- Open mode

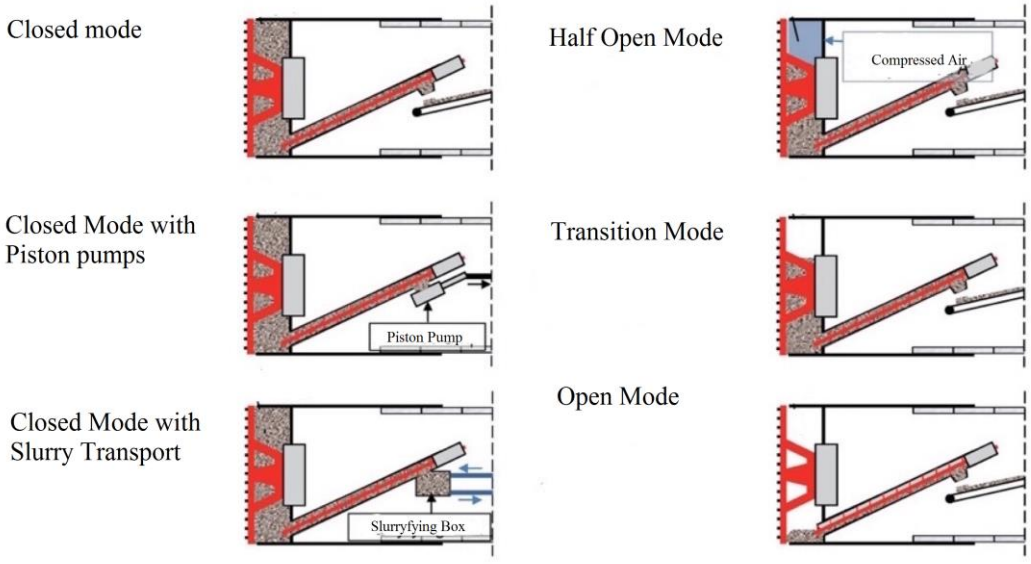

Figure 2.4: Working modes of EPB TBMs (Herreknecht et al., 2011).

Closed mode is used in unstable ground conditions under the groundwater table, so that the face can be supported and surface settlements can be controlled. In liquid and slurried fine-grained and coarse-grained soils, very permeable soils below the groundwater table, and when the screw conveyor is very long, the pressure gradient cannot be fully dissipated. In practices, this means that as soon as the screw conveyor gate valve is opened, without the screw turning at the same time, fluidized soil or water will uncontrollably pour out. In this case, the screw conveyor can be combined with an additional pressure-tight pumping system. The additional equipment shown in Figure 2.4 (closed mode with piston pumps and close mode with slurry transport), has been developed for this purpose. One possibility is to install a piston pump similar to a concrete pump at the end of the screw conveyor thus enable continuous pumping with a controlled release of pressure. This operating mode is called closed mode with piston pumps.

Another possibility is to connect the screw conveyor in a hydraulic circuit with feed and return pipes, as is known from slurry-supported (hydroshield) tunneling. The outlet of the screw conveyor is connected to a closed container (slurryfying box), which is then connected to the pumped circuit. This operating mode is called closed mode with slurry transportation. The extra construction cost compared to a normal EPB shield is considerable, as screening equipment is normally required in addition to the pumped circuit. Suspension can also be fed directly into the excavation chamber in this mode. With a mostly stable face below the groundwater table, half open mode can be used in the lower part of the excavation chamber being supported by the EPB support medium and in the upper part by compressed air. Regulation of the air pressure then enables tunneling below the groundwater table provided that the pressure loss through the face or the screw conveyor is sufficiently low. The level of the support medium in the excavation chamber is hard to control, and the support pressure calculation has to take the various degrees of filling into account.

With a mostly stable face above the groundwater table, or for tunnel drives without water ingress, the application of compressed air can be omitted in contrast to half open mode, (a change to transition mode becomes possible). The residual filling of the excavation chamber allows a comparatively rapid return to closed mode.

When the face is stable and water ingress is slight, open mode can be used. In this condition, the excavation chamber is not filled and is under atmospheric pressure.

Because of the low filling level of the excavation chamber, the cutting wheel torque required and the wear on the excavation tools are much less than in the previously described modes.

2.3 Adhesion and Clogging Problem in Mechanical Excavation of Tunnels in Soft Ground

During tunnel excavation, especially in clayey grounds, there is a possibility of sticking the clay on the cutterhead, which can significantly decrease the excavation performance. This problem is faced more frequently in urban tunneling. Figure 2.5 shows the cutterhead of a TBM almost completely clogged by clay. In clayey ground conditions, covering the cutterhead with clay drops the performance of the TBM and hence, the excavation should stop in order to clean up the cutterhead. This requires additional time and cost. The adhesion amount of the excavated material to the steel surface of the cutterhead depends on properties of the ground and the surface with which the ground is in contact. One of the major problems during a tunnel excavation is adhesion of the ground to the cutters and metal parts of the TBM cutterhead, which is called clogging. During an excavation operation, stickiness of the ground increases with increasing water content in the soil (up to a certain level) and this may cause to the problems either in cutting or conveyance system.

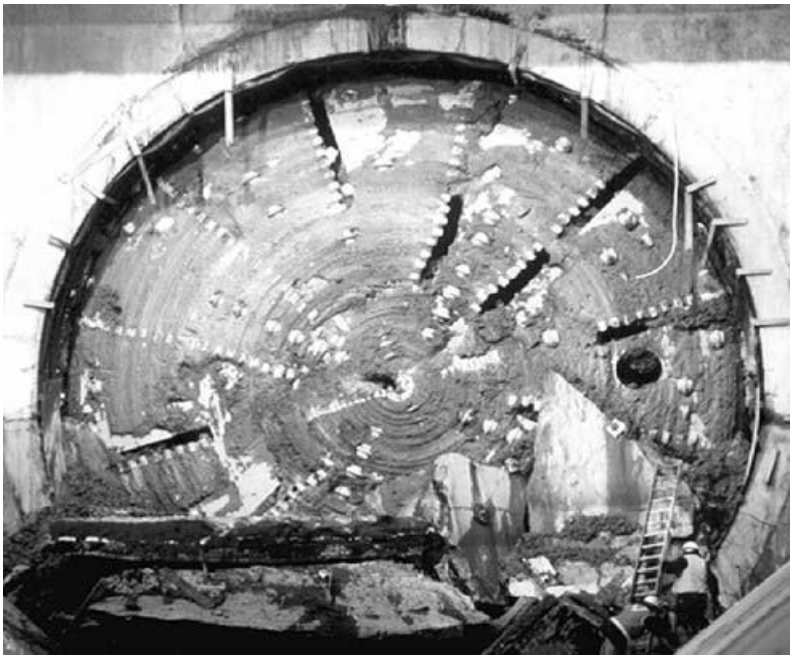

Figure 2.5: Cutterhead of a TBM clogged by clay (Maidl et al., 2012).

2.4 Soil Conditioning

The term of soil conditioning refers to using suitable additives (conditioning agents) in order to alter the properties of the soil to a desired condition. Conditioning agents have been used for many years, especially in tunneling and drilling operations, to enhance the performance of excavation machine.

The application range of EPB TBMs and type of conditioning suggested by Budach and Thewes (2015) is illustrated in Figure 2.6 and is considered during this study.

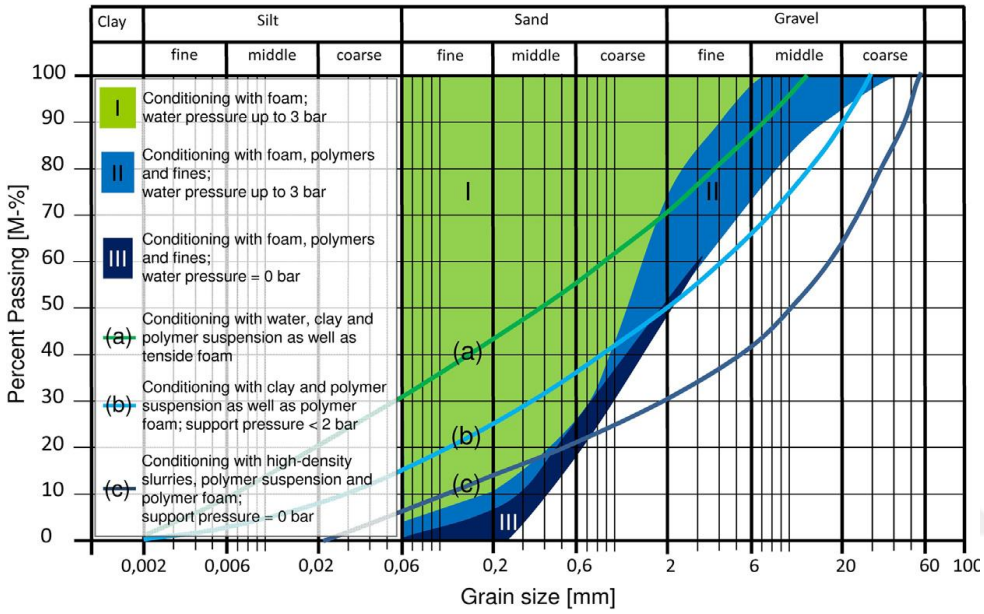

Figure 2.6: Application ranges of EPB TBMs and suggested conditionings based on laboratory research (Budach and Thewes, 2015).

Soil conditioning agents enhance the performance of the different parts of the TBM and may be introduced through the following procedures:

2.4.1 Tunnel face

The main role of the conditioning agents at the tunnel face is to reduce friction between ground and the cutters of the machine. The reduction of friction decreases wear and torque requirement for the cutterhead. This results in lower operational cost and longer life for machine parts.

2.4.2 Machine head

The main goal is to reduce friction within the machine head and create a homogeneous mass in order to avoid clogging. Reduction of friction results in reduced wear within the head. Moreover, it decreases the power requirements for turning the excavated

material into a suitably plastic paste. Creating a homogenous and plastic excavated mass (muck), improves its workability and hence, allows for better control of the pressure changes at the tunnel face. This improves the stability of tunnel face and provides better control of ground movements and thereby contributes to safer working conditions for the personnel and environment. In EPBs, the addition of the conditioning agents is necessary so that the excavated material can be transformed into an earth-paste supporting the tunnel face. The excavation chamber, which is filled with the excavated material, can be conditioned with suitable agents.

The ports on the cutterhead must ensure early mixing of the conditioning agent with the excavated material. At the cutterhead, each injection point should have its own delivery line in order to avoid blockages. Improving the flow characteristic of the excavated material results in high advance rates.

2.4.3 Handling the excavated material

Soil conditioning agents also improve handling process by reducing the wear of the parts of the muck removal system. In EPB shields, screw conveyors receive and transport the excavated material from the pressurized excavation chamber to the atmospheric pressure. The removal process is significant because it is related to the advance rate of the excavation. Preferably, the two rates should be compatible, otherwise, loss of the support pressure at the tunnel face occurs. When the soil in the excavation chamber has not reached a low permeability, a further injection of conditioning agents to screw conveyor prevents excessive flows of water. The position of the screw conveyor is important. When it is placed at the bottom of the excavation chamber, it is easier to discharge. The spoil (muck) should be in a suitable plastic state in order to allow controlled extrusion through the screw conveyor without causing excessive wear or consumption of power (Milligan 2000).

2.5 Previous Studies

Soil conditioning is a new subject for field engineers and researchers. Therefore, studies in this field are limited and defined as black art.

A research on changing the properties of soil by using polymer has been conducted by Lambe (1953). The first soil conditioning practice has been done in 1976 in Japan by pumping a high density slurry to the excavation chamber in order to increase fluidity

of the excavated material. In 1984, during a project in Japan, foam was used for the first time for soil conditioning purpose. In 1987, again in Japan, during the excavation of a soft ground tunnel, a polymer with absorbing properties was injected in order to avoid water bursts on the screw conveyor exit. The polymer used in this project was not effective enough in salty water or water containing high metal ions. For this reason, a special polymer was designed and suggested to be utilized by (Williamson et al., 1999). The first soil conditioning operation in Europe was carried out in 1994 in Passante Ferroviario project by an 8 m diameter EPB TBM produced by Obayashi Japan company (Peron and Marcheselli 1994). During the Valencia Metro Line 5 project in a high permeable clayey soil, conditioning operations were performed by using foam and a decrease of 20 % was reported for cutter head and screw conveyor torque (Wallis 1995, Herreknecht & Maidl 1995).

During the excavation of a mixed ground in north America, by using foam and polymer, the excavation was processed in semi EPB mode (Webb & Breeds 1997).

In a tunnel project in France, performed by a 7.7 m diameter EPB TBM, soil conditioning operations resulted in reduction of the cutterhead torque from 8825 kNm to 3922 kNm and also reduction of thrust from 19928 kN to 11956 kN (Babendererde 1998, Mauroy 1998). Another example for early soil conditioning operations was in Izmir -Turkey in 1999, where a sticky and granular soil was faced under the water table. For that case, a combination of bentonite and foam was used in order to increase advance rate and avoid settlements (Jancsecz et al., 1999).

Tolouei et al. (2016) has investigated relationship between foam optimization and EPB TBM performance in a waste water tunnel project in Istanbul where a 3.95 m diameter EPB TBM was used in a sticky and clayey soil and reported reductions in cutterhead torque and increase in penetration and advance rates of the machine.

In addition to the mentioned researches, the effect of soil conditioning in tunneling with EPB TBM has been repeatedly reported by several researchers. The effect of soil conditioning on decreasing the frictions in tunnel face was reported by Pellet and Castner (1998). A successful soil conditioning operation using foam, is reported by Maidl (1999) in Netherlands where 350 kpa earth pressure was encountered in a clayey-sandy-silty formation. Maidl and Jonker (2000) investigated workability of EPB TBM via soil conditioning under high earth pressure and water ingress. A successful soil conditioning case in Istanbul was reported by Copur et al. (2013).

During the mass-transit tunnel project in Singapore in a mixed ground with a 350 kpa earth pressure, application of foam+ polymer and bentonite resulted in reduction of torque and surface settlements (Reilly 1999).

The effect of soil conditioning has been investigated in the last two decades in different universities all over the world:

Bochum University – Germany (1995), Lille University – France (1996), Delft Geotechnics – Netherlands (1999), Oxford University (1998), Cambridge University (1999), Politecnico di Torino (2007), ETH Zurih (2009), Istanbul Technical University (2010), Colorado School of Mines (2016).

Additionally, in 2005, EFNARC published "Specification and guidelines for the use of specialist products for mechanized tunneling (TBM) in soft ground and hard rock, which can be assumed as one of the first standardization attempts.

Methods and findings of mentioned studies are summarized as follows:

Penetration of Foam: The aim of this test is to find out the amount of foam injected from cutterhead to the ground. If the penetration amount is too high, the water ingress cannot be avoided and as a result, creating the face pressure and the pressure in the excavation chamber will be more difficult. If the foam penetration is too low, again water ingress cannot be avoided. The first penetration of foam to a sandy formation was about 30 mm reported by Quebaud (1998). On the other hand, Thewes & Budach (2010) proved that, these results could not be realistic due to differences in foam injection systems. Bezuijen (1999) reported no penetration of foam in sandy formations when sand+foam+water was used.

Mixing Test: This test is carried out in different ways but commonly it is performed using concrete or food mixer. The procedure of the test includes mixing the soil by a mixer and measuring the power requirement and compare it with the power requirement of mixing when foam is added. It was observed that after soil conditioning operations, the power requirement value decreased by 50% (Quebaud 1998). The test was also performed by Bezuijen (1999) in order to simulate EPB TBMs under 350 kpa earth pressure.

Permeability test: The test is performed for conditioned soil as constant and falling head. The desired coefficient of permeability (k) during EPB TBM excavations is

lower than 10^{-5}. The coefficient of permeability decreases up to 50% where soil conditioning was carried out (Quebaud 1998, Bezuijen 1999).

Slump Test: This test was developed to evaluate the behavior and consistency of the conditioned soils. The slump test was used by many researchers such as Peron and Marcheselli (1994), Quebaud (1998), Bordachar and Nicholas (1998), Jancsecz et al. (1999), Williamson et al. (1999), Langmaack (2000), Vinai et al. (2007), Peila et al. (2015).

The effect of soil conditioning on resolving clogging problems of EPB TBMs was investigated by several researchers. Hollman and Thewes (2013) evaluated approaches to indicate the clogging potential of clayey soils and developed a classification scheme for clogging of soft ground TBMs. Quantifying the stickiness of different non-conditioned clays at different consistencies using a cone pull-out test was suggested by Feinendegen et al. (2011).

Adhesion plate test was suggested by Sas and Burbaum (2008) in order to evaluate the sticking potential of the clayey soils. Evaluating sticking potential of soils using mixing test was suggested by Ball et al. (2009). The shear plate device offers the possibility to measure accurately the tangential adhesion and sliding resistance between soft soil pastes and steel at different applied confining pressure (Zumset and Puzrin 2012). In the light of the mentioned studies, it is indicated that clogging and sticking amounts can be decreased using additives such as foam, polymer and anti-clay agents.

Yoshikawa (1996) performed tests using a full scale EPB TBM screw conveyor on a plastic soil with different screw speeds. Marritt and Mair (2006), Peila et al. (2007), Vinai et al. (2008), Rivas et al. (2009), Peila (2014) used laboratory screw conveyor devices to extract conditioned soil from a pressurized tank. Pena (2003), Mair et al. (2003), Merrit and Mair (2006), in a joint research for Oxford and Cambridge universities, investigated the effect of conditioned soil on operational parameters of the screw conveyor. They concluded that soil conditioning decreased the screw conveyor torque. To determine whether the adopted conditioning was able to reduce both the wear on the metallic parts of the machines and the friction of the muck, different test devices were developed by various authors (Nilsen, 2006; Gharahbag and Rostami 2011). A test device for determining the wear of tools is developed at Politecnico di Torino. The device consisted of a disk spinning in soil at a constant

speed for a pre-defined time. The test was carried out with the measurement of the loss of material of an aluminum disk after the test and the measurement of the applied torque with and without conditioning (Peila 2014). The effect of soil conditioning on penetration rate was investigated using cone penetration tests (Jancsecz, 1999). A study by Mooney et al. (2016), at Colorado School of Mines, illustrated how pressure influenced the behavior of conditioned soil and how atmospheric test results had to be viewed in the context of expected chamber pressures. The influence of pressure on foam bubble size (including time) was reported with measurements through digital image analysis. A study by Salazar et al. (2016) showed the influence of water content on the wear phenomenon based on tests performed using a device especially designed by TUSC (Tunneling and Underground Space Center) DIATI, Politecnico di Torino. Another important factor was the addition of wear reduction chemical products capable to reduce the consumption of cutting tools.

Guidelines for application of foam suggested by EFNARC (2005) are summarized below:

The foam concentration (C_F) is typically in the range 0,5 - 5,0%, however one should follow the manufacturer's recommendations if they suggest a different value. Concentration heavily depends on the amount of water injected or already present in the soil and affects the activity and stability of the used tunnel foam.

$$C_F = 100 \times m_{surfactant}/m_{foam\ solution}, (\%) \quad \textbf{(2.1)}$$

Where:

$m_{surfactant}$ = mass of surfactant in foaming solution

$m_{foam\ solution}$= mass of foaming solution

The foam expansion ratio (FER) should be between 5 and 30. The higher the FER the drier the generated foam will be. The wetter the soil, the drier the foam should be.

FER is estimated by:

$$FER = V_{foam}/V_{solution} \quad \textbf{(2.2)}$$

Where:

V_{foam}=volume of foam at working pressure

$V_{solution}$=volume of foaming solution

The foam injection ratio (FIR) can range between 10 and 80%. In most cases, it ranges between 30 and 60%. To determine the optimum FIR value, laboratory tests have to be carried out. The water content of the soil or the amount of injected water plays an important role. FIR is estimated by:

$$FIR = 100 \times V_{foam}/V_{soil} \ , (\%) \qquad \textbf{(2.3)}$$

2.6 Soil Cutting Tools

The most commonly used soil cutters are summarized below (Maidl et al., 2012):

Scrapers: the term scraper is used for the cutters which cutting heads are discontinuous. The scrapers should ideally have a cutting action, with chips peeling off over the front edge of the blade. There are various types of scrapers available for use in different soil types, mostly with hard metal blades and additional wear protection (Figure 2.7).

Figure 2.7: Different types of scraper tools used for soil cutting (Maidl et al., 2012).

According to the type of soil to be excavated, scrapers can be the sole excavation tool or can be mounted slightly behind disc or chisel cutters to work in the intermediate

parts of the face. Originally designed to be used in clay, scrapers have now developed into universal tools for use in a wide range of loose ground.

Drag picks: are blunt tools of round or square section set at right angles to the face. Figure 2.8 demonstrates square-section drag picks on the central ridge and the spokes of a cutterhead.

