Journal of Mining and Environment (JME), Vol. 12, No. 2, 2021, 501-513

Shahrood University of Technology

Iranian Society of Mining Engineering (IRSME)

Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

THOMSON REUTERS

Calculation of Optimum Soil Conditioning in EPB Tunneling (Case Study: Ahwaz Metro Project, Line 1)

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Article Info

Received 28 March 2021

Received in Revised form 17 May 2021

Accepted 22 May 2021

Published online 22 May 2021

DOI:10.22044/jme.2021.10664.2025

Keywords

EPB tunneling machine
Soil conditioning
Slump test
Foam expansion ratio
Foam injection ratio

Abstract

Determination of the optimum soil conditioning parameters in the earth pressure balance-tunnel boring machines (EPB-TBMs) plays an important role in reaching an optimum thrust force and advance speed. Silty-clay (CL-ML) in line 1 of the Ahwaz metro project is used in order to find the conditioning parameters of slumps with different water contents and foam agents. The results obtained are a quantitative comparison between the parameters with different soil conditioning and water contents. Hence, the test results can be used to determine the most economical and technical conditioning parameters for a special condition of soil. The optimum quantity of foam expansion ratio (FER), foam injection ratio (FIR), percent ratio between the surfactant agent and the water volume (Cf), and cost for foam in this soil (based on the soil conditioning production cost) are 10, 157%, 2.07, 248 units, respectively. Soil conditioning with the optimum parameters obtained are tested in a TBM in two stages during excavation of 140 rings. This results in a lower soil conditioning cost and almost 40% higher advance speed.

1. Introduction

Earth Pressure Balance (EPB) shield tunneling has been widely utilized for tunneling in urban areas in various ground conditions (Lambrughi, Medina Rodríguez, and Castellanza 2012; Peila, Picchio, and Chieregato 2013; Sirivachiraporn and Phienwej 2012) [1-3]. The bulk chamber in EPB-TBM is filled with the excavated material (mud); in most cases, in order to obtain the suitable mud, the conditioning additives should be used according to the type of the in-situ soil. Sometimes only water is sufficient; however, most of the times, adding foam and a certain amount of air is necessary in order to obtain a homogeneous soil and a proper tunnel face support pressure (Hu and Rostami 2021) [4]. The requirement of torque in the EPB shield increases rapidly as the cutter head diameter increases. The certain characteristics of mud as it is being excavated such as the consistency and plastic behavior can significantly affect the drive torque. The appropriate usage of modern soil conditioning technologies can significantly reduce the drive torque for both the screw conveyor and the cutter head (Copur et al. 2014; Hu et al. 2020; Jin, Zhang, and Yuan 2021; Li et al. 2020; Lin et al. 2021) [5-9].

Soil conditioning means improving several properties of soil. It is carried out by injecting polymers, foam, water and/or fillers at the back of the tunnel face into the bulk chamber and along the screw conveyor. This procedure is done in order to achieve several goals, as follow:

- Soil conditioning transforms soil into a plastic ‘‘pulpy’’ medium. It transmits the pressure in the excavation chamber and along the screw conveyor (Anagnostou and Kov 1996; Herrenknecht and

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Maidl 1995; Nomoto, Imamura, and Hagiwara 1999) [10-12].

- Soil conditioning reduces the frictional forces. Therefore, it reduces the tool and mechanical wear. It also reduces the required mechanical torque of the cutting head as well as the required mechanical torque of the screw conveyor.
- Soil conditioning removes the adhesion effects of sticky clayey soils.
- The procedure determines the optimum technical and economical soil condition agent.

The properties of the conditioned soil are evaluated by the laboratory tests. The properties are used in order to calculate the optimum conditioning in a certain environment. Also the properties allow an easy comparison of various additives on the market (Vinai, Oggeri, and Peila 2008) [13].