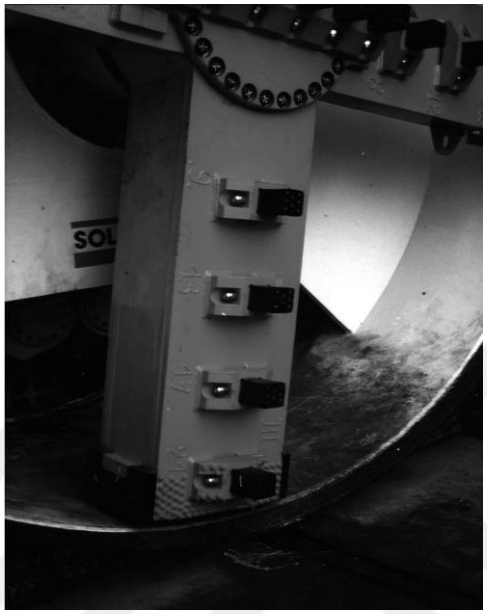

Figure 2.8: Square section drag picks on a cutterhead (Maidl et al., 2012).

Drag picks work by destroying the structure and tearing in silt, sand and gravel soils, although they are only able to knead cohesive soil. In order to increase their lifetime, drag picks are often built up by welding or equipped with hard metal inserts. The orientation at right angles to the face makes drag picks independent of the direction of rotation, i.e. they can excavate in either direction.

Chisel tools: are narrow tools suitable for breaking hard soils, generally with an replaceable tip. They are used as breaking tools in percussive hammers and a special type with hard metal core and round shaft is used in an angled arrangement in the milling cutting heads of open shields. The described angled arrangement of round-shafted chisels can also be used in the caliber or gauge area of a cutterhead. In the flat face area of a cutterhead, narrow round shafted chisels are subjected to single-sided loading, which leads to a short lifetime and justifies their use only as a repair measure (Figure 2.9).

Figure 2.9: Chisel tools arranged as a repair solution on a cutterhead (Maidl et al., 2012).

Narrow flat chisels are often mounted at right angles to the face on Japanese cutting wheels for the localized loosening of a consolidated soil structure before the arrival of scrapers (Figure 2.10). Square-section drag picks in the early Hydroshields and Mixshields were often mounted on tool holders on the front of the cutting wheel with a transverse securing bolt. The limited accessibility for tool changing and the disturbance to the material flow of the excavated soil into the muck openings have reduced the use of square section drag picks in favor of scrapers (Maidl et al., 2012).

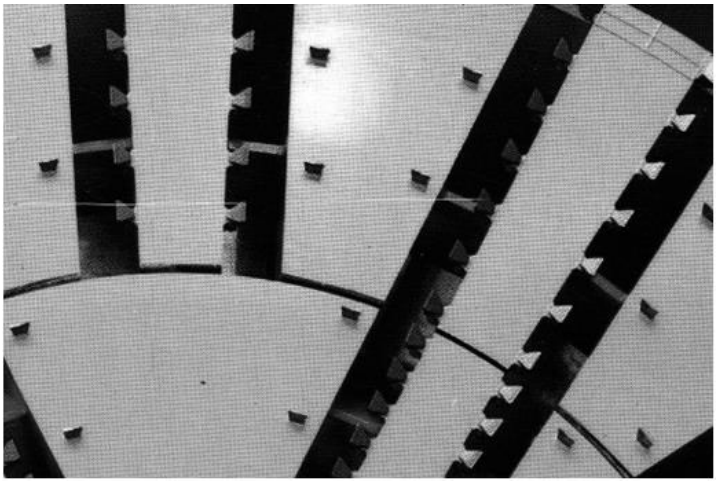

Figure 2.10: Flat chisel tools (Maidl et al., 2012).

Chisels are increasingly installed in current cutterhead designs as heavy ripper heads on a support construction, set into the housings of previously removed disc cutters (Figure 2.11).

Figure 2.11: Heavy duty ripper tools (Maidl et al., 2012).

2.7 Performance Terminology of TBMs

Predicting the performance of the TBM is such a significant issue since underestimation of basic parameters would reduce excavation performance. Furthermore, during the study on TBM tunneling, the following parameters should be considered (Copur 2015).

Instantaneous (net) cutting rate (ICR) is production rate during actual cutting time excluding stoppages. (m^3/h).

Instantaneous penetration rate (IPR) is calculated by dividing the ICR to cross section area of the tunnel. (m/h).

Machine utilization time (MUT) is defined as percentage of project time used only for excavation job. (%).

Advance rate (AR) is the rate of tunnel or drift advance over the whole shift time. (m/day, m/week, m/mounth).

2.8 Empirical Performance Prediction of EPB TBMs

Empirical thrust force and torque requirement for EPB type TBMs were suggested by Ates et al. (2013) and Bilgin et al. (2014), known as ITU model, is shown in Figure (2.12) and (2.13). The figures illustrate the relationship between TBM diameter, thrust and torque values of EPB type TBMs.

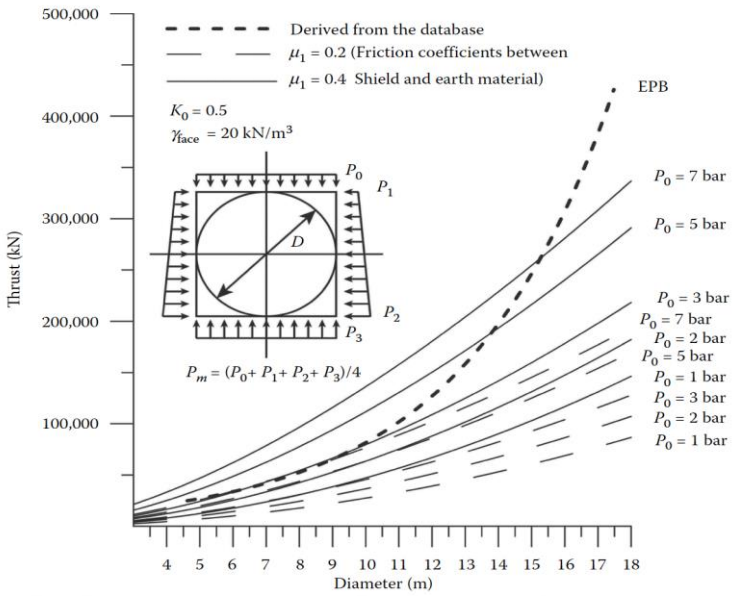

Figure 2.12: Relationship between EPB TBM diameter and thrust (Bilgin et al., 2014).

Dotted bold lines in the Figures 2.12 and 2.13 represent statistically derived equations and the other lines represent those ascertained theoretically for different values of earth pressure and the friction coefficient between shield and the geological formation to be excavated. Figure 2.14 shows the variation of maximum rotational speed of TBM with respect to the EPB machine diameter. Figure 2.15 corresponds to variation of number of cutters of TBMs as the machine diameter increases. The weight of EPB TBMs predicted by Bilgin et al. (2014) is also given in Figure 2.16.

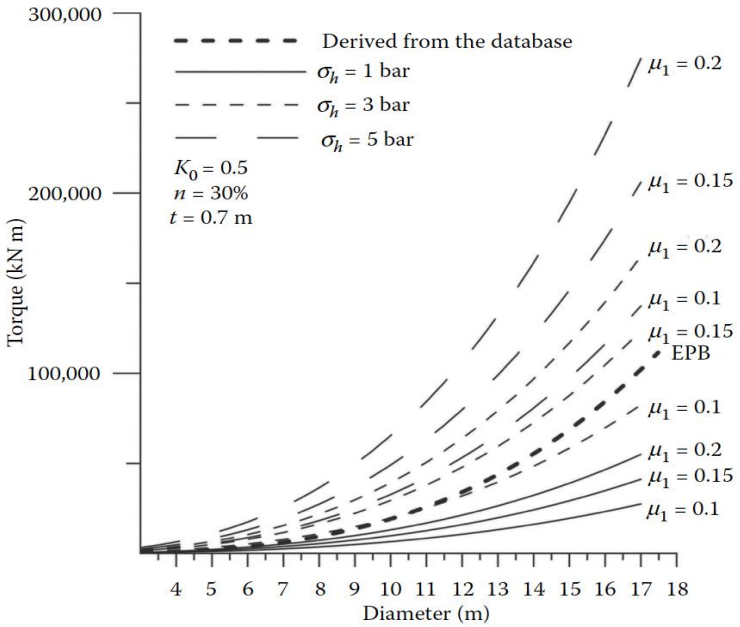

Figure 2.13: Relationship between TBM diameter and torque (Bilgin et al., 2014).

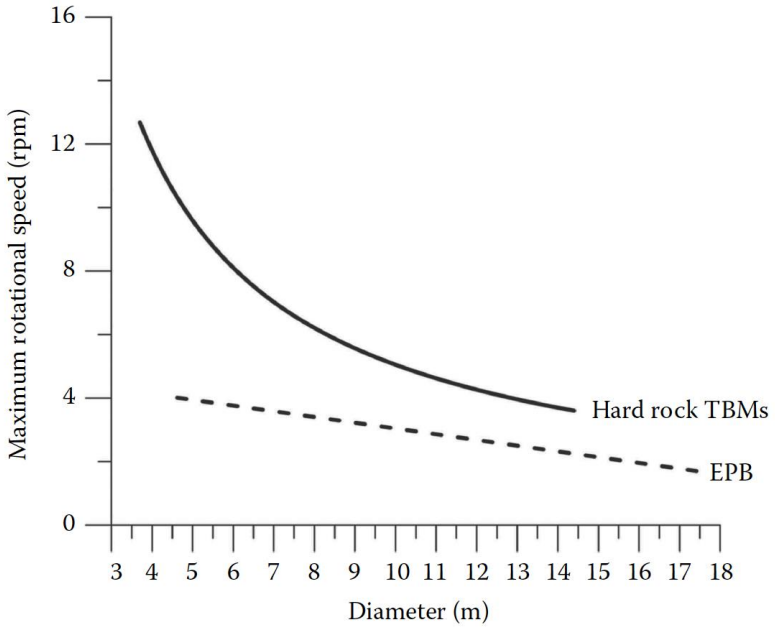

Figure 2.14: Relationship between TBM diameter and maximum rotational speed (Bilgin et al., 2014).

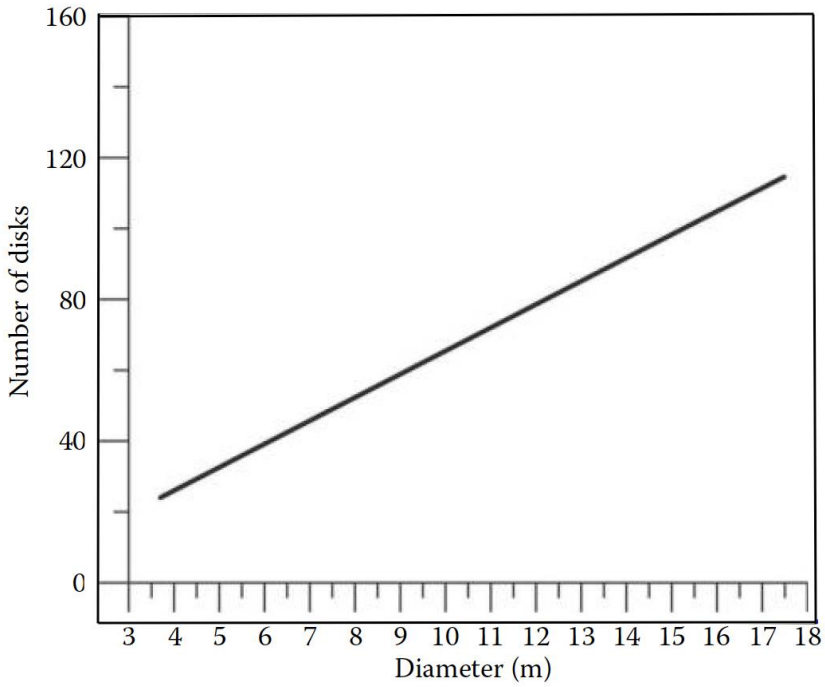

Figure 2.15: Relationship between TBM diameter and number of discs (Bilgin et al., 2014).

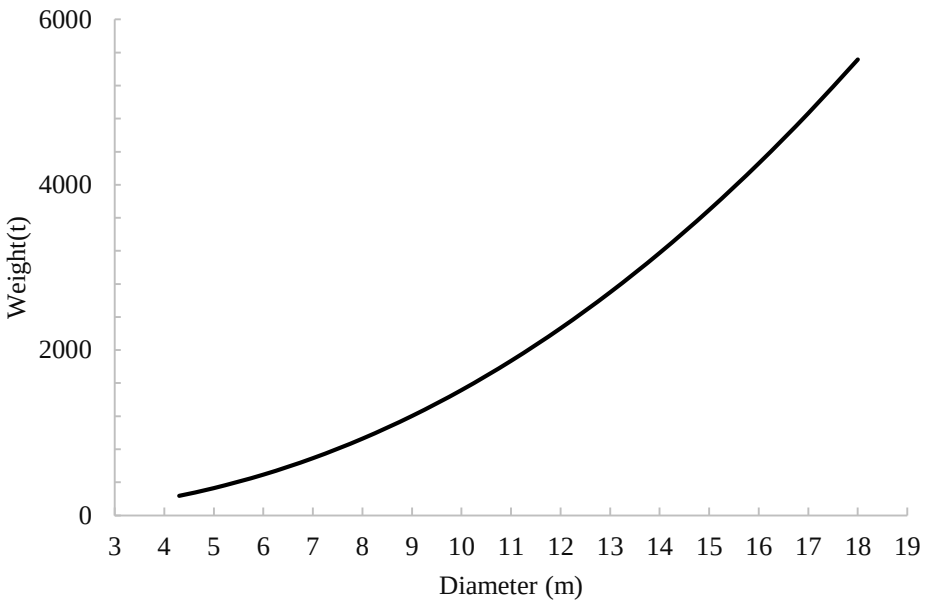

Figure 2.16: Relationship between TBM diameter and weight of the machine (Bilgin et al., 2014).

The equations given in Table 2.1 presents a basis for performance prediction of EPB TBMs.

Table 2.1: Statistically determined equations to predict EPB TBM design parameters by using cutter head diameter (x) as a predictor.

Thrust (kN)	Torque (kNm)	Total Weight (t)	Rotational speed(rpm)
$8972.6e^{02208x}$ R^2=0.79 n=86 Lower limit=-40% Upper limit=+47%	$T=13.438x^{3.154}$ R^2=0.85 n=86 Lower limit=-63% Upper limit=55%	$W=9.673x^{2.1956}$ R^2=0.86 n=31	RPM=-0.180x+4.864 R^2=0.17 n=46

An empirical model for torque requirement estimation is suggested by JSCE (2007):

$$Tq = \alpha . D^3 \ (KNm) \qquad \textbf{(2.4)}$$

Where:

D= Cutterhead diameter (m)

α= Torque factor (10-25 for EPB)

2.9 Theoretical Cutting Force Estimation for Soils

Labanov (1980) (from Copur et al. 2015) from suggested the following equation for predicting the cutting force acting on knife cutters working under hydrostatic pressure (valid for α of greater than 20°):

$$Fc = 2.5.[1 + \cot(90 - \alpha).\tan\delta].d.w.\frac{1 - \sin\emptyset\cos 2\varepsilon}{1 + \sin\emptyset\cos 2\varepsilon}.\sigma_s.\cos\emptyset \quad \textbf{(2.5)}$$

$$\varepsilon = 2\pi - 2\alpha - \delta - \arcsin(\sin\phi\sin\delta) \quad \textbf{(2.6)}$$

δ = angle of friction between cutter and ground (30°)

p = penetration per revolution (0.0193 m/rev)

W = width of the cutter (0.10 m)

ϕ = internal friction angle of the ground (25°)

c = shear strength (cohesion) of the ground (100 kPa)

α = tool rake angle (30°)

2.10 Theoretical Torque and Thrust Requirements Estimation for Soils

The cutterhead torque requirement estimation for soft ground TBMs is suggested by JSCE (2007) as a sum of six basic torque components.

$$Tq = Tq_1 + Tq_2 + Tq_3 + Tq_4 + Tq_5 + Tq_6 \quad \textbf{(2.7)}$$

Where:

Tq= Total torque requirement of the soft ground TBMs

Tq_1= Torque required to overcome the cutting resistance of the soil

Tq_2= Torque required to overcome the frictional resistance of the soil

Tq_3= Torque required to overcome the resistance of the soil mixing and stirring

Tq_4= Torque required to overcome mechanical loses in the reduction gears

Tq_5 = Torque required to overcome the frictional resistance of the bearing seals

Tq_6= Torque required to overcome mechanical losses in the reduction gears

Torque requirement for cutting the soil is estimated as follows (Copur 2015):

$$Tq_1 = \sum_{i=1}^{Nc} r_c \,.\, Fc.F_L \approx Nc.Fc.\frac{r}{2}.F_L \quad \textbf{(2.8)}$$

Where:

Tq_1= Torque required for cutting the soil

Fc= Mean cutting force

Nc= Number of cutters

r_i= Distance of cutter to the cutterhead center

F_L= A constant for frictional loses (usually F_L=1.2)

Total thrust requirement for soft ground TBMs is also suggested by JSCE (2007) as the sum of five thrust components.

$$Th = F_1 + F_2 + F_3 + F_4 + F_5 \quad \textbf{(2.9)}$$

Where:

Th= Normal thrust force for soft ground TBMs

F_1= thrust force required to overcome friction (adhesion) between shield and ground due to earth pressure.

F_2 = thrust force required to overcome the chamber pressure acting on bulkhead.

F_3 = thrust force required to overcome the drive force caused by direction changes in curved alignments (If the tunnel is straight, (F_3) is taken to be 0).

F_4 = thrust force required to overcome the frictional force acting between the segments and the tail seals.

F_5= thrust force required to overcome the hauling force of trailing (backup) units (If the backup is self-propelled, (F_5) is taken to be 0). An additional thrust component might be added as F_6 of thrust force required to penetrate the cutters into the ground (Copur 2015) and can be estimated as:

F_6= Thrust force required to overcome the penetration (normal) force of cutting tools into the ground.

3. AYVALI-2 WASTE WATER PROJECT

Zeytinburnu Ayvali-2 Tunnel is a wastewater project being excavated in European side of Istanbul the goal of which is to transport wastewater from Zeytinburnu to Yenikapi Treatment Plant through the Bayrampasa, Bagcilar, and Gungoren alignment. The 1969 m long tunnel is being excavated between Kazlicesme and Cirpici. The tunnel alignment is shown on Figure 3.1.

Figure 3.1: Ayvali-2 tunnel alignment.

The tunnel alignment is mostly located in Cekmece formation, Bakirkoy division, as it is shown in Figure 3.2. The orange/pink colored part consists of greyish beige, low plasticity, consisting of gravels-carbonate lumps-iron oxides, sandy and silty rigid clay. The cream colored part consists of off-white, porous, calcareous surface layer, low-mid strength, clay intercalated limestone with weathering degree of W2 to W3 and the grey upper part is backfill. The studied area in this research mainly consists of grey coloured low plasticity carbonated hard silt containing clay (Figure 3.2) (Borehole SK15).

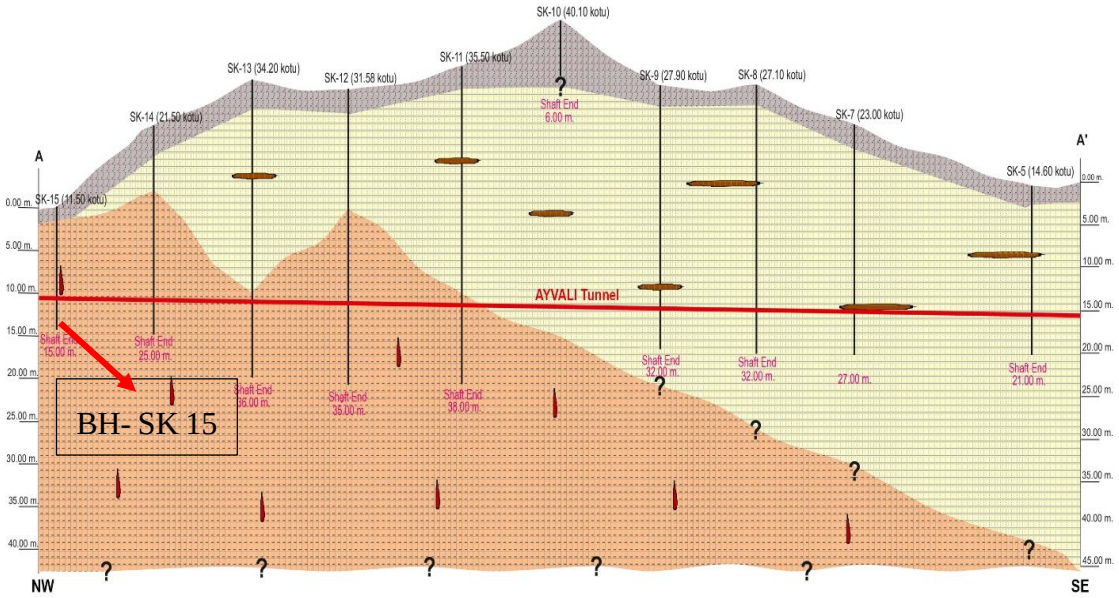

Figure 3.2: General geological cross section along the tunnel alignment.

The tunnel lining system consists of recast segment with reinforced concrete. Each ring includes 6 segments. The thickness of each segment is 20 cm, the inner and outer diameter of segments are 3300 and 3700 mm while the length of each is 1300 mm (Figure 3.3). When excavation is finished, the segments will be lined by PVC of 15 cm thickness. Moreover, the space between ground and segments are filled with grout injections. Bio component injection is being used in this project since it is under urban areas and because of the special ground conditions. The main component of the injection is bentonite, cement and water and the other component is sodium silicate.

Figure 3.3: Segments used in Ayvali-2 tunnel project.

The EPB TBM used for the project was manufactured by a Chinese company, LOVSUNS (Figure 3.4). Technical specifications of the TBM are presented in Table 3.1.

Table 3.1: Technical specifications of the TBM used in Ayvali-2 waste water tunnel project.

Cutterhead diameter	3.95 m
Cutterhead opening ratio	25%
Cutterhead motor power	524 Kw
Maximum torque	1497 (kN.m)
Maximum cutterhead RPM	0-6 RPM
Maximum thrust force	1200 ton
Inner diameter of screw conveyor	550 mm
Screw conveyor length	12 m
Screw conveyor	0-30 RPM
Number of disc cutters	28
Diameter of disc cutters	15.5 in
Shield length	10 m
Backup length	70 m
Number of wagons	4 m
Volume of wagons	7.2 m^3/each

The muck is transported by a belt conveyor to a locomotive convoy with 4 wagons and then leaves the tunnel through the shaft (Figure 3.5).

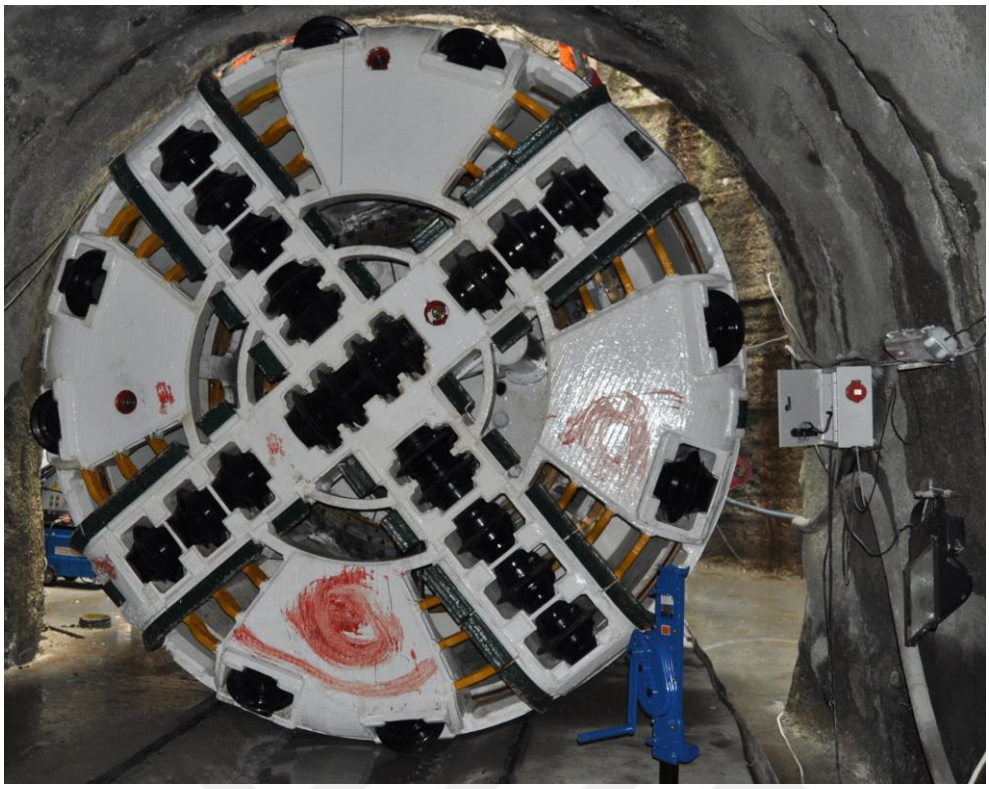

Figure 3.4: TBM used in Ayvali-2 waste water tunnel project (with permission of Sener Kahya).

Figure 3.5: Shaft winch and muck transportation using wagons during the project.

4. EXPERIMENTAL METHODS AND PARAMETERS

4.1 Introduction

This chapter explains the laboratory tests which has been carried out during this thesis. The tests are selected in such a way that their result can serve to optimizing the performance of the EPB TBM used in Zeytinburnu- Ayvali 2 waste water tunnel project. In the three main parts, the chapter explains the tests and the standards used for performing those tests. The first part describes soil characterization tests the results of which are the fundamentals of performance optimization. The second part includes foam characterization tests. The third part of this chapter describes foam+soil and soil+water optimization tests and their standards.

4.2 Soil Characterization Tests

4.2.1 Determination of natural water content

Determination of natural water content of the sample is necessary in order to do further tests. ASTM D2216-10 is the standard procedure under the instructions of which this test is performed. To measure the natural water content of a given sample, mass of an empty, clean and dry moisture can is recorded (M_c) and then the moist sample should be placed into the can. After determination of the mass of the moisture can containing the moist soil (M_{cms}), it should be placed in a drying oven (Figure 4.1) the temperature of which is set at 105° C for about 24 hours and then the mass of moisture can containing dried soil (M_{cds}) has to be determined. The data obtained from the test can be analyzed as follows:

- Mass of soil:

$$M_s = M_{cds} - M_c \quad \textbf{(4.1)}$$

- Mass of water:

$$M_w = M_{cms} - M_{cds} \quad \textbf{(4.2)}$$

- Water content:

$$W = \left({}^{M_w}/_{M_s}\right) \times 100, (\%) \quad \textbf{(4.3)}$$

Figure 4.1: Drying moist sample in the oven.

4.2.2 Grain size distribution

The distribution of grain sizes influences the properties of the soil. Grain size analysis provides the grain size distribution, which is required for classifying the soil.

Sieve analysis and hydrometer analysis are carried out to get the grain size distribution curve. The standard for this test method is reached under the code ASTM D 422.

4.2.2.1 Sieve analysis

Sieve analysis test is shaking the soil sample through a set of sieves that successively have smaller openings. Firstly, oven dried sample should be weighted, then sieves have to be assembled with the pan underneath and soil poured on the top sieve. The assembled set of sieves should be mounted on a mechanical shaker (Figure 4.2) and shaken for 10 to 15 minutes. Then, the sieves should be dismantled from the shaker and the mass of soil retained on each sieve should be weighted. Calculation associated with sieve analysis is as follows:

$$(\%)Mass\ retained = mass\ of\ dry\ soil\ in\ respective\ sieve / mass\ of\ total\ dry\ sample \quad \textbf{(4.4)}$$

Figure 4.2: Sieve sets placed on a mechanical shaker.

4.2.2.2 Hydrometer analysis

Hydrometer analysis has been conducted to measure the particle size of the samples smaller than 0.075 mm. The equipment required for performing this test are listed below:

- ASTM 152H hydrometer
- Mixer
- Two 1000cc scaled cylinders
- Thermometer
- Sodium hexametaphosphate
- Squeeze bottle
- Rubber stopper

After performing sieve analysis and preparing the equipment mentioned above, 50 g of soil sample retained on pan (finer than 0.075 mm) is combined with 125 ml of sodium hexametaphosphate solution. While soil is soaking, 125 ml of dispersing agent is added to a control cylinder and filled the cylinder is filled with distilled water to take the zero correction and meniscus correction. Zero correction is obtained by reading at the highest level of the meniscus formed by the hydrometer stem and the control solution. A reading less than zero is recorded as a negative correction and a reading between zero and sixty is recorded as a positive correction. The meniscus correction is the difference between the top of the meniscus and the level of the solution in the control cylinder.

After transferring the soil slurry to the mixer and mixing it for approximately 5 minutes it is immediately transferred to an empty sedimentation cylinder and the open end is covered by a rubber stopper. The cylinder turned upside down and back upright for a period of one minute and then cylinder is set down and time is recorded. After removing the stopper from the cylinder, the hydrometer should be inserted to the cylinder and the displayed number should be recorded as the first reading (Figure 4.3).

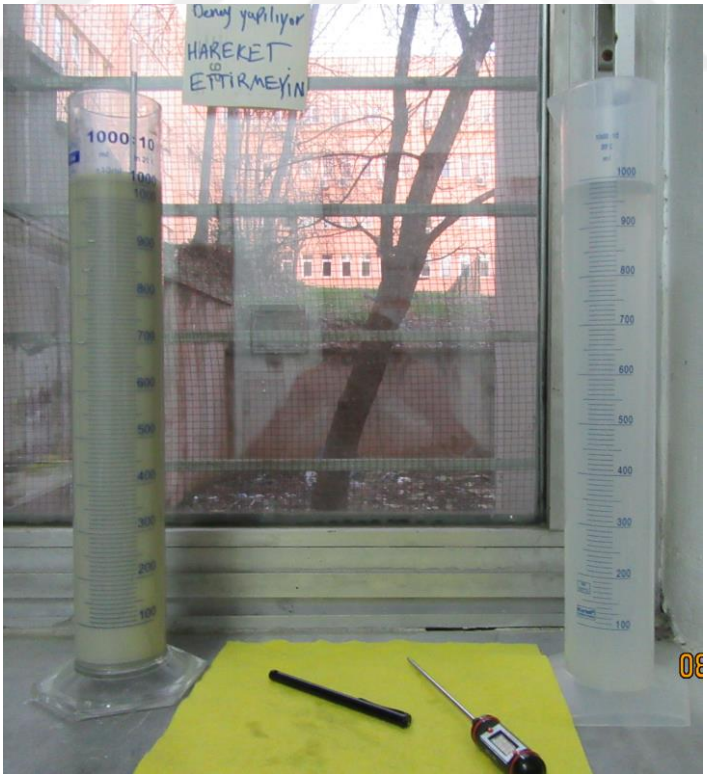

Figure 4.3 Hydrometer analysis.

The reading has to be taken after elapsed time of 0.5, 2, 4, 6, 8, 15, 30, 60, 120, 1380 and 1440 minutes, respectively.

Calculations associated with the hydrometer analysis are as follows:

- Applying the meniscus correction to actual hydrometer reading
- Obtaining the effective hydrometer depth (L) from Table 4.1 (for meniscus corrected reading)
- Obtaining the value of K factor for known specific gravity of soil obtained from Table 4.2
- Calculating the equivalent particle diameter (D) using the following formula

$$D = K\sqrt{\frac{L}{t}} \quad \textbf{(4.5)}$$

Where:

D= diameter of particle, mm

K= constant depending on the temperature of the suspension and the specific gravity of the soil particles.

- Determining the temperature correction (C_T) from Table 4.3
- Determining correction factor "a" from Table 4.4
- Calculating the corrected hydrometer reading using the following equation:

$$R_c = R_{actual} - Zero\ correction + C_T \quad \textbf{(4.6)}$$

- Calculating the percent finer (P) using the following equation:

$$P = \frac{R_c \times a}{W_s} \times 100 \quad \textbf{(4.7)}$$

- Adjusting percent fines as follows using the following equation:

$$P_A = \frac{P \times F_{200}}{100} \quad \textbf{(4.8)}$$

F_{200}=%finer of #200 sieve as a percent

Table 4.1: Effective depth of 152 H hydrometer (ASTM D422).

Actual Hydrometer Reading	Effective Depth, L, cm	Actual Hydrometer Reading2, cm	Effective Depth, L, cm
0	16.3	31	11.2
1	16.1	32	11.1
2	16.0	33	10.9
3	15.8	34	10.7
4	15.6	35	10.6
5	15.5	36	10.4
6	15.3	37	10.2
7	15.2	38	10.1
8	15.0	39	9.9
9	14.8	40	9.7
10	14.7	41	9.6
11	14.5	42	9.4
12	14.3	43	9.2
13	14.2	44	9.1
14	14.0	45	8.9
15	13.8	46	8.8
16	13.7	47	8.6
17	13.5	48	8.4
18	13.3	49	8.3
19	13.2	50	8.1
20	13.0	51	7.9
21	12.9	52	7.8
22	12.7	53	7.6
23	12.5	54	7.4
24	12.4	55	7.3
25	12.2	56	7.1
26	12.0	57	7.0
27	11.9	58	6.8
28	11.7	59	6.6
29	11.5	60	6.5

Table 4.2: Values of K for use in equation for computing diameter of particles in hydrometer analysis (ASTM D422).

Temperature °C	Specific gravity of soil samples								
	2.45	**2.50**	**2.55**	**2.60**	**2.65**	**2.70**	**2.75**	**2.80**	**2.85**
16	0.01511	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356	0.01338
17	0.01492	0.01467	0.01443	0.01421	0.01399	0.01378	0.01359	0.01339	0.01321
18	0.01474	0.01449	0.01425	0.01403	0.01382	0.01361	0.01342	0.01323	0.01305
19	0.01456	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307	0.01289
20	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291	0.01273
21	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276	0.01258
22	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261	0.01243
23	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246	0.01229
24	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232	0.01215
25	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218	0.01201
26	0.01511	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356	0.01338
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204	0.01188
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01255	0.01208	0.01191	0.01175
29	0.01312	0.0129	0.01269	0.01269	0.0123	0.01212	0.01195	0.01178	0.01162
30	0.01298	0.01276	0.01256	0.01236	0.01217	0.01199	0.01182	0.01165	0.01149

Table 4.3: Temperature correction factor (C_T) for hydrometer analysis (ASTM D422).

Temperature(°C)	Correction factor (C_T)
15	1.10
16	-0.90
17	-0.70
18	-.0.50
19	-0.30
20	0
21	0.20
22	0.40
23	0.70
24	1.0
25	1.30
26	1.65
27	2
28	2.50
29	3.05
30	3.80

Table 4.4: Correction factor (a) value for different specific gravity of soil samples (ASTM D422).

Specific gravity of soil solids g/cm^3	Correction factor (a)
2.85	0.96
2.80	0.97
2.75	0.98
2.70	0.99
2.65	1.00
2.60	1.01
2.55	1.02
2.50	1.04

4.2.3 Liquid limit test

The liquid limit is an empirically determined water content at which soil passes from liquid state to plastic state. Cone penetrometer test was chosen for liquid limit determination. In this study, the standard used for performing this test is British Standards BS 1377-2. During the test, oven dried samples, which are retained on 0.425 mm sieve, have been removed and roughly 300 g of sample was picked for the test. The equipment required for performing this test are as follows:

- A penetrometer with an approximately 35 mm long cone of stainless steel or duralumin, with a smooth, polished surface and an angle of 30 degrees ± 1 (Figure 4.4)
- One or more metal cups with the diameter of 55 ± 2 mm and depth of 40 ± 2 mm
- A wash bottle containing distilled water
- A glass plate
- A spatula

Figure 4.4 Cone penetrometer device used in testing**.**

After preparing the sample and equipment, 300 grams of sample is taken and mixed with proper amount of distilled water for approximately 10 minutes. Then, a portion of mixed soil is pushed into the cup taking care not to trap air and excess soil is stroked off, to give it a smooth surface level, and placed under the cone. It is important that when the cone is in the correct position a slight movement of the cup should leave just a mark on the soil surface. After placing the cup in the correct position and pushing the button on the device, the first penetration value is recorded. The test should continue with different water contents until the desired value of penetration, 20 mm for liquid limit, is reached. The amount of added water should be such that penetration values of approximately 15 mm to 25 mm is covered by four or more test runs and the values are evenly distributed. For each penetration value recorded, a sample of about 10 grams is measured for water content. After determining the moisture content of

samples, a graph of cone penetration versus moisture content is created and the moisture content corresponding to a cone penetration of 20 mm is reported as the liquid limit of the soil sample.

4.2.4 Plastic limit test and plasticity index determination

The plastic limit of a soil is the moisture content, expressed as a percentage of the weight of the oven-dried soil, at the boundary between the plastic and semisolid states of consistency (Figure 4.5). The standard for this test is given by ASTM D 4318. The plastic limit is alternatively determined by pressing and rolling a small portion of plastic soil into a 3.2 mm diameter thread until its water content is reduced to a point at which the thread is crumbled and could no longer be pressed together and re-rolled. The water content of the soil at this point is reported as the plastic limit value.

The plasticity index is also calculated as the difference between the liquid limit and the plastic limit values.

Figure 4.5 Plastic limit test.

4.2.5 Specific gravity

Specific gravity of the soil is determined by using a pycnometer. Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. The standard for this test is given by ASTM D 854-14 and requirement equipment used are as follows:

- Pycnometer
- Balance
- Vacuum pump
- Funnel
- Spoon

The weight of the empty clean and dry pycnometer (W_P)is determined and 10 g of a dry soil sample is placed in the pycnometer. The weight of the pycnometer containing the dry soil (W_{PS}) is determined and recorded. distilled water is added to fill about half to three-fourth of the pycnometer and then sample is soaked for 10 minutes. A partial vacuum is applied to the contents for 10 minutes to remove the entrapped air and then vacuum is stopped and the vacuum line removed from the pycnometer. Thereafter, the pycnometer is filled with distilled water and the exterior surface is cleaned and dried. The weight of the pycnometer and contents (W_B) is determined. Subsequently, the pycnometer discharged, cleaned and filled with distilled water and the exterior surface is cleaned. Lastly the weight of the pycnometer and distilled water is determined. The specific gravity of the soil is calculated using the following

formula:

$$G_S = \frac{W_0}{W_0 + (W_A + W_B)} \quad \textbf{(4.9)}$$

Where:

W_0 = weight of sample of oven-dry soil, g = $W_{PS} - W_P$, (g)

W_A = weight of pycnometer filled with water, (g)

W_B = weight of pycnometer filled with water and soil, (g)

4.3 Foam Characterization Tests

4.3.1 Foam generator

All the tests relating to foam were performed by laboratory type foam generator at Istanbul Technical University, Mining Engineering Department, soil conditioning laboratory. The generator was designed and produced by soil conditioning group in Mining Engineering Department together with IKSA construction chemicals company in Ankara (Figure 4.6). The foam generator is capable of producing foams with different FER and C_F values by adding foaming solution manually. The foam lens of the generator is filled with plastic beads which can produce foam in the range between 2 and 4 bars of air pressure.

Figure 4.6 Laboratory type foam generator in ITU soil conditioning laboratory.

4.3.2 Foam characterization

Foam characterization test is essential due to the fact that observing the behavior of soil+foam mixtures and its effects on conditioning and EPB TBM performance requires determining characteristics of materials used in conditioning operation.

In this study, density and half-life of the foam were determined as fundamental characteristics of foam.

4.3.2.1 Density of foam

The density of the foam was determined using a cylinder the volume of which is known. The cylinder was filled with the foam and then it was weighted using a scale with accuracy of 0.1 g. The density of foam is calculated using the following formula:

$$D_{foam} = {}^{m_{foam}}/_{v_{foam}} \ , \qquad ({}^{g}/_{cm^3}) \tag{4.10}$$

Figure 4.7 Determination of foam density.

4.3.2.2 Foam half-life

Since it is a significant factor during conditioning operation, stability of foam is also determined during foam characterization tests. The suggested instructions for half-life test is given by EFNARC 2005 and the required equipment used are as follows:

- A filter funnel of 1-liter capacity with a non-absorbent filter
- A graduated container of 1 or 2-liter capacity made from plastic or non-breakable material
- A 50 ml graduated cylinder

- A retort stand
- A foam generator
- Weighing balance with accuracy of 0.1 g
- Stopwatch
- Foaming agent
- Distilled water

After preparing the equipment, test is carried out by making solution of foaming agent in distilled water. 80 g of foam generated with different FER and C_F values is filled into the filter funnel and the time required for drainage of 40 ml of liquid into the lower cylinder is measured (Figure 4.8).

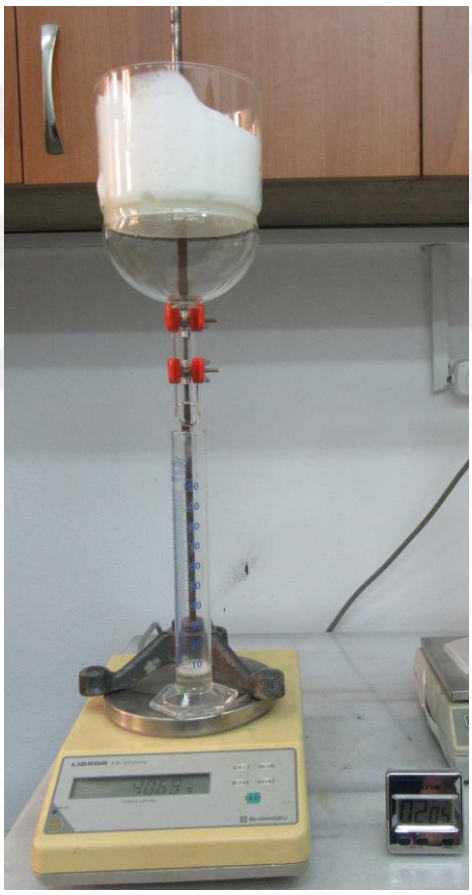

Figure 4.8: Half-life test.

4.4 Soil+foam and Soil+water Mixture Tests

After determination of characteristics of both soil sample and foam, soil+foam and soil+water laboratory tests were carried out with the purpose of observing the effectiveness of foam and water on soil behavior. Mixing with measuring power

requirement, cone penetration test, and flow table test have been carried out and the results recorded with the goal of improving the performance of EPB machine in this study. It should be mentioned that regarding the clayey behavior of sample and its sticky properties, 2 types of foam with anticlay properties were used in this study.