The foam properties are related to the expansion ratio and the concentration of the foaming agent in the liquid. In a typical application, the values for FER are generally within the 8–15 range; higher values correspond to the granular soils (Gatti and Cassani 2007) [14]. Generally, foam contains 1% to 3% of concentrate and 97% to 99% water. Thus even when a large quantity of foam is required, and also an expensive concentrated agent is used, the cost of the foam may be quite modest. Similarly, increase in the volume of solid material and water of the excavated soil would be much less than the usage of a clay slurry additive.

Bezuijen *et al*. have provided a different method with a different required foam volume. They have suggested that the quantity of mixed foam should produce a higher porosity in the soil than the porosity of soil alone at the existing pressures in the chamber (Bezuijen, Schaminee, and Kleinjan 2012) [15]. By decrease of the pressure in the screw conveyor, the porosity increases due to the expansion of the air bubbles in the foam. The required foam volume for mixing with stiff clays is not yet well-defined. Cash and Vine-Lott have recommended that the foam flow rate should be equal to the void content of the cut material (Cash and Vine-Lott 1996) [16].

Laboratory tests involving both conditioning and interaction of soil are large-scale or actual-scale TBM tests. National French Research Program (NFRP) has suggested a 1/10 scale model for the EPB excavation simulation. The suggested model has a geometric scale between 1/4 and 1/20. It consists of a 0.55 m cutter head, a screw conveyor inclined at an angle of 10º, a conical working chamber, a cylindrical steel shield tail, a horizontal screw conveyor, a frame carrying the whole assembly, four thrust hydraulic jacks, and a stiff steel container placed in front of the TBM frame. The dimensions of the test ground were 2 m in length, 1.3 m in width, and 1.3 m in height. The system had several monitoring transducers for the driving parameters, the soil stresses and deformation control (Berthoz, Branque, and Subrin 2012) [17].

Merritt and Mair have used a laboratory screw conveyor. The conditioned clay soil was extracted from a tank by a sub-horizontal screw. They obtained proper results for this type of soil (Merritt and Mair 2006) [18]. Their laboratory device was made of a 1-m long and 0.1-m diameter horizontal screw conveyor, which was connected to a pressurized tank. Four monitoring devices were installed on the screw conveyor. Each monitoring device had two load cells to measure the total normal stress and the components of the shear stress on the soil-casing interface and a pressure transducer to measure the pore pressure in the soil. The screw torque was also measured. Various soil pressures over a wide range of screw speeds with different discharge outlet conditions were used in the performed tests.

Yoshikawa has performed several tests using plastic soil with different screw speeds on a full-scale EPB screw conveyor (Yoshikawa 1996)[19]. He reported a linear pressure gradient in the screw conveyor.

At the first part of the work, a series of slump tests are carried out with different percentages of conditioning foam and water contents in order to find some general rules to link these parameters together. Then the technical and economical conditioning are optimized.

At the second part of the work, the soil conditioner is changed by changing the included parameters in an actual EPB tunneling machine. It is injected on the cutter head and chamber. Also different foam parameters affecting the torque, thrust, advance rate, and foam agent consumption are analyzed.

2. Research methodology

2.1. Engineering background

The Ahwaz metro, line 1, is located in the NS of the city of Ahvaz. Many residential areas lie along the tunnel alignment. Therefore, the tunnel passes beneath the urban areas with traffic or dense underground petroleum pipelines as well as crowded buildings. The tunnel longitudinal axis is always horizontal. The only exception is when the tunnel crosses the Karoon River with the maximum gradient of 3.35%. The overburden is mainly kept at almost 1.5D (D is tunnel diameter).

The tunnel from the Zargan to the Naderi stations is located in the north of Ahvaz. The north district part of the tunnel starts from the Eqbal station along the Pasdaran Street to the Naderi Street station, which is about 7.195 km long, with its chainage from 18 + 288 to 11 + 092. The outer diameter of the tunnel is 6.88 m, and it is constructed using the EPB shield machine.