4.4.1 Mixing test with power measurement (Quebaud 1998)

Mixing test starts by taking 1500 g of oven-dried soil sample and mixing it with a desired amount of distilled water (Figure 4.9) until it becomes completely homogeneous. Using a foam generator, the desired amount of foam is added to the soil (FIR) and mixed with the mixer until a homogeneous mixture was achieved. The amount of power required to mix the foam with the soil is measured and recorded. Upon stopping the mixer, the blade is carefully uninstalled and weighed in order to determine the amount of sample sticking on the blade.

Figure 4.9: Mixing test equipment.

4.4.2 Cone penetration test

Penetration tests on soil+ foam and soil+water mixture are carried out in order to determine the desirable consistency of the conditioned sample. For this reason, approximately 1000 g of oven-dried sample is mixed with a known amount of water until it becomes homogenous. Then, the desired amount of foam is added and mixed until it reaches homogeneous consistency. Without wasting time, about 60 g of mixed

soil is taken for cone penetration test and test is carried out as it is in liquid limit test and penetration value for different amounts of FIR values are recorded.

4.4.3 Flow table test

The flow table test is performed in accordance with DIN EN 12350-5 standard. In this test, the sample is placed in a 5 lt mixer, an arbitrary amount of water or foam is added to it, and it is placed inside the cone shaped mold (Figure 4.10). Thereafter, the mold is removed and vibrating plate is dropped within roughly 15 seconds. The diameter of sample after 15 drops is measured and the changing amount are reported as flow table test value.

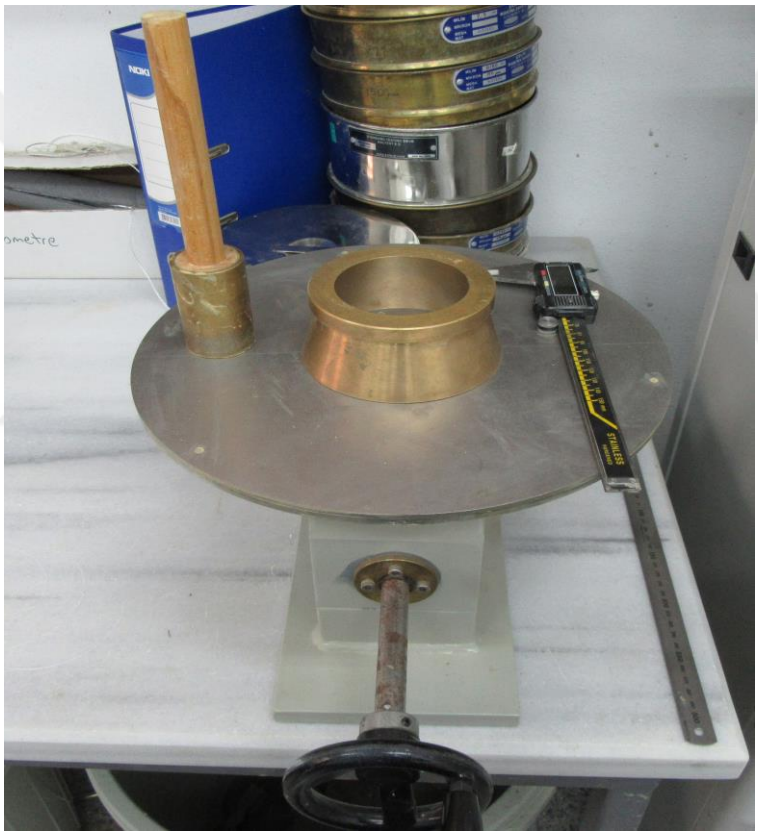

Figure 4.10: Flow table test device.

5. RESULTS OF THE EXPERIMENTAL STUDIES

5.1 Introduction

This chapter presents results obtained from laboratory tests the procedure of which was presented in the previous chapter. All of the tests in this study were conducted at the Istanbul Technical University, Mining Engineering Department, Soil Conditioning Laboratory. The chapter consists of 3 main parts. The first part presents soil characterization test results, the second part presents foam or anticlay characterization test results and the third part presents results of mixture tests.

5.2 Soil Characterization Test Results

5.2.1 Natural water content

The natural water content of the soil sample taken from Zeytinburnu-Ayvali2 waste water tunnel project is determined to be around 33%. The results of natural water content for 3 specimens of the soil sample batch is given in Table 5.1.

Table 5.1: Natural water content of the soil sample

M_C	M_{CDS}	M_{CMS}	M_S	M_W	W%
18.60	50.10	60.50	31.50	10.40	33.01
18.00	58.00	71.2	40.00	13.20	33.00
18.00	64.4	79.80	46.40	15.40	33.20

5.2.2 Grain size distribution

5.2.2.1 Sieve analysis results

Sieve analysis of the soil sample was performed by using mechanical shaker and amount of sample retained on each sieve are presented in Figure 5.1.

Figure 5.1: Photograph of the samples retained on sieves.

Using sample weights, the retaining percentage of the sample on each sieve was recorded and is presented in Table 5.2.

Table 5.2: Results of the sieve analysis.

Diameter (mm)	Soil retained(g)	Percent retained	Percent passing
+9	0	0	100
+4.75	83.08	24.10	94.46
+2	52.27	15.17	90.97
+0.85	26.39	7.66	89.21
+0.425	21.65	6.28	87.77
+0.25	12.54	3.64	86.93
+0.15	36.18	10.50	84.52
+0.075	97.66	28.33	77.01

5.2.2.2 Hydrometer analysis results

Using the results of the sieve analysis, hydrometer analysis performed for soil samples finer than 0.075 mm and the results are presented in table 5.3. Using table 5.2, the grain size distribution graph has been drawn (Figure 5.2). Analyzing the semi logarithmic plot shows that the sample contains around 80 percent of fines which means 80 percent of clay+silt.

Table 5.3: Results of the hydrometer analysis.

Time (min)	Act reading	Temperature °C	meniscus	L	k	D(mm)	C_t	a	R_c	P	Pa (%)
0.5	54	21	55	7.3	0.01348	0.05151	0.2	1	47.2	94.4	73.632
2	53.5	21	54.5	7.35	0.01348	0.02584	0.2	1	46.7	93.4	72.852
4	51.5	21	52.5	7.7	0.01348	0.01870	0.2	1	44.7	89.4	69.732
6	50.5	20.8	51.5	7.85	0.01348	0.01542	0.2	1	43.7	87.4	68.172
8	49.5	20.8	50.5	8	0.01348	0.01348	0.2	1	42.7	85.4	66.612
15	48	20.5	49	8.3	0.01357	0.01009	0.1	1	41.1	82.2	64.116
30	45	20.1	46	8.8	0.01365	0.00739	0	1	38	76	59.28
60	42	19.5	43	9.2	0.01374	0.00538	0.15	1	34.85	69.7	54.366
120	38	18.4	39	9.9	0.01391	0.00399	-0.4	1	30.6	61.2	47.736
1380	28	16.5	29	11.5	0.01426	0.00130	-0.8	1	20.2	40.4	31.512
1440	27	16.5	28	11.7	0.01426	0.00129	-0.8	1	19.2	38.4	29.952

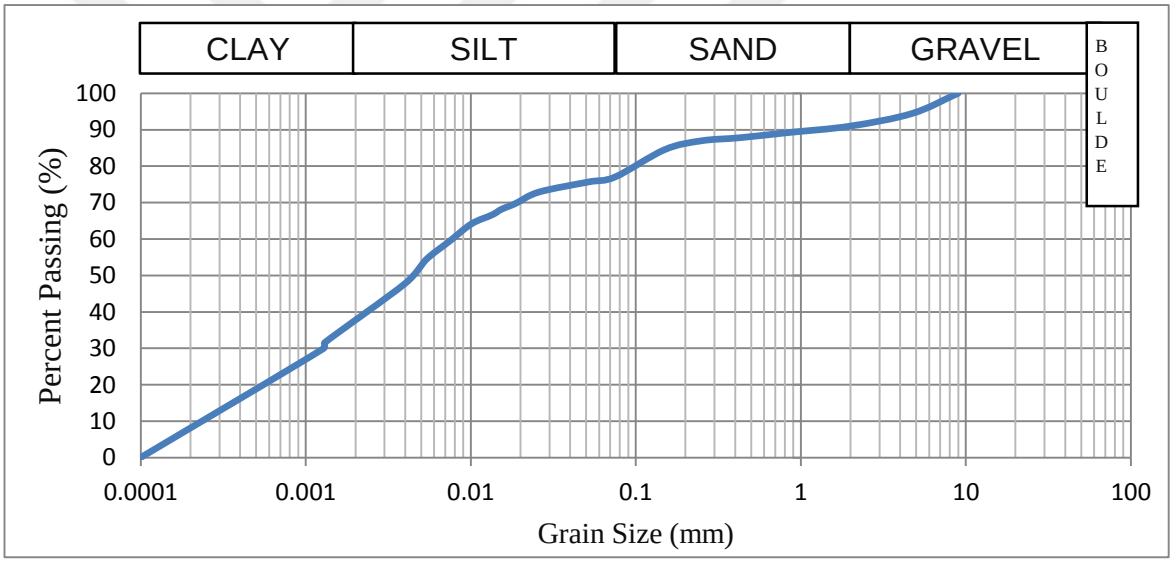

Figure 5.2: Grain size distribution of the sample.

Analyzing the grain size distribution graph, the following parameters are ascertained:

Clay%=38 Silt%=38 Sand%=14.1 Gravel%=9.9

Moreover, place of the soil sample on application range of the EPB TBMs and suggested conditioning chart (Budach and Thewes 2015) is located and illustrated with red line on Figure 5.3.

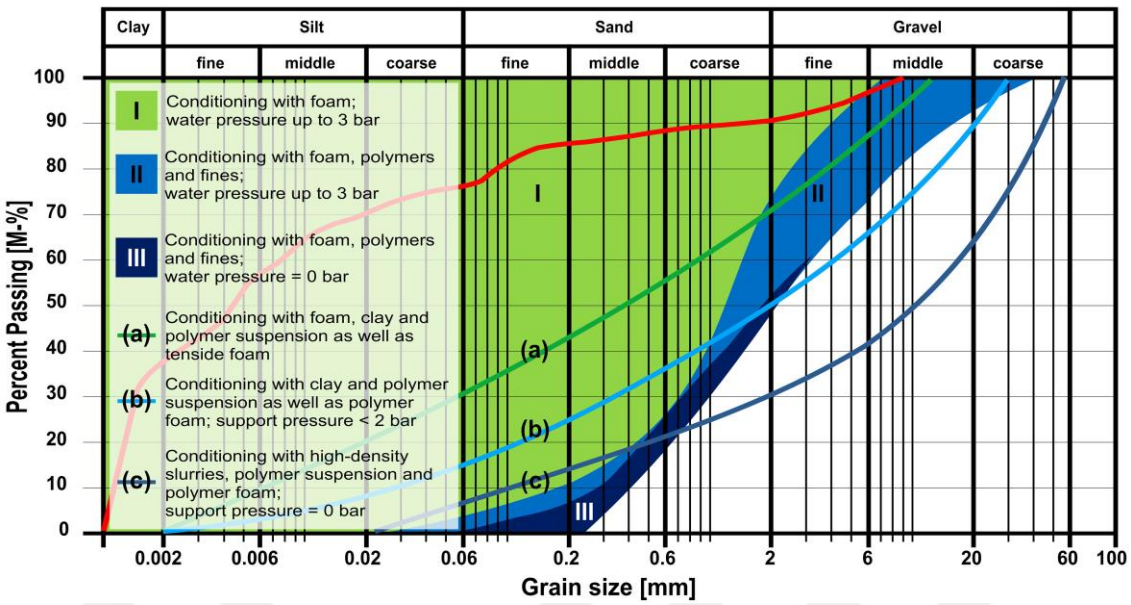

Figure 5.3: The place of soil sample on application range of EPB TBMs and suggested conditioning based on laboratory research suggested by Budach and Thewes (2015).

5.2.3 Liquid limit and plastic limit test results

The penetration amount reaches to 20 mm at water content of 54.4% which represents the liquid limit value. The results for a set of tests while determining the liquid limit are given in Figure 5.4.

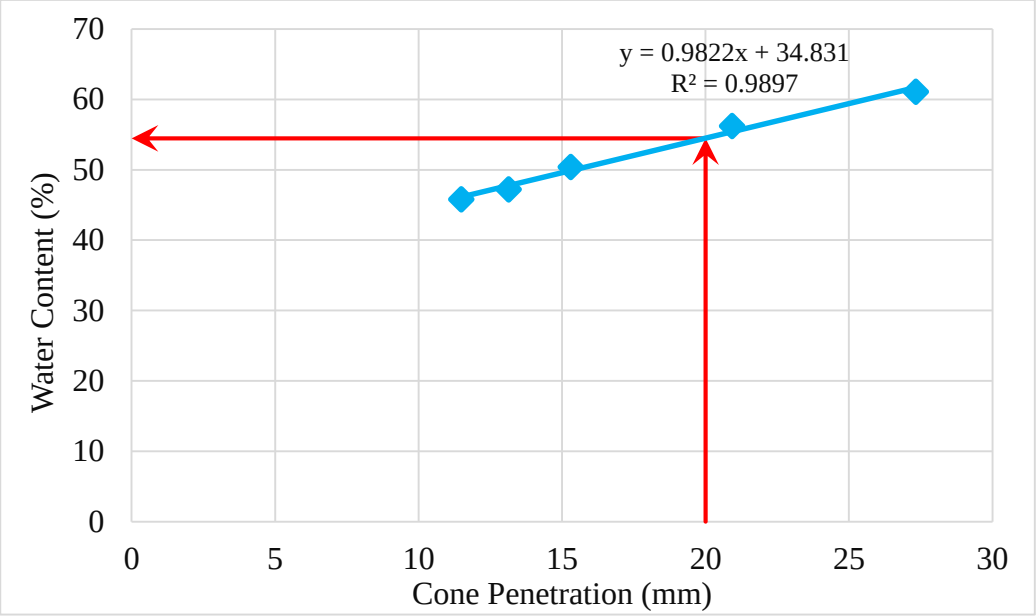

Figure 5.4: Variation of water content with cone penetration.

On the other hand, plastic limit is determined as being 29.7%. Thus plasticity and consistency indexes are estimated as follows:

$$Pi = LL - PL = 54.4 - 29.7 = 24.7\ \% \quad \textbf{(5.1)}$$

$$Ci = (LL - W)/(LL - PL) = (54.4 - 33)/(24.7) = 0.86 \quad \textbf{(5.2)}$$

Using plasticity index and liquid limit, the place of the soil sample in plasticity chart is located (Figure 5.5) which indicates that the soil sample is inorganic clay of high plasticity.

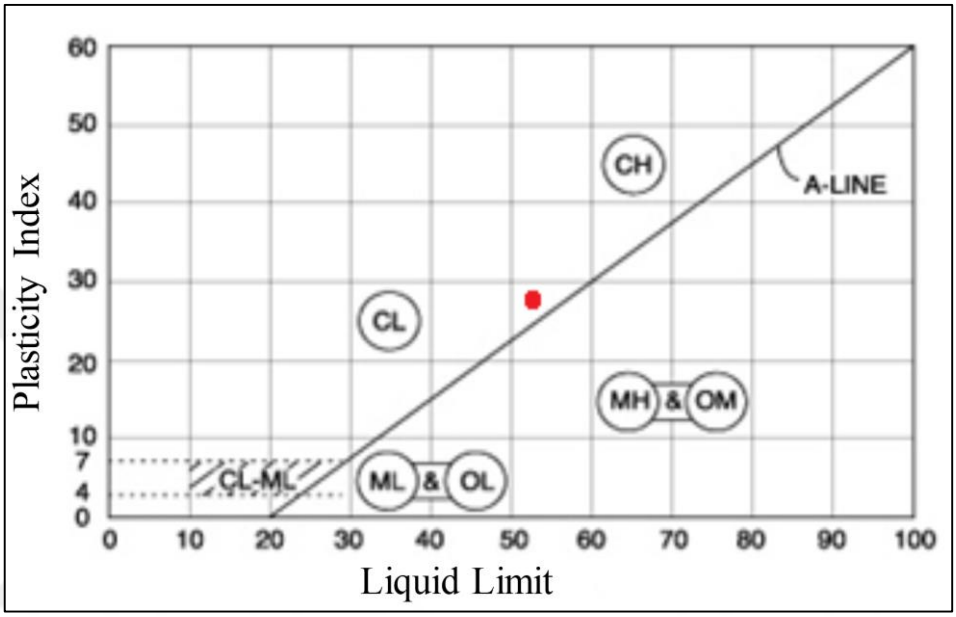

Figure 5.5: Place of the sample on the plasticity chart.

Furthermore, the place of the sample on clogging risk chart (Figure 5.6) and consistency chart for open mode EPB applications (Figure 5.7) given by Holmann and Thewes (2013) are presented in order to give more information about clogging potential and consistency of the sample. From Figure 5.6, it can be inferred that the sample is stiff and has a medium to high potential for clogging. On the other hand, analysis of the chart given in Figure 5.7 using the available data, reveals that the natural water content of the sample should be increased by roughly 12% additional water in order to reach the desired consistency.

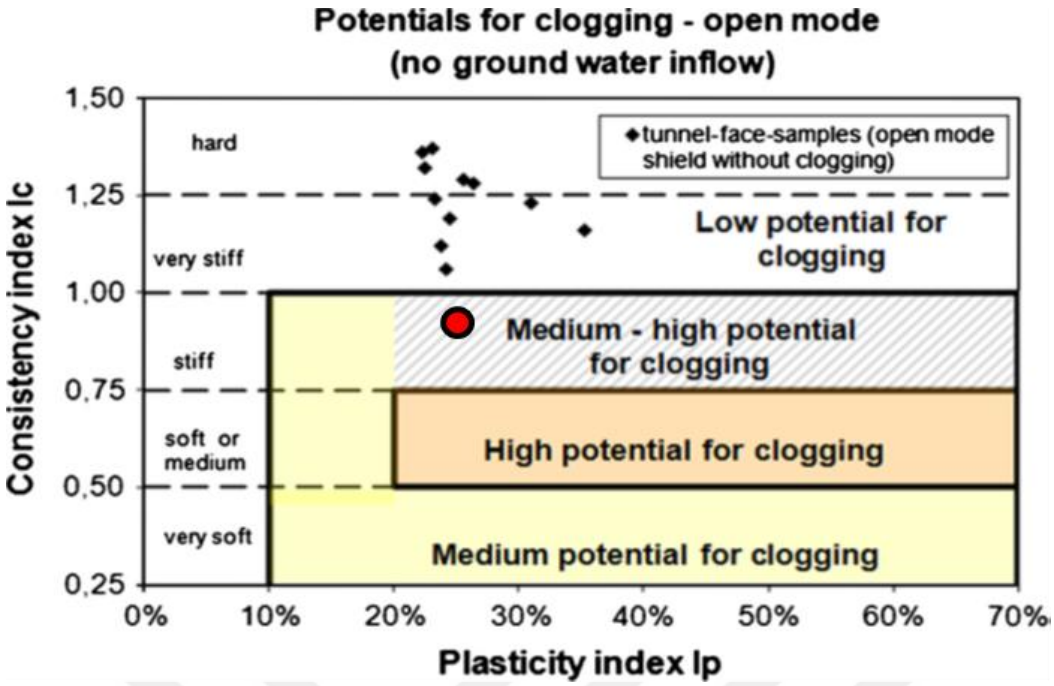

Figure 5.6: Place of the sample on the clogging risk chart given by Holmann and Thewes (2013).

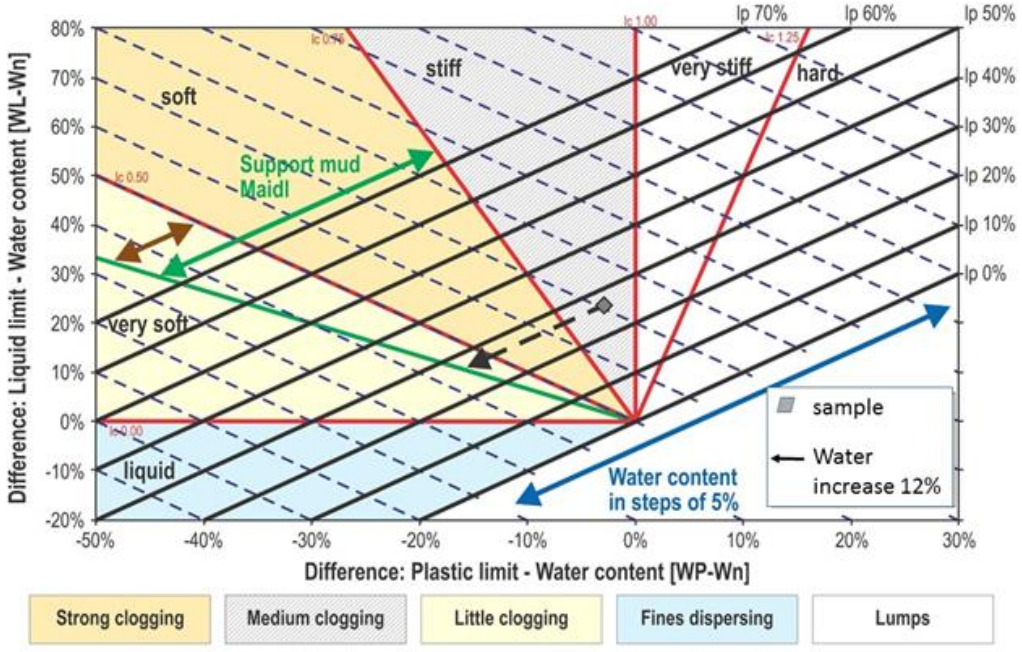

Figure 5.7: Place of the sample in the consistency chart for open mode EPB applications given by Hollman and Thewes (2013).