2.2. Geological condition (north part of line 1)

The half of the whole railway path is located in the north of Ahvaz. This part has three layers with different geological and geotechnical characteristics. The thickness of the layers changes through the whole path. According to the geological profile, the characteristics of these layers have been explained as follow:

- Fill: This layer has 1 m to 3 m thickness, which is its characteristics change.
- Clay and silt fine grained soil: This layer is located between the filled soil and the rock layers. Thickness of this layer changes from zero (in some places that rock layers have outcrops), and in the most part of the path, approximately becomes 9 m. The geotechnical characteristics of this layer is nearly constant but in some cases they change through thickness of layers alternatively.
- Rock layer: This layer is located under silty and clayey layers, and mostly includes siltstone and claystone and new sandstone. The characteristics of rock layer vary through the path as explained below:

A: Rock layer- type 1: This layer typically constructs the major part of the rock layer. The slope of this layer is between 10° and 20°; the thickness of the layer changes but the average thickness is 1 m.

B: Rock layer- type 2: This layer is a small part of the path. The thickness is approximately 1 m; there are two or three outgoings in this region.

The geotechnical characteristics are demonstrated in Table 1 and Figure 1.

Table 1. Geotechnical parameters.

Layer	Fine grained soil (CL)	Rock type 1	Rock type 2
Dry density (g/cm^3)	1.63	2.20	2.35
Saturated density (g/cm^3)	2.01	2.35	2.40
Moisture (%)	19.5	11.6	11.6
Void ratio	0.43-0.86	0.24-0.41	0.24-0.41
PI	11-30	-	-
SPT	5-15	-	-
RMR	-	40-55	50-60
RQD	-	95-100	95-100
C_u (kg/cm^2)	0.4-0.7	-	-
C' (kg/cm^2)	0.1-0.2	0.2-0.5	15-20
friction angle (φ)	15-30	25	25
E (Mpa)	15-25	250-300	650-750
K (10^{-6} cm/s)	3.8	< 1	< 1

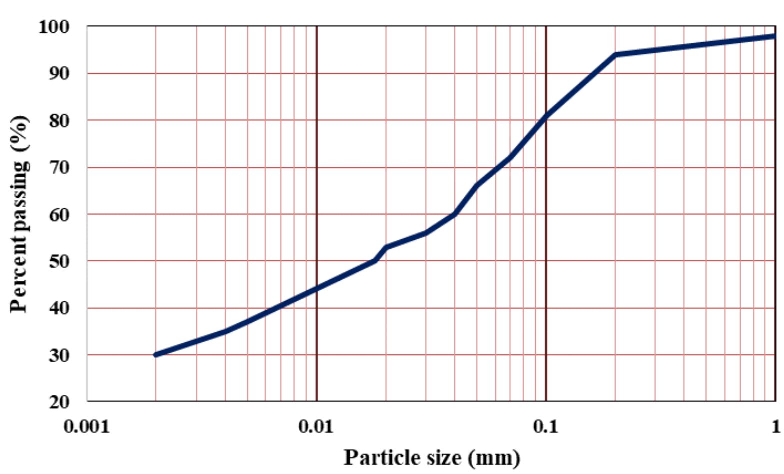

Figure 1. Soil grain size distribution curve.

3. Soil conditioning in EPB machine

The investigations on soil conditioning in tunneling process have not yet established a suitable correlation between the volume of conditioners (e.g. foams and polymers) and their performance with soils. Most studies have suggested general guidelines for conditioning treatments in various soils. They have mentioned the effect of certain types of polymers and foams in their results that provide suitable properties. Merrit has performed several consolidation tests with conditioned clay as well as other fall cone tests on the conditioned soil and screw conveyor tests with conditioning clay soils (Merritt 2005)[20]; Bezuijen and Schaminee have modeled the drilling process with EPB shield that uses foam (Bezuijen and Schaminee 2000)[21]. Unfortunately, their results are not always applicable. Therefore, these results are practical in the tunneling process, and their applications are largely based on trial-and-error. The soil conditioner in this research work was MEYCO SLF 41D. The general soil conditioning for different EPB tunnelings is shown in Figure 2.