5.2.4 Specific gravity test result

The results of determination of the specific gravity of the soil sample is presented in Table 5.4.

Table 5.4: Specific gravity determination data sheet.

Specimen number	1
WP =Mass of empty, clean pycnometer	38.40 g
WPS =Mass of empty pycnometer + dry soil	63.49 g
WB = Mass of pycnometer + dry soil + water	153.61 g
WA = Mass of pycnometer + water	137.37 g
Specific gravity	2.65

5.3 Foam Characterization Test Results

Density and half-life tests were performed to characterize the foaming agents used in this study. Foam characterization tests were carried out on two different types of anticlay produced by different companies and the detailed results of the tests are presented in this chapter. Exfoam 2 from IKSA construction chemicals and ACP 143 from BASF were used as anticlay agents (foam+polymer) in order to observe the effect of different agents on the soil sample.

5.3.1 Exfoam 2

5.3.1.1 Density

Density was determined for 3 different anticlay concentrations (3%, 4%, 5%) and foam expansion ratios (8.5, 11, 16). Table 5.5 shows the reaction of density to changes of C_F and FER values.

Table 5.5: Density values of Exfoam 2 for 3 different C_F and FER values.

FER	C_F=3%	C_F=4%	C_F=5%
8.5	0.046	0.042	0.046
11	0.025	0.024	0.025
16	0.018	0.016	0.019

5.3.1.2 Half-life

Half-life tests were also carried out for 3 different anticlay concentrations (3%, 4%, 5%) and FER values (8.5, 11, 16). Figures 5.8, 5.9, and 5.10 show the results for variation of drainage time with drainage amount at C_F of 3, 4 and 5% for 3 different FER values (16, 11 and 8.5).

Figure 5.8 shows the amount of drainage with respect to drainage time for FER values of 8.5, 11 and 16 while anticlay concentration is fixed at 3%. Based on Figure 5.8, it may be inferred that drainage amount is directly proportional to drainage time. Moreover, the half-life is determined to be 600, 660 and 792 seconds for FER values of 8.5, 11 and 16 respectively. In other words, half-life of the conditioning chemical increases with increasing FER.

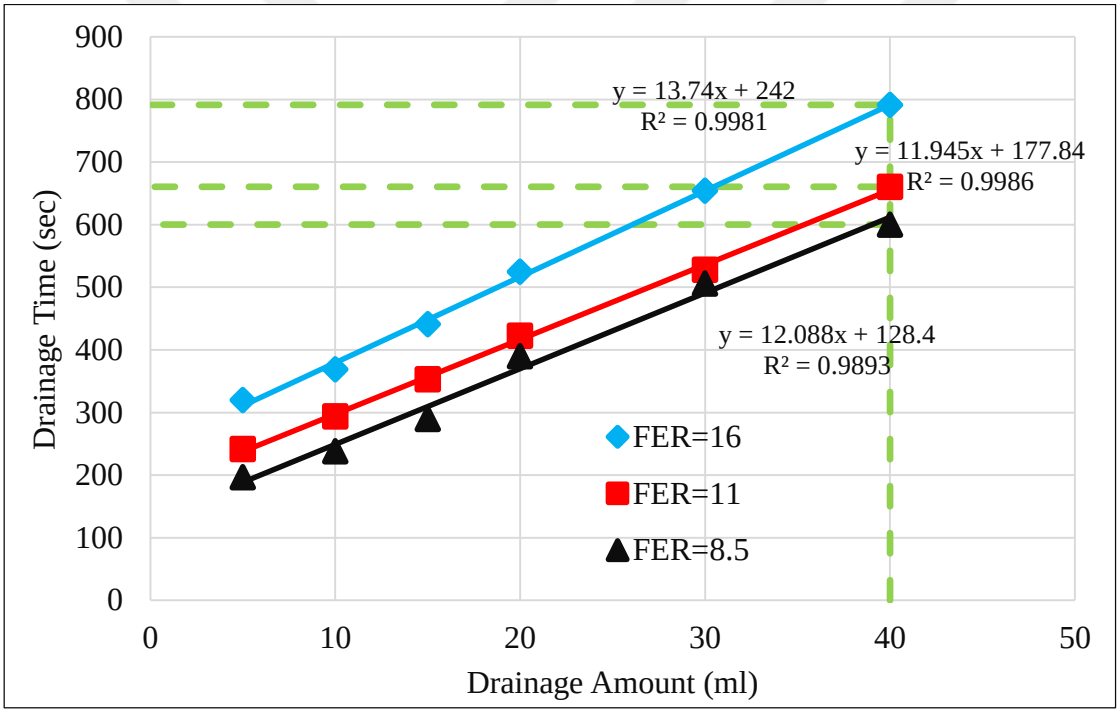

Figure 5.8: Variation of drainage time with drainage amount at CF of 3% for different FER values (Exfoam 2).

The following graph (Figure 5.9) shows the relationship between drainage amount and drainage time while C_F is 4%. As Figure 5.9 demonstrates, half-life increases from 530 to 620 and finally to 734 seconds for 8.5, 11 and 16 FER values, respectively.

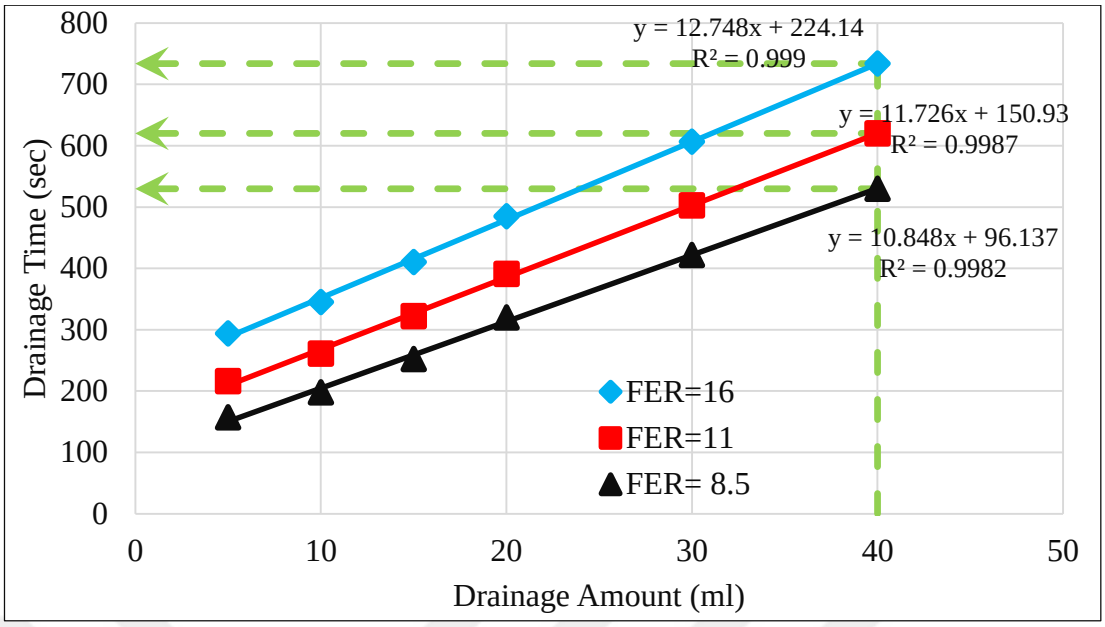

Figure 5.9: Variation of drainage time with drainage amount at CF of 4% for different FER values (Exfoam 2).

Figure 5.10 shows the relationship between drainage amount and drainage time while C_F is fixed at 5%. The half-life values for FER of 8.5, 11, 16 are 493, 568 and 696 seconds respectively.

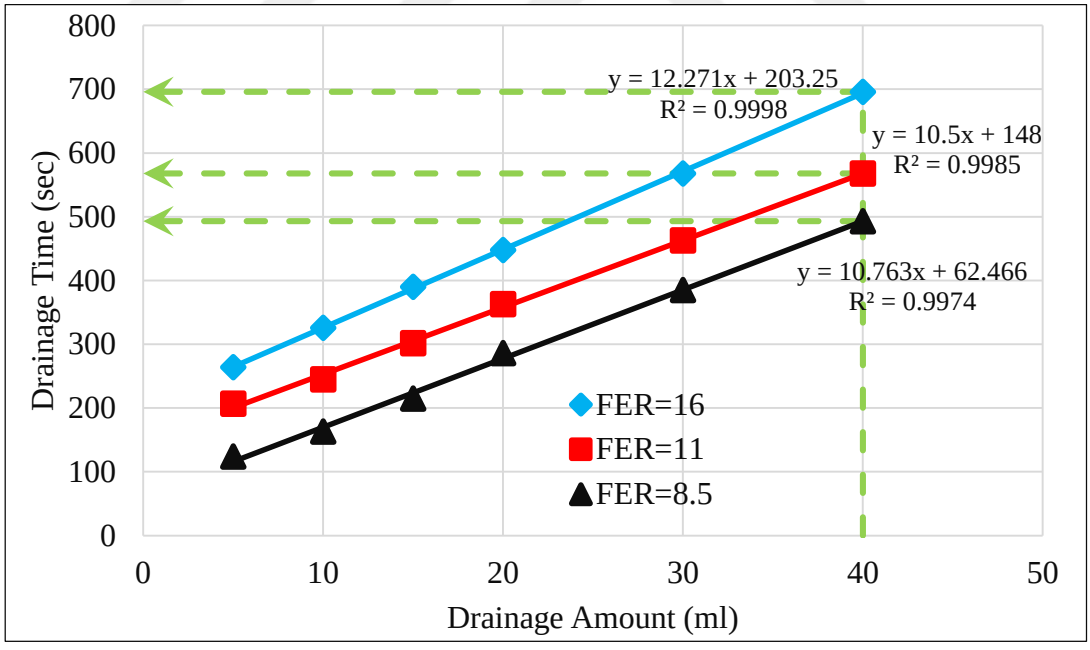

Figure 5.10: Variation of Drainage time with drainage amount at CF of 5% for different FER values (Exfoam 2).

The relationships between half-life of the anticlay and C_F for different FER values are presented in Figure 5.11. As it is shown on the graph, for a fixed value of FER, Half-life decreases by increasing C_F. As it can be understood from the graph, half-life amount decreases with increasing the C_F and decreasing the FER amount.

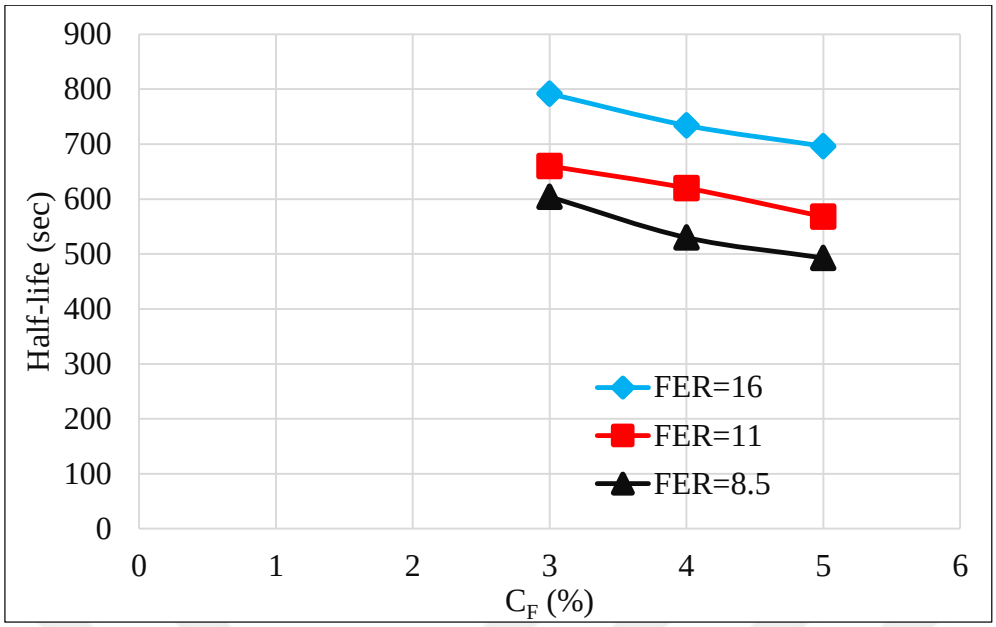

Figure 5.11: Variation of half-life with anticlay concentration for different FER values (Exfoam 2).

5.3.2 ACP143

5.3.2.1 Density

Density measurements for ACP143 are presented in Table 5.6 for different C_F values.

Table 5.6: Anticlay density values of ACP 143 for 3 different C_F and FER values.

FER	C_F=3%	C_F=4%	C_F=5%
8.5	0.041	0.040	0.039
11	0.022	0.022	0.022
16	0.017	0.018	0.019

5.3.2.2 Half life

Similar to the previous tests conducted on Exfoam 2, the tests were performed for 3 different C_F and FER values. The results are shown in Figures 5.12, 5.13, 5.14.

Figure 5.12 shows drainage amount versus drainage time for 3 different FERs when C_F is held constant at 3%.

As it can be understood from the graph, half-life slightly increases as FER rises. The half-life value for FER of 8.5, 11 and 16 are 466, 684 and 761 seconds respectively.

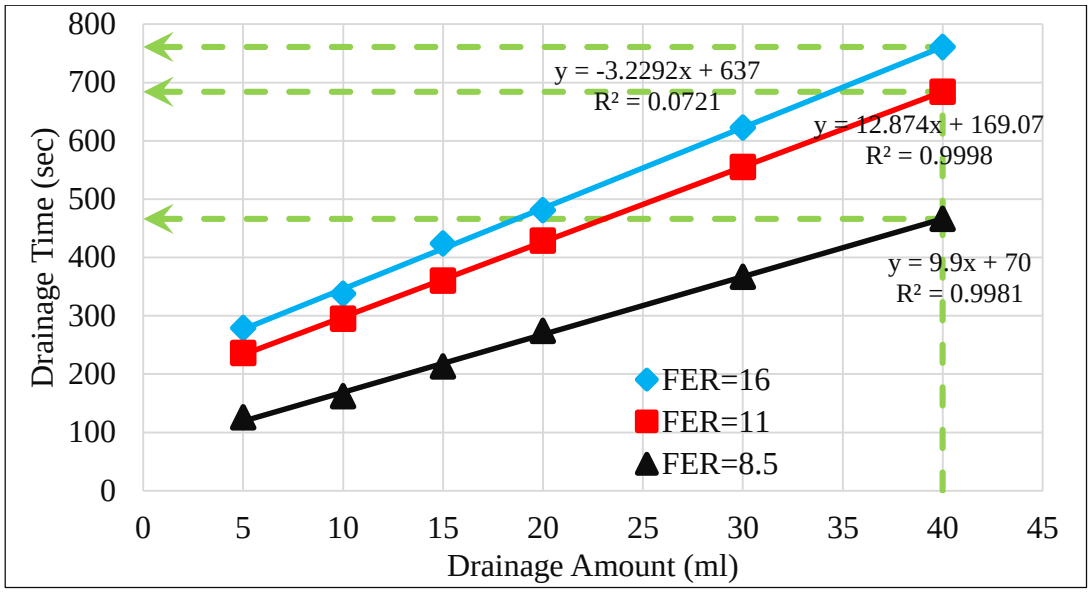

Figure 5.12: Variation of Drainage time with drainage amount at CF of 3% for different FER values (ACP 143).

Figure 5.13 presents the drainage amount changes in contrast to drainage time for C_F of 4%. The half-life value for FER of 8.5, 11, 16 are 464, 670 and 742. seconds respectively.

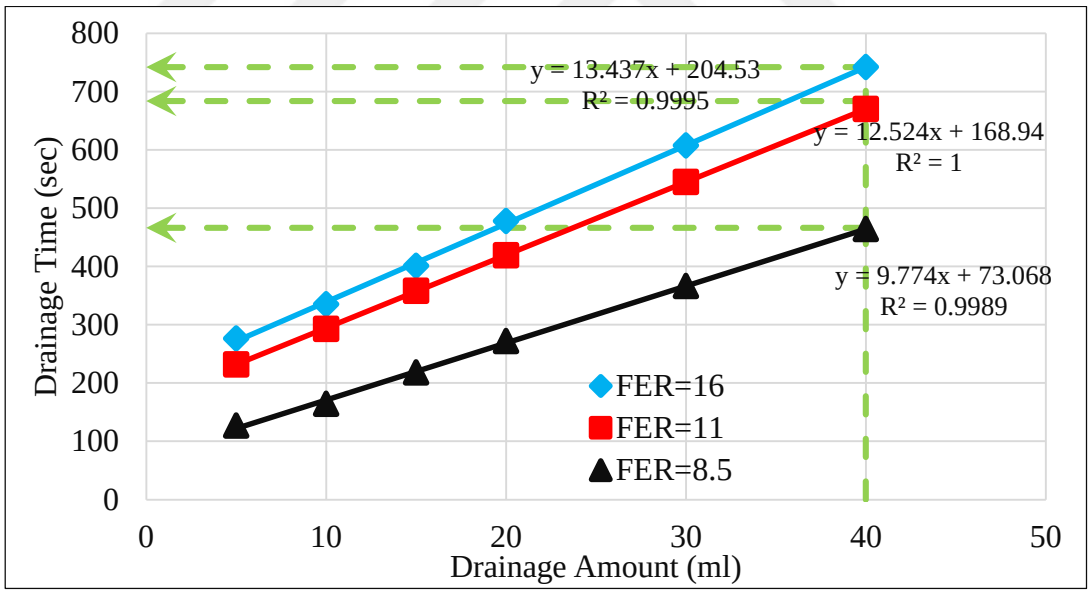

Figure 5.13: Variation of Drainage time with drainage amount at CF of 4% for different FER values (ACP 143).

Figure 5.14 shows drainage amount versus drainage time for C_F of 5 % and different FER amounts. As the graph demonstrates, the half-life for FER of 8.5, 11, 16 is 466, 661 and 737 seconds respectively.

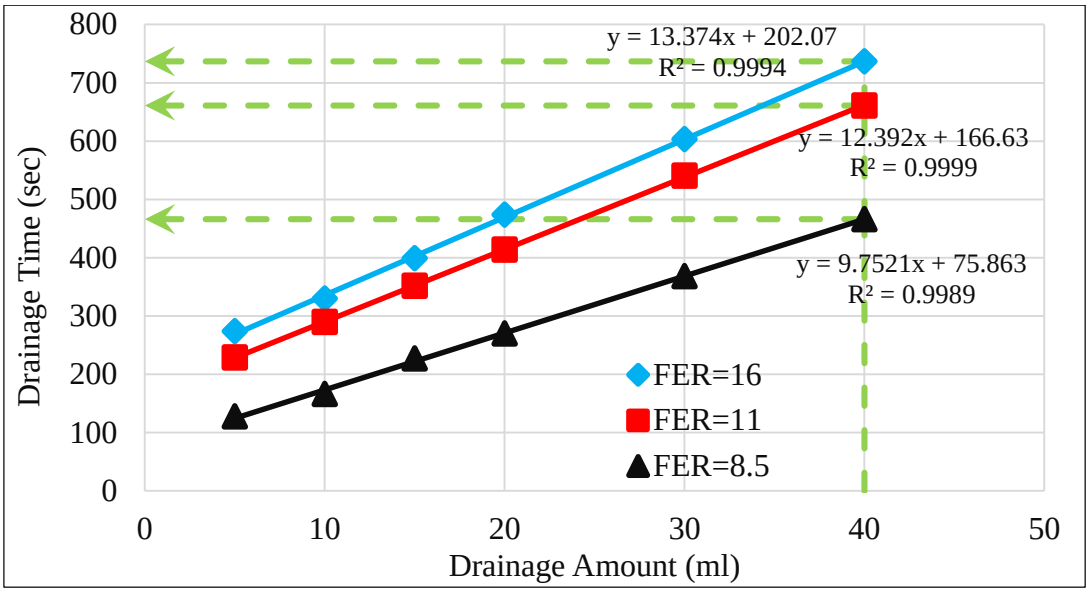

Figure 5.14: Variation of Drainage time with drainage amount at CF of 5% for different FER values (ACP 143).

The relationship between half-life and C_F for different FER values is given in Figure 5.15. For a fixed value of FER, drainage amount is not changed notably by increasing C_F.

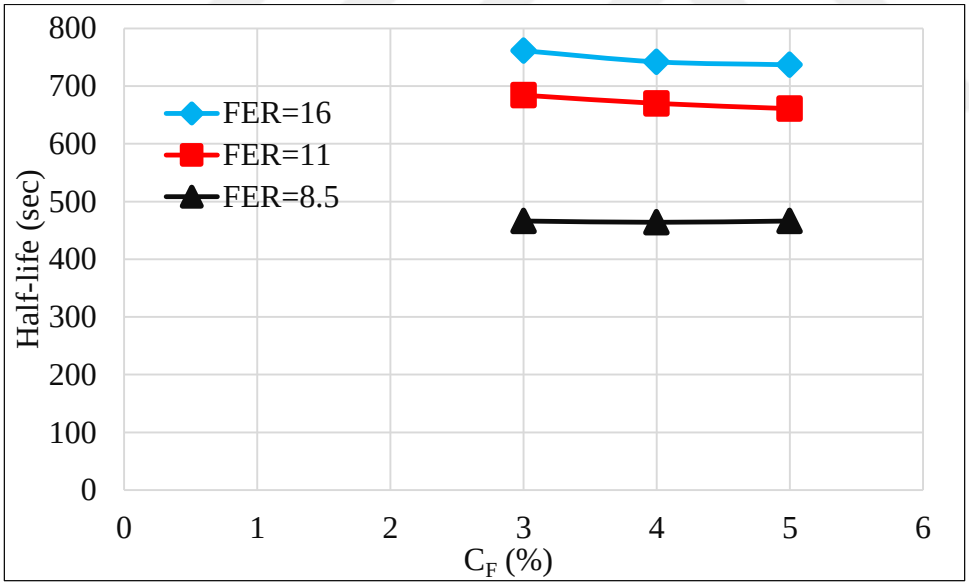

Figure 5.15: Variation of half-life of anticlay with CF for ACP 143.

5.3.3 Comparison of the anticlay agents

The relationships between half-life and C_F for different FER values and 2 types of anticlay agents (ACP 143 and Exfoam 2) are given in Figure 5.16. For Exfoam 2 the reduction of half-life by increasing C_F is more remarkable. The relationships between density and C_F for different FER values and 2 types of anticlay agents (ACP 143 and Exfoam 2) are presented in Figure 5.17. As it can be seen from Figure 5.17, density of

Exfoam 2 for all C_F values is higher than ACP 143 except for C_F of 4 % and 5% at FER of 16. For FER of 16, C_F of 4% density of ACP 143 is higher than Exfoam 2 and for the same FER and C_F of 5% the density values are almost the same for Exfoam 2 and ACP 143.

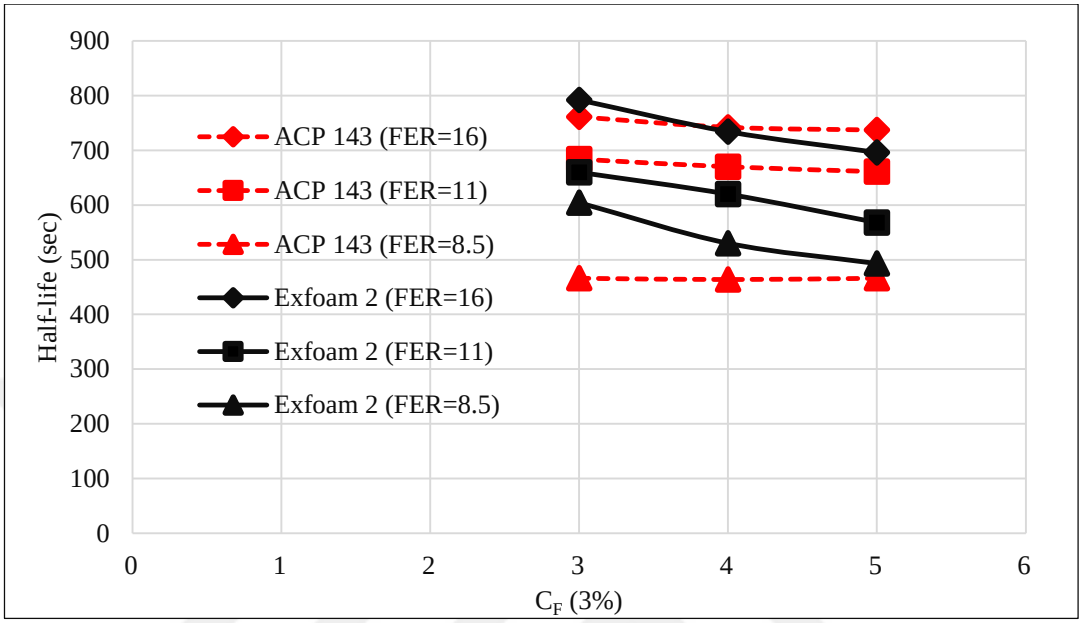

Figure 5.16: Variation of the half-life with C_F for Exfoam 2 and ACP 143.

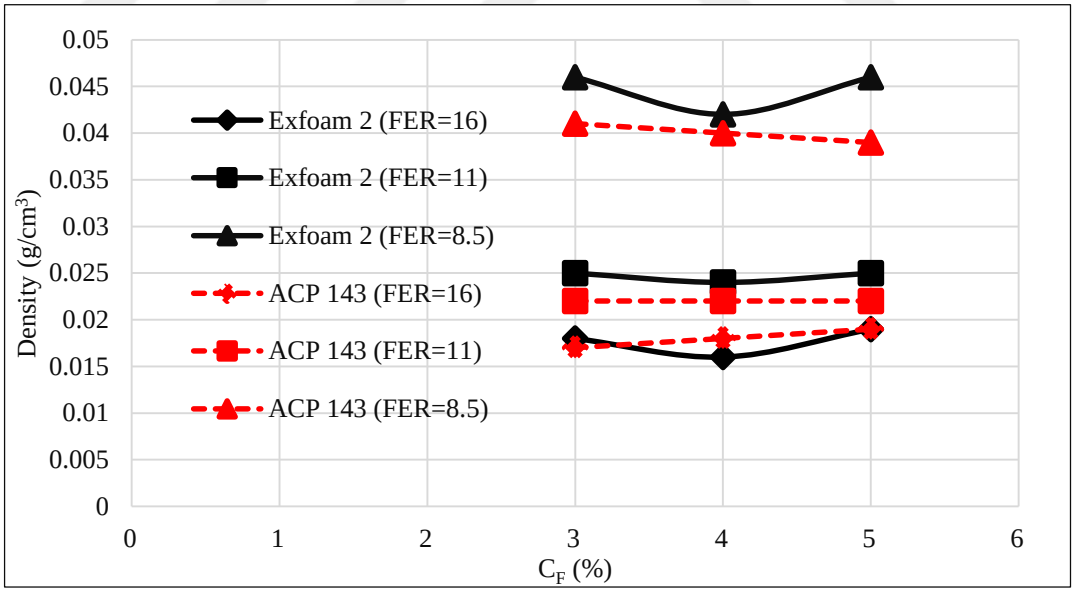

Figure 5.17: Variation of the density with C_F for Exfoam 2 and ACP 143.

5.4 Mixture Tests

The mixture tests were carried out to determine the characteristics of soil when mixed with anticlay or water. Firstly, the tests were carried out with just adding distilled water with required amount to the soil in order to observe the soil behavior when there was

only water and no additional chemical agents. Subsequently, the tests on the mix of soil with 2 different anticlays (Exfoam 2 and ACP 143) from different companies were performed as well as tests on the mix of the soil with anticlay and water.

5.4.1 Soil+water tests

Conditioning tests were performed on the mix of soil and water. Firstly, the water content was set to 33% which is the natural water content of the soil. At the next stages, more amounts of distilled water were added and parameters such as net power requirement for mixing the mixture of the soil and water, the sticking amount on the mixer's blade, cone penetration index, and spreading amount in flow table were measured at each water content. Net power requirement is estimated by subtracting the power recorded in idle position from the power recorded during the test.

5.4.1.1 Mixing tests with power measurement

Mixing tests started with the natural water content of the soil (33%), however because of sticking behavior of the sample, it did not appropriately mix and get a value from wattmeter. Thus, by adding more distilled water, the water content was increased and the tests were performed. Figure 5.18 shows power requirement for mixing soil with different water contents.

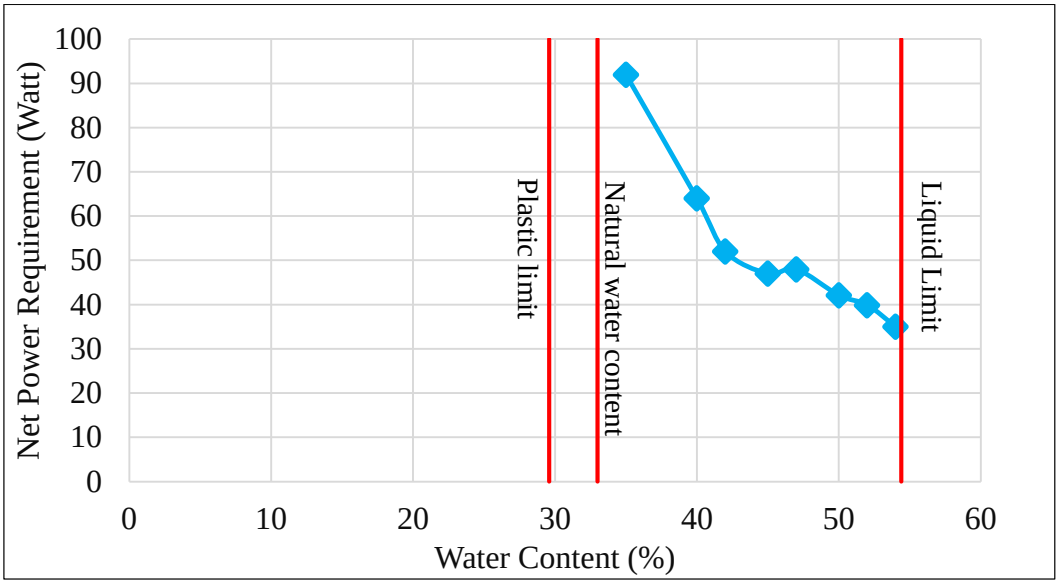

Figure 5.18: Variation of net power requirement with water content in mixing tests (only water).

As it is shown in Figure 5.18, the net power requirement for water content of 35% is determined to be 92 W. Power requirement associated with water content between

35% and 45 % decreases sharply and then slightly to 54%. When the water content reaches to 54%, power requirement is equal to 35 W, which is almost half of the power requirement for 35% of water content (starting point).

5.4.1.2 Sticking amount (adhesion to mixing blade)

While mixing the soil with water, the amount of the soil sample that stuck on the mixer's blade was measured in order to determine stickiness of the sample. Tests were carried out at each water content tested with the mixer to observe changes of sticking soil amount.

Figure 5.19 shows the amount of sticking soil for different water contents. As it can be clearly seen in the graph, from water content of 35% to 45% soil amount remaining on blade is almost the same. After adding 12% of water to the natural water content of the soil sample (45% total water content), sticking decreases sharply down till liquid limit value (54%). The lowest value of sticking, which is around 295 g, is associated with water content of 54%.

The amount of sample remaining on the blade for all 8 testing points presented in Figure 5.19 is depicted in Figure 5.20.

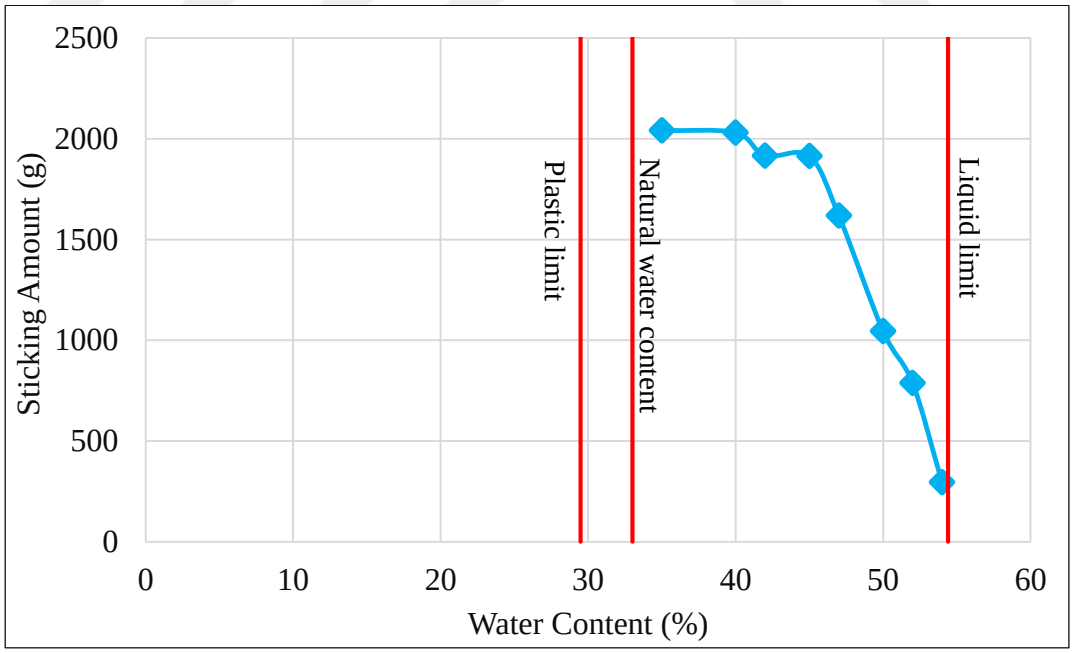

Figure 5.19: Variation of sticking amount with water content in mixing tests (only water).

Figure 5.20: Photographs of sticking material on mixing blade for each test (only water).

5.4.1.3 Cone penetrometer tests

The results of the cone penetrometer tests are summarized in Figure 5.21. as it is seen there is a linear relationship between cone penetration and water content.

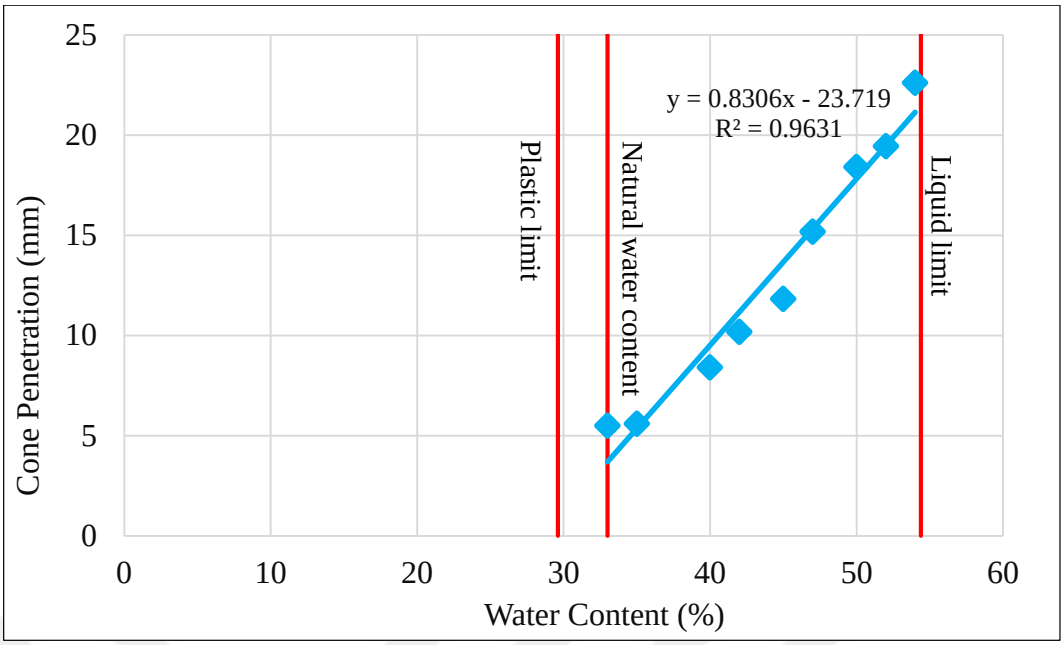

Figure 5.21: Variation of cone penetration amount with water content (only water).

5.4.2 Mixture of soil + Exfoam2 tests

5.4.2.1 Mixing test with power measurement

Soil+Exfoam2 mixing tests were carried out at water content of 35%, FER of 16 and C_F of 3% and with varying FIR amounts. The results are given in Figure 5.22 as a line graph where the power requirement decreases slightly from 87 to 44 Watts for changing FIR values from 50 to 400 %.

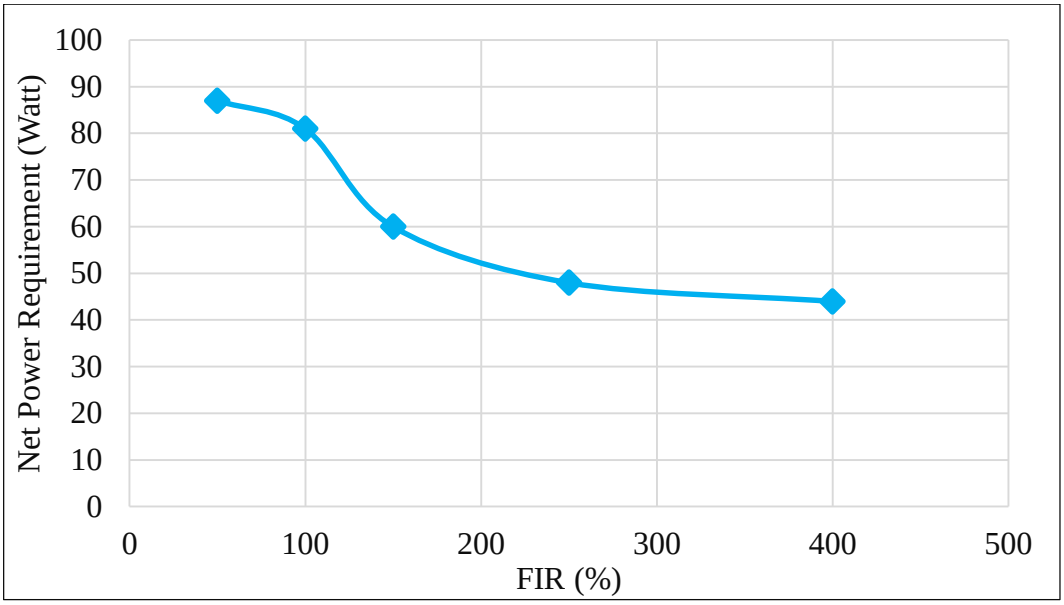

Figure 5.22: Variation of net power requirement with FIR values at water content of 35 %, FER of 16, and C_F of 3% (Exfoam 2).

5.4.2.2 Sticking amount (adhesion to mixing blade)

Figure 5.23 indicates the sticking soil amount associated with different FIR values. As it is shown on the graph, there is not a significant decrease in amount of sticking with increasing FIR values when using Exfoam2. Sticking on the mixer's blade decreased from 1958 g to 1570 g when FIR increased from 50 to 400 %.

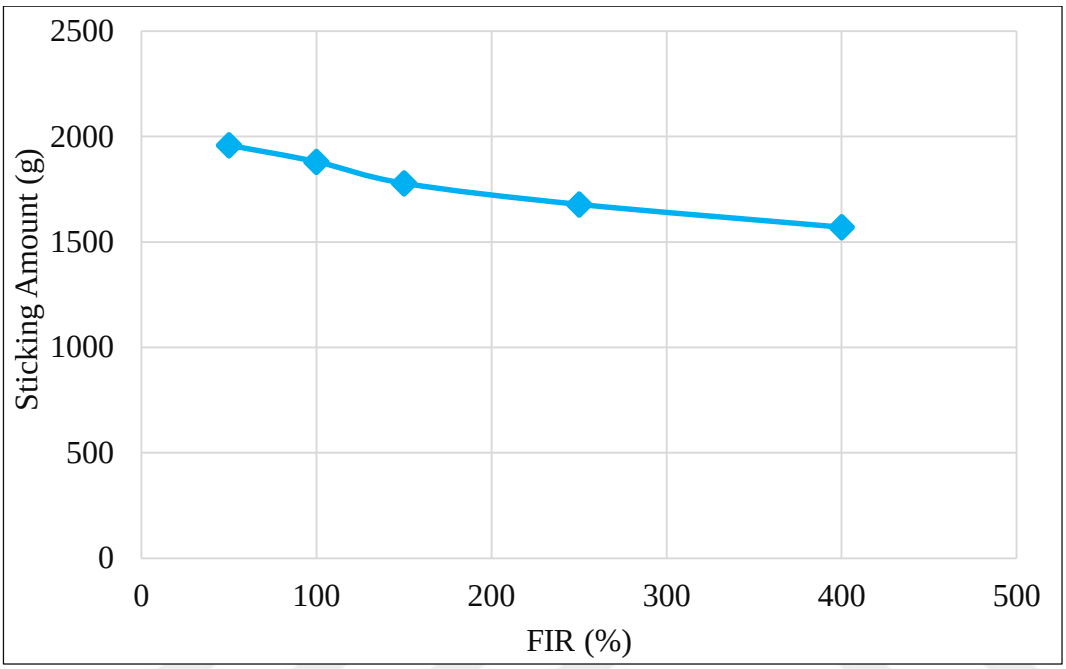

Figure 5.23: Variation of sticking amount with FIR at 35 % water content, 16 FER and 3% FER (Exfoam 2).

5.4.2.3 Cone penetrometer test

Figure 5.24 illustrates the cone penetration values for different FIR amounts. It can be seen from the graph that when FIR is 50 %, penetration value is around 5.5 mm. This amount increases to 6.5 mm by rising the amount of FIR to 100 %. For FIR of 400 % the amount of penetration is 10.9 mm which is still too far from the desired consistency conditions (~20 mm) which means this kind of anticlay is not preferable for the test even for excessive usage.