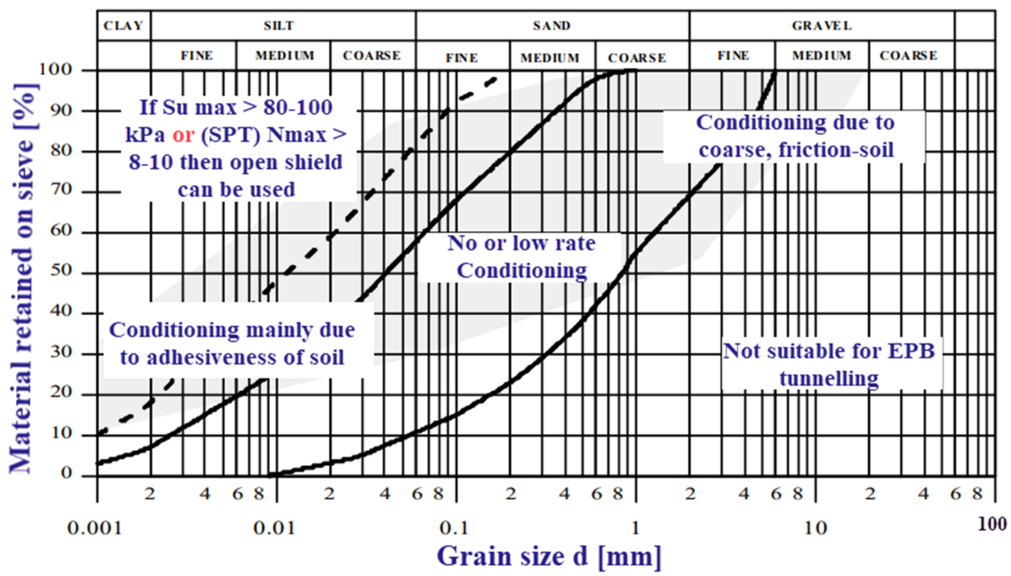

Figure 2. General soil conditioning for EPB tunneling (EFNARC 2001)**[22].**

Foam should be used under specific conditions in the site that are defined by specific parameters. The influence of each parameter is required to be determined using the preliminary laboratory tests. The three most important foam parameters on the TBM are the percent ratio of the surfactant agent and water volume (C_f), Foam Injection Ratio (FIR), and Foam Expansion Ratio (FER) (Jancsecz, Krause, and Langmaack 1999)[23].

Merritt has experimentally investigated the soil conditioning for clays. He also investigated the mechanics of a EPB screw conveyor model that was operated with clay soils (Merritt 2005)[20]. Furthermore, he performed many index tests in order to investigate the effects of foam and polymer conditioning treatments on the undrained strength of London Clay samples.

As illustrated, different ground conditions require different soil conditioning parameters. Table 2 can be used as a general guide for selecting an appropriate soil conditioning system for a particular type of ground.

Table 2. Soil conditioning summary.

Ground type	Soil property	Foam type	Polymer type
Gravelly sand Fine to coarse sand	No plasticity High permeability	Use a relatively stable foam with a higher FIR	Use a high plastic polymer (biopolymer, cellulose, CMC)
Silty sand Clayey sand	Plasticity depends on the fines content	Use a general foam with a low to medium FIR	Depending on the water content, use a polymer to control the muck consistency
Sandy clay Pure clay	High plasticity Cohesiveness and stickiness of soil depend on clay type	Use a high dispersing foam with a medium to high FIR	Use an anti-clay polymer to help reduce the stickiness and cohesiveness

Generally, the conditioners adjust the soil conditions to suit the machine rather than adapting the machine to the ground conditions. The purpose is to create a low permeability compressible soil that is soft and has suitable flow properties and low shear strength. Milligan summarized the various applications of soil conditioning in tunneling machines, and the use of soil conditioning in the EPB machines (Milligan 2000) [24] (see Table 3).

Table 3. Plastic fluidity terminology according to the slump range.