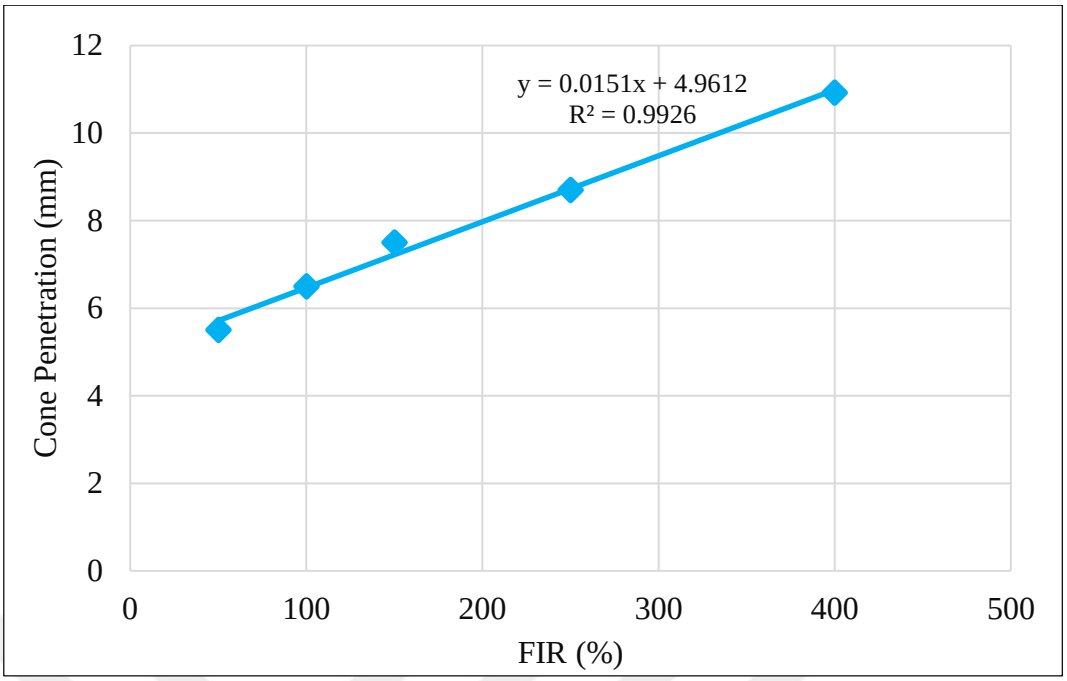

Figure 5.24: Variation of cone penetration with FIR (Exfoam 2).

5.4.3 Soil + ACP143 tests

In order to determine the effect of different anticlay agents on soil conditioning, ACP 143 was chosen as an alternative to Exfoam 2 due to the fact that the results of conditioning tests using Exfoam 2 was far from desirable conditions.

5.4.3.1 Mixing test with power measurement

The mixing tests were performed using ACP143 anticlay agent in a manner similar to Exfoam 2 and the results are presented in Figure 5.25. C_F and FER are held constant at 3% and 16, respectively. As it can be seen on Figure 5.25, the test starts with FIR of 50 % where the power requirement is 67.5 W. From FIR of 50 to 200 % the power requirement falls rapidly from 67.5 to 44 W and when FIR increases from 200 to 300 % the power requirement decreases slightly from 44 to 42 W (almost it levels of). In other words, the power requirement decreases by almost 38% over the range of FIR.

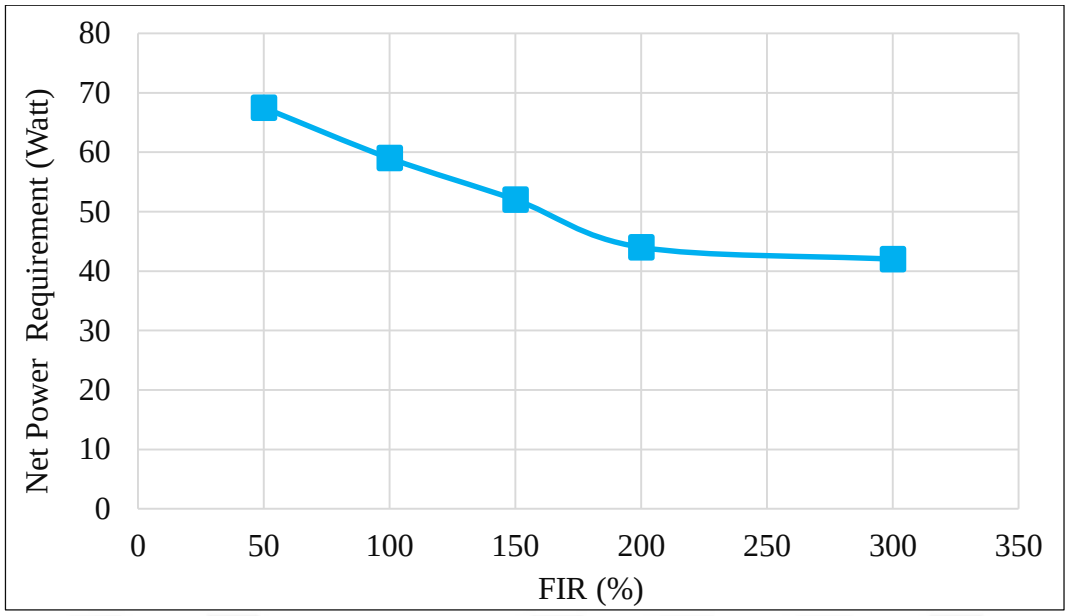

Figure 5.25: Variation of net power requirement with FIR at 35 % water content, 16 FER and 3% C_F (ACP 143).

5.4.3.2 Sticking amount (adhesion to mixing blade)

As it is shown in Figure 5.26, the sticking amount for FIR of 50 % is approximately 1800 g which reduces to 1785 g when FIR rises to 100 %. Sticking decreases from 1785 g to 1600 g when FIR increases from 100 to 300 %. The stickiness of soil on mixing blade can be seen in Figure 5.27.

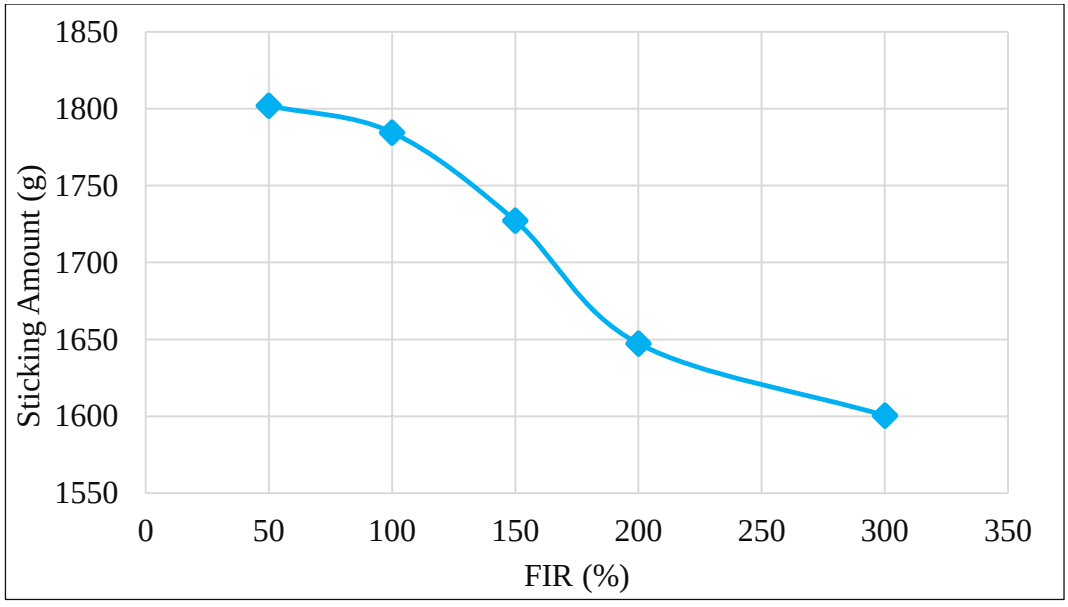

Figure 5.26: Variation of sticking amount on mixing blade with FIR values at 35 % water content, 16 FER and 3% C_F (ACP 143).

Figure 5.27: Photographs of sticking material on mixing blade for each test at 35 % water content, 16 FER and 3% C_F (ACP 143).

5.4.3.3 Cone penetrometer tests

The results of the cone penetrometer tests are presented in Figure 5.28. Penetration amount for FIR of 50 % is 7.5 mm. This amount increases by roughly 17 % (8.9 mm) when FIR reaches to 100 %. The penetration increases from 8.8 mm to 13.1 mm when FIR rises from 100 to 300 %.

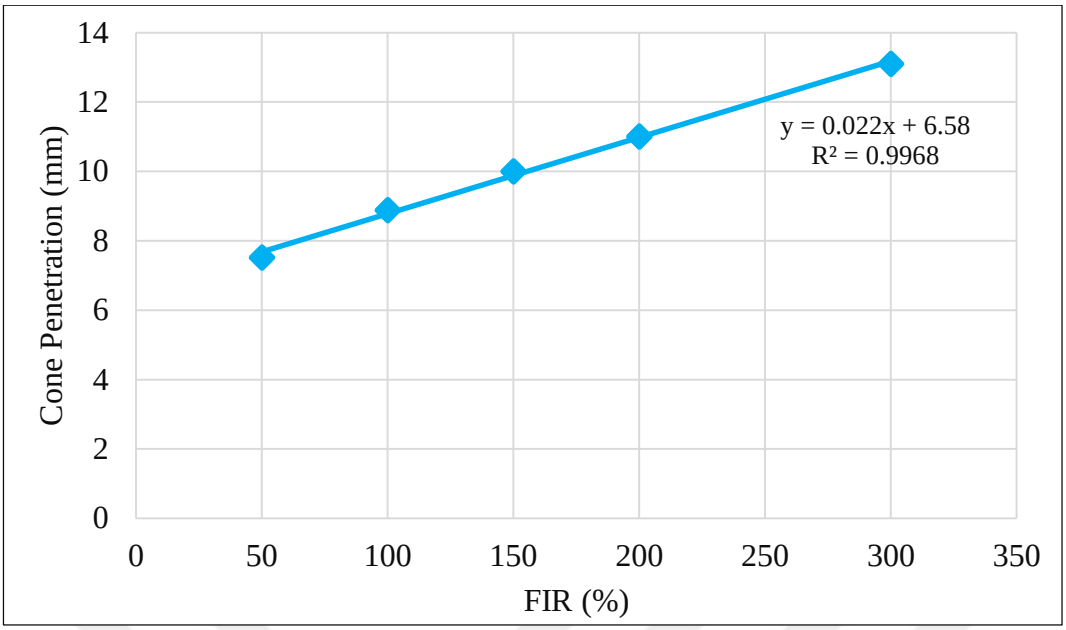

Figure 5.28: Variation of cone penetration with FIR values at 35 % water content (ACP 143).

5.4.4 Soil + ACP143 + water tests

Soil+anticlay mixture tests were carried out with an additional water to natural water content of the soil and mixing with anticlay in order to facilitate conditioning and reach the desirable consistency conditions. For this reason, in excess of the natural water content, approximately 12% of water was added to soil sample (total 45 % water content) and conditioning tests were performed in the same manner as before (C_F of 3% and FER of 16).

5.4.4.1 Mixing test with power requirement

The outcome of mixing tests for ACP143 anticlay and additional water is presented in Figure 5.29. C_F and FER are fixed at 3% and 16, respectively, with varying FIR values. The graph shows power requirement reduction with decreasing FIR. Power requirement decreases from 45 to 37 W for FIR of 50 to 150 %. The power requirement remains almost constant (37 W) from FIR of 150 to 250 % and again it begins to fall from 37 to 30 W while FIR reaches 300 %.

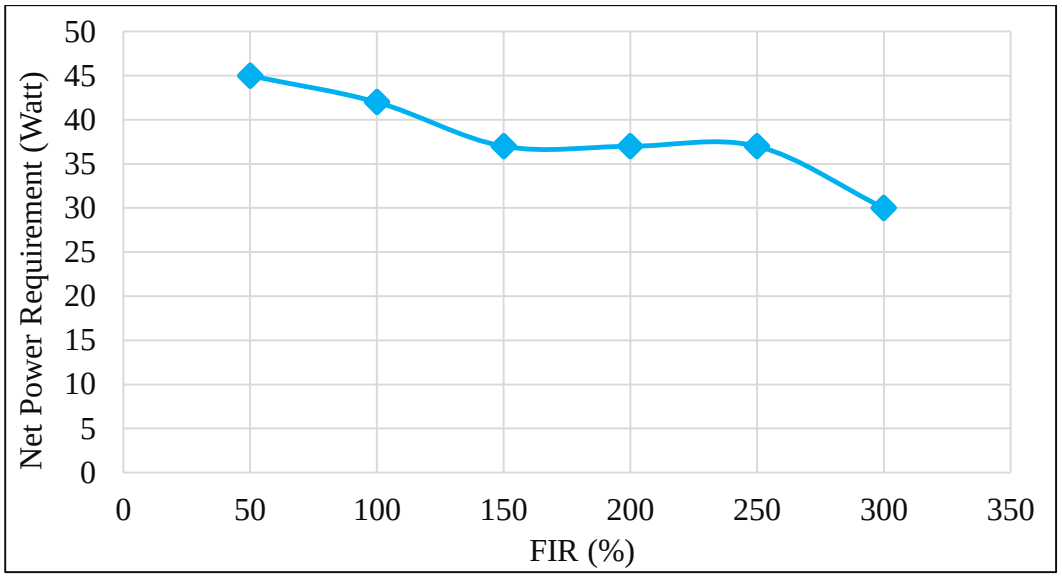

Figure 5.29: Variation of net power requirement with FIR at 45 % water content, 3% C_F and 16 FER (ACP 143+water).

5.4.4.2 Sticking amount (adhesion to mixing blade)

The amount of soil sample remained on the mixing blade is determined and the results are presented in Figure 5.30. From FIR of 50 to 100 %, there is almost no change on stickiness. The stickiness amount decreases gradually from 1932 to 600 g while FIR increases up to 300. The photographs of sticking material for each test are presented in Figure 5.31.

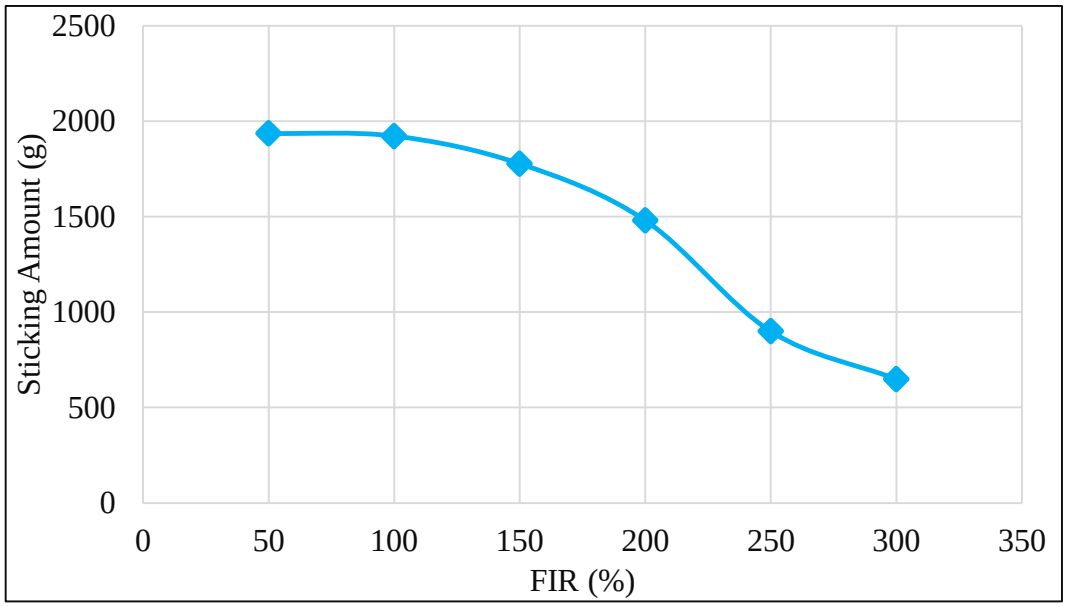

Figure 5.30: Variation of sticking amount on mixing blade with FIR at 45 % water content, 3% C_F and 16 FER (ACP 143+water).

Figure 5.31: Photographs of sticking material on mixing blade for each test at 45 % water content, 3% C_F and 16 FER (ACP 143+water).

5.4.4.3 Cone penetrometer tests

The cone penetrometer test results for increasing FIR are presented in Figure 5.32. As it can be clearly seen in the graph, penetration rises gradually by increasing FIR. Penetration amount changes from 13.5 to 22.4 mm while FIR rises from 50 to 350 %.

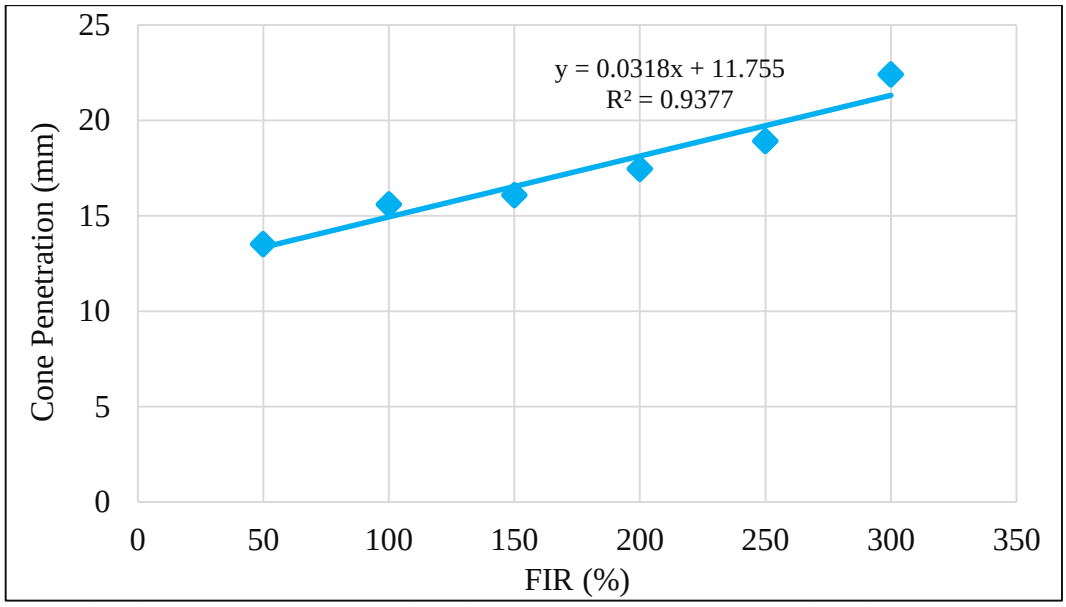

Figure 5.32: Variation of cone penetration with FIR at 45 % water content, 3% C_F and 16 FER (ACP 143+water).

5.4.4.4 Flow table test results

Figure 5.33 illustrates the flow table test results. Because of specific sticky behavior of the soil sample, it was impossible to obtain a flow table value for FIR values smaller than 200 %. In other words, the result of the flow table test was zero when FIR was less than 200 %. As it is shown in the graph, the amount of flow table is 1.1 cm for FIR of 200 %. This value rises to 2 cm when FIR is equal to 250 % and reaches to the ending point of 4 cm by increasing FIR to 300 %. The view of samples tested on the flow table is presented in Figure 5.34.

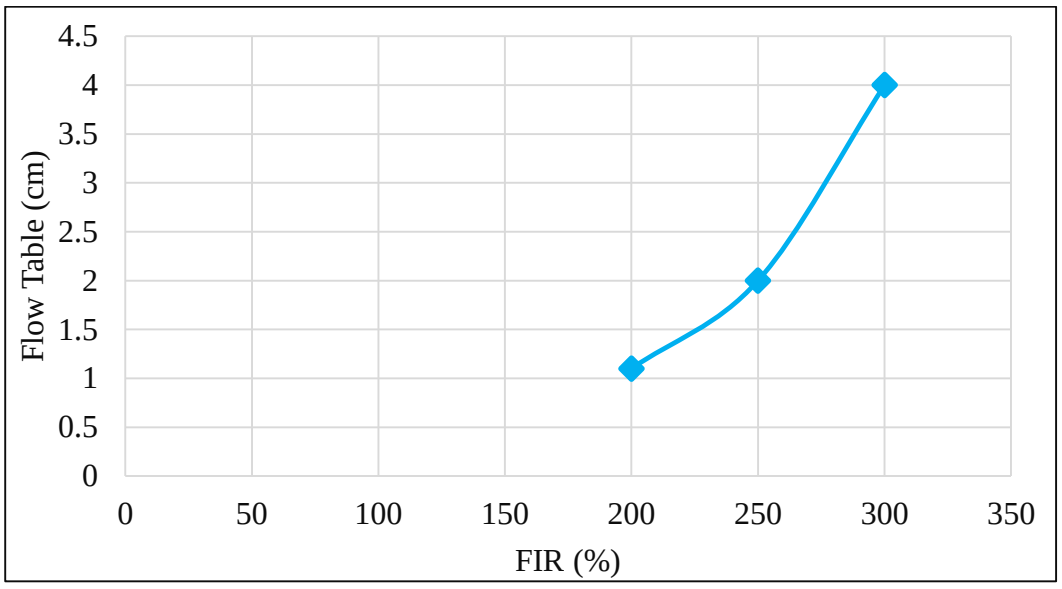

Figure 5.33: Flow table versus FIR values at 45 % water content.

Figure 5.34: View of flow table test after 3 tests.

5.5 General Evaluation of the Test Results, Foam Optimization and Discussions

Using data obtained from the experimental studies, following parameters were evaluated and summarized in Table 5.7 and 5.8.

Table 5.7: Experimental parameters used for soil conditioning with anticlays.

Test	Dependent Parameters	Independent Parameters	Constant Parameters
Power requirement (Watt)	Net power requirement (Watt)	Surfactant (Exfoam 2, ACP143), FIR (50,100,150,200,300,400%)	FER (16), C_F (3%), W (35 and 45%)
Sticking amount (g)	Sticking amount (g)	Surfactant (Exfoam 2, ACP143), FIR (50,100,150,200,300, 400%),	FER (16), C_F (3%), W (35 and 45%)
Penetrometer (mm)	Penetration (mm)	Surfactant, (Exfoam 2, ACP143) FIR (50,100,150,200,300, 400%),	FER (16), C_F (3%), W (35and 45%)
Flow table (cm)	Spread amount (cm)	Surfactant, (ACP143) FIR (200,300, 300%),	FER (16), C_F (3%), W (45%)
Foam Density (g/cm^3)	Density (g/cm3)	Surfactant, (Exfoam 2, ACP143) FIR (50,100,150,200,300, 400%),	FER (16, 11, 8.5), C_F (3%, 4%, 5%)
Half-life (sec)	Drainage time (sec)	Surfactant, (Exfoam 2, ACP143) FIR (50,100,150,200,300, 400%),	FER (16, 11, 8.5), C_F (3%, 4%, 5%)

Table 5.8: Experimental parameters used for conditioning with only water.

Test	Dependent Parameters	Independent Parameters	Constant Parameters
Power Requirement (Watt)	Net power requirement (Watt)	W (33, 35, 40, 42, 45, 47, 50, 52, 54%)	W (35%)
Sticking amount (g)	Sticking amount (g)	W (33, 35, 40, 42, 45, 47, 50, 52, 54%)	W (35%)
Penetrometer (mm)	Penetration (mm)	W (33, 35, 40, 42, 45, 47, 50, 52, 54%)	W (35%)

An optimum FIR or water range achieved for each conditioning test stage (only water, Exfoam 2, ACP 143 and ACP 143+water) is presented in Table 5.9. It should be mentioned that the best result is for conditioning with ACP 143+water where FIR, Penetration, adhesion and net power requirements values was 250%, 19 mm, 900 g and 37 W. Although the flow table value of 2 cm for ACP 143+water is lower than the desired optimum value of 4 cm, the other three tests lead to suggest an optimum FIR of 250%. Although good consistency and low sticking are obtained with only water (52%), the water content of 52% is very close to the liquid limit of the soil, which is considered that it might be very difficult to adjust the consistency of the muck continuously. Therefore, it is suggested using an anticlay agent, which also provides moist sample until it is dumped onto waste dump. Also, it is forbidden to dump very moist soil in many countires.

Table 5.9: Optimization stages and optimum values for each test.

Conditioning agent	Water range (%)	C_F (%)	FER	FIR range (%)	Optimum values based on laboratory results				
					Net power requirement	Sticking	Cone penetration	Flow table	FIR or Water
Only water	35-54%	3%	16	_____	40 W	789 g	~20 mm	_____	52%
Exfoam 2	35%	3%	16	50-400%	44 W	1570 g	~11 mm	_____	400%
ACP 143	35%	3%	16	50-300%	42 W	1600 g	13.1 mm	_____	300%
ACP 143+water	45%	3%	16	50-300%	37 W	900 g	~19 mm	2 cm	250%

Although different soil samples and conditioning parameters used in the previous literature may have different outcomes as summarized below:

Quebaud et al. (1998) investigated the evolution of the power reduction for different FIR and water content amounts in granular soils of which the natural water content of 23 % and FIR of 0 to 30 %, the power requirement decreased by 60 % from the starting point. The power reduction decreased to 55% when the water content reduced to 16%

and the total power reduction for water content of 9 % was 50 %. Moreover, the three additional FIR values did not affect the power requirement anymore for water content of 9 %.

Copur et al. (2013) studied on a claystone sample where the penetration and power requirement amounts were measured. The penetration amounts for FIR of 5 %, 10 %, 20% and 40 % was 7.5, 10, 17 and 24 mm respectively at water content of 45 % and constant C_F of 1 %. The variation of net power requirement with water content was also investigated. It was observed that the sample starts sticking to the mixing apparatus at 20% water content and net power consumption steadily increases from 20% up to 35% water content, and then, sharply decreases at 40% water content.

Jancsecz et al. (1999) has investigated the effect of soil conditioning in a sandy clay condition and concluded that the more foam added to the soil, the higher the penetration depth. The higher the surfactant concentration, the higher the plastifying effect due to a higher amount of surfactant molecules available for the foam and the soil particles.

Aksu (2010) measured foam stability for FER of 10 and C_F of 1 % where half-life was measured as 474 seconds. Levent et al. (2013) determined the quality of foam by half-life test and found out that the average half-life of "Exfoam 3 was found to be 300 seconds by taking C_F of 1% and FER of 8.

In the light of experimental studies an optimum soil conditioning is suggested in this study using soil and foam (anticlay) characterization, mixing with power requirement and sticking tests. Soil and foam characterization is fundamentals for starting such a study due to the fact that it is impossible to suggest a conditioning design without a deep knowledge of basic properties of soil and foam or anticlay. Subsequently mixing tests with adding only water, 2 different foaming agents (Exfoam 2 and ACP 143) and ACP 143+water were done respectively in order to observe the net power requirement, sticking amount, penetration and consistency (flow table test) of the sample in different water contents and FIR values.

In consideration of experimental studies an optimum anticlay design with FER of 16, FIR of 250 %, C_F of 3 %, total water content of 45 % (12 % additional to natural water content) and ACP 143 is suggested for the soil sample.

Optimum soil conditioning design suggested in this study is the outcome of set of different tests which has been done in Istanbul Technical University Mining Engineering Department Soil Conditioning Laboratory.

On the other hand, following studies should be mentioned where:

Peila et al. (2015) used slump and adhesion tests as soil conditioning method in order to assess the optimal consistency of soil sample. Dal Negro et al. (2013) investigated a ground conditioning method for Abu Dhabi sewer project using slump and soil abrasion tests. Psomas and Houlsby (2002) performed a soil conditioning suggestion through compression tests in a conventional Rowe cell.

To increase the reliability of the suggested soil conditioning parameters as a result of this research, it should be based on a wider variety of tests compared to some of the previously conducted studies.

It should be noted that as the EPB TBM used in Zeytinburnu-Ayvali 2 project was working without support (face) pressure since the face was stable, soil conditioning tests were carried out in atmospheric pressure. On the other hand, the effect of pressure on behavior of conditioned soil is significant and makes it dramatically different from its behavior under atmospheric pressure. In case of instability on the tunnel face, there would be a support pressure in the excavation chamber and hence conditioning parameters would be affected. The effect of pressure on a conditioned soil was investigated by Mooney et al. (2016). The bubble size analysis of the foam within 0 to 4 bar pressure showed significant reduction on the bubble diameter with increasing pressure and half-life measurements revealed that foam degraded more slowly with higher pressure and this might result in decreasing FIR amount in higher pressures.

6. VALIDATION OF THE RESULTS IN THE FIELD

6.1 Introduction

The outcomes of laboratory test/studies are reliable only if they are in agreement with the field observations. In parallel with laboratory tests, the performance of the EPB TBM used in Zeytinburnu Ayvali2 waste water tunnel was observed (Figure 6.1).

Figure 6.1: Field investigations in Ayvali 2 waste water tunnel.

6.2 Discussions on Field Studies and Laboratory Findings

As it is mentioned in Chapter 5, the soil sample tested in laboratory has a medium to high potential of clogging (Figure 5.5), which means the performance of the EPB TBM may be threatened by the possibility of clogging/blocking on the cutterhead and reduced performance. On the other hand, based on the data collected from laboratory mixing tests and problems observed, high torque values (especially if face pressure is applied) would be expected during tunnel excavation. Low performance issue due to

clogging was exactly observed while excavating the tunnel and hence the excavation was stopped for remediation actions. To address the mentioned problem, firstly, grizzly bars on the cutterhead (Figure 6.2) were uninstalled in order to reduce sticking amounts and easy transportation of the muck.

Figure 6.2: Grizzly bars on TBM cutterhead.

Thereafter, as a result of the laboratory studies, a new conditioning design was utilized to optimize the TBM performance. FER of 15-16, FIR of 150-200% and total water content of 50% (around 17% additional water to natural water content of 33%) and available anticlay of Exfoam 2 (at~1.5% C_F) were defined as the target conditioning parameters and applied in the field / the EPB TBM by the contractor company. It should be mentioned that although the conditions and facilities such as foam generator used in laboratory and field are not exactly the same, the range suggested by the outcomes of the laboratory studies may be achieved with sufficient accuracy. The effects of the applied changes were clearly noticed on the performance of the EPB TBM. Figure 6.3 presents the resulting changes in the cutterhead torque before and after changing the soil conditioning parameters. As it can be seen, the cutterhead torque was reduced from 1072 to 930 KNm (13% reduction). Since there is no face pressure applies on the cutterhead, the low reduction on torque can be considered as normal.

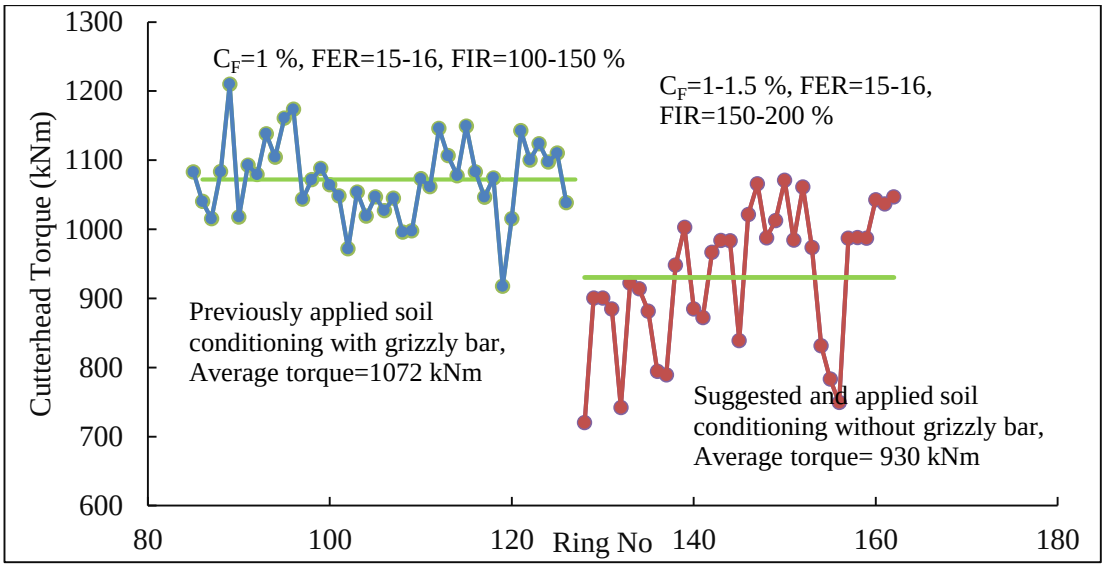

Figure 6.3: Cutterhead Torque before and after improvement.

Figure 6.3 shows the cutter head torque changes for each ring in periods before and after grizzly bars uninstallation and application of the new soil conditioning design. Moreover, field observations verified that sticking problem and torque were reduced with the suggested conditioning parameters. Penetration rate is also increased totally after improvement (Figure 6.4). As it is seen in Figure 6.4, maximum penetration rate before revision is around 30 mm/rev while this amount increases to 50 mm/rev after revision. The average penetration rate is increased from 24.3 mm/rev to 32.1 mm/rev (32% increase).

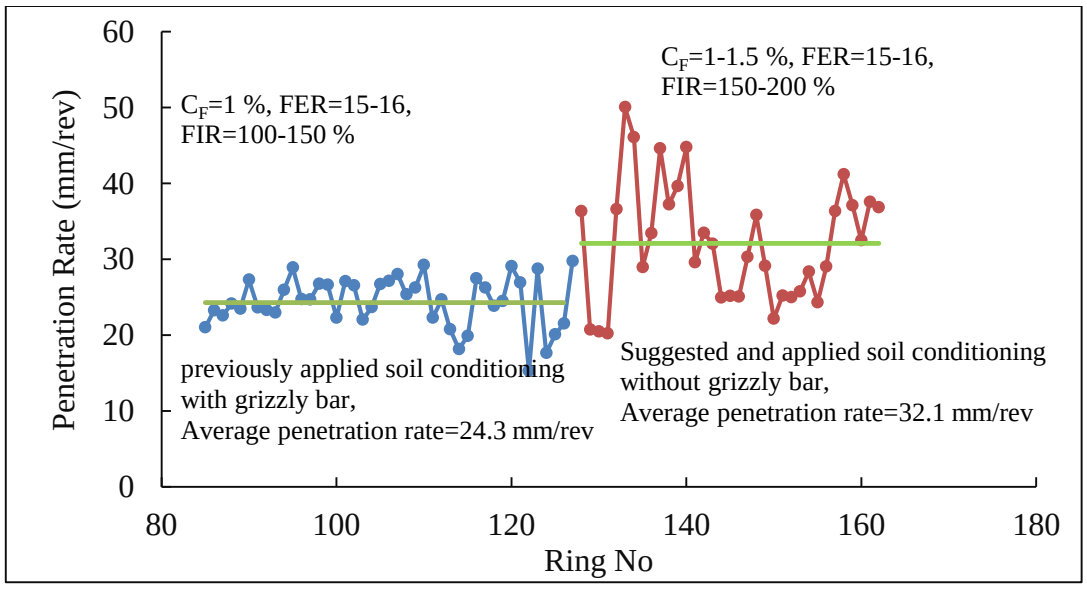

Figure 6.4: Penetration rate before and after improvement.

Figure 6.5 presents the thrust force for each ring in periods before and after grizzly bars uninstallation and application of the new foam (anticlay) design. As the face was

stable and thus the TBM worked on semi open mode, the thrust force did not change notably.

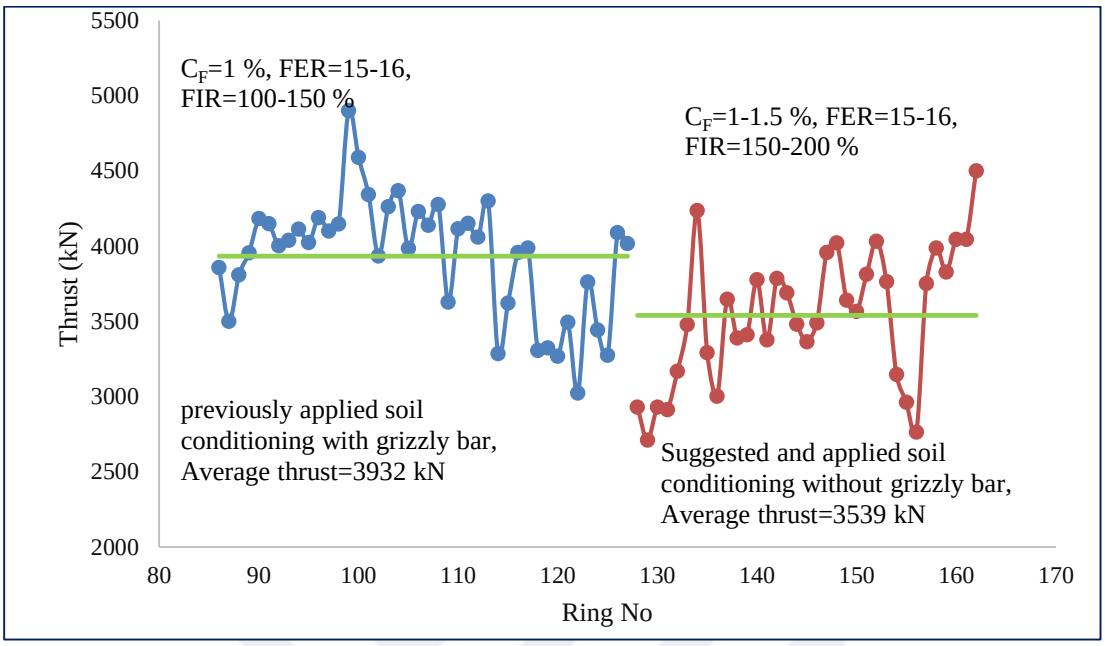

Figure 6.5: Thrust before and after improvement.

It should be mentioned that the improvement in TBM performance is caused by both uninstalling the grizzly bars and applying the suggested soil conditioning design. However, based on field observations and data obtained from the TBM, the effect of each suggestion (uninstalling the grizzly bars and applying new soil conditioning design) on performance of the TBM could not independently be detected.

Similar studies could be found in literature in which the performance of the TBM was improved by soil conditioning operations. A decrease of 20% for cutterhead and screw conveyor torque of an EPB TBM used for excavation of the Valencia metro line is reported by Wallis (1995). Soil conditioning operation resulted in reduction of cutter head torque from 8825 to 3922 kNm and also reduction of thrust from 19928 to 11956 kN (Babenderede 1998).

7. CONCLUSIONS AND RECOMMENDATIONS

One of the main issues during excavation with an EPB machine is soil conditioning, which is known to be a performance improvement factor. In this study, a set of laboratory tests was carried out on samples taken from the Zeytinburnu Ayvali 2 waste water tunnel, paralleled with field observations and measurements, in order to investigate the effect of soil conditioning. Laboratory tests started with basic characterization tests in order to figure out the soil and anticlay properties and then continued with soil+water and soil+anticlay mixture tests. Basic soil characteristic tests of specific gravity, natural water content, grain size distribution, liquid and plastic limit tests were carried out. Anticlay characterization tests were also performed by determination of half-life and density of two different anticlay agents (Exfoam 2 and ACP 143). Furthermore, mixture tests by mixing with power and sticking measurements and cone penetration tests were carried out by adding just water to the soil sample in order to figure out the effect of water on consistency of the conditioned sample. Then, mixture tests were carried out for soil+anticlay with two different anticlay types in order to determine whether adding the anticlay will resolve the sticking problem, decrease the power requirement and help to reach desired consistency or not. Using Exfoam 2 demonstrated that adding anticlay instead of water could improve the test results and, according to the results, ACP143 was a better choice. However, the superior results were achieved when approximately 12% of water was added to the sample with natural water content and conditioned with anticlay. On the other hand, optimum anticlay design which was obtained in the laboratory, was applied in the field and, in order to validate the results obtained in the laboratory, TBM's performance was analyzed before and after applying the suggested soil conditioning.

In the light of experimental studies carried out in the laboratory, for the mixing tests performed with Exfoam 2, the power requirement decreased around 50 % for FIR 400 %, however adhesion of the soil was not significantly reduced. The cone penetration values ranged from 5.5 to 10.9 mm, but it was still far from desirable value of around 20 mm. By using ACP143, the power requirement of the mixing decreased

approximately 50 %, the adhesion amount almost did not change while cone penetration increased from 7.5 to 13.1 mm. On the other hand, conditioning the soil by using ACP143+water (12 % additional to the natural water content), which corresponds to consistency chart for EPB applications suggested by Holmann and Thewes (2013), the measured test values were more effective where FIR was around 250 %, the cone penetration was around 19 mm, the adhesion amount was 900 g and the power requirement was around 37 W.

The results of the laboratory tests were validated by the field trials. The suggested conditioning design was applied in the field after a revision and the performance of the EPB TBM was improved. Penetration rate increased from 24 mm/rev to 32 mm/rev and cutterhead torque decreased from 1072 to 930 kNm. Thrust force decreased from 3932 to 3539 kN. Since the face was stable and without pressure, the thrust force and torque did not change notably, although penetration rate increased more than 30%.

It should be mentioned that the company revised the suggested conditioning design with C_F of 1-1.5%, FIR of 150-200%, additional water of 17% and tried to solve the clogging and transportation problems, however performing the conditioning with C_F of 3%, FER of 15-16 and FIR of 250% could help to further reduce the mentioned problems and improve excavation performance; the experimental studies in the field and laboratory may be continued.

To increase the reliability of soil conditioning parameters, a new soil conditioning method was used in this study and thus different types of experiments with enough number of tests were performed instead of using only one type of conditioning test.

Future studies could be carried out with different soil types to build up a large database of optimum conditioning parameters for different soils. The effect of parameters such as different surfactant (foam or anticlay) properties, conditioning agent concentration and combination of different conditioning agents on the properties of conditioned soils could also be investigated further. Moreover, the effect of different foam generators using variable foam expansion ratios and the foam bubble size in soil conditioning could be evaluated. A database and improved knowledge of effective conditioning behavior for different soils based on standard index tests would be advantageous for tunneling practice.

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