Plastic fluidity	Slump range (mm)
Firm	10-40
Plastic	50-90
Very plastic	100-150
Fluid	>=160

4. Slump test procedure

In this work, the slump cone test is performed following the procedure described by ASTM 143C (Anon 2003) [25]. These tests have already been used to provide an evaluation of the conditioned soil quality by several researchers (S. J. Boone, Artigiani, and Shirlaw 2005; Jancsecz et al. 1999; Kuribashi, Yagi, and Ishimoto 1993; G. E. Williamson, Traylor, and Higuchi 1999)[23,26-31]. Quebaud *et al*. have suggested the use of a 12-cm slump to produce an optimum mixture of characteristics for a plastic flow in an EPB machine (Quebaud, Sibai, and Henry 1998) [27], while Williamson *et al*. (G. Williamson, Traylor, and Higuchi 1999) [28], Jancsecz *et al*. (Jancsecz et al. 1999) [23], and Boone *et al*. (S. Boone, Artigiani, and Shirlaw 2005) [31] have suggested a slump of 21 cm, 20–25 cm, and 8–10 cm, respectively.

4.1. Test procedure

At first, the conditioning soil is mixed with a predicted volume of foam and water in a concrete mixer. Then it is pounded into 2 slump cones. Allowing a minute to pass, then the cone is lifted without stroking or mixing the soil. The fall value and the general behavior of the mix are then observed and classified. Figs. 3 and 4 show the schematic views of the performed test. The shape of the slump, the water drainage from the conditioned soil, and the break path of the soil cone are observed and accounted for to define the material behavior. Based on the mentioned parameters, the mix will be classified as “suitable”, “borderline” or “not suitable”. Three main behaviors were observed consisting of too stiff and dry behavior due to an insufficient water or foam content, very fluid and wet behavior due to excessive water or foam content and suitable behavior of the mix where the ground behaves plastically (Figs. 3 and 4).

4.2. Results

Table 4 and Figure 4 present the results obtained for the conducted test on a low plastic clay.

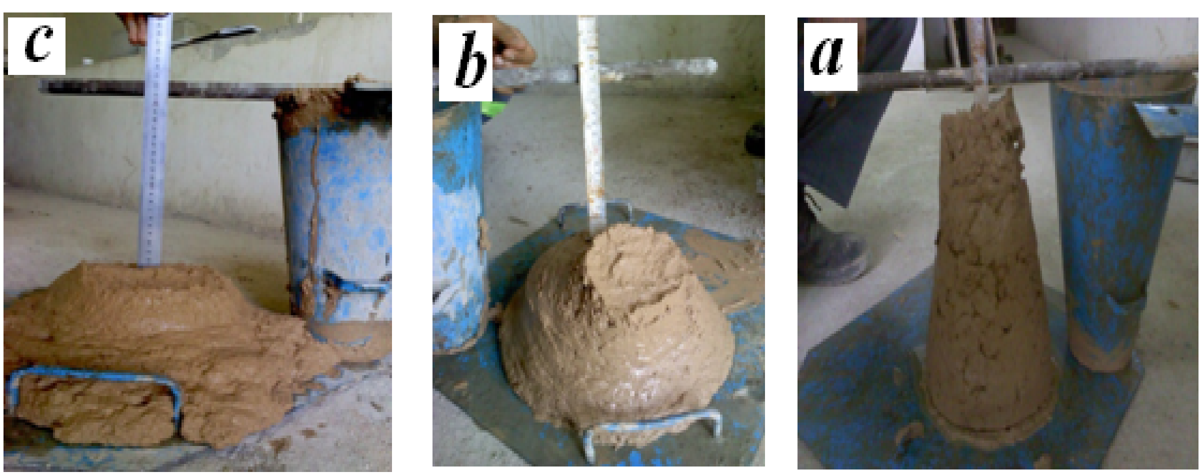

Figure 3. Assessment of quality of the tested material after slump test (a) not suitable (due to being very stiff and dry), (b) suitable, (c) not suitable (due to being fluid and wet).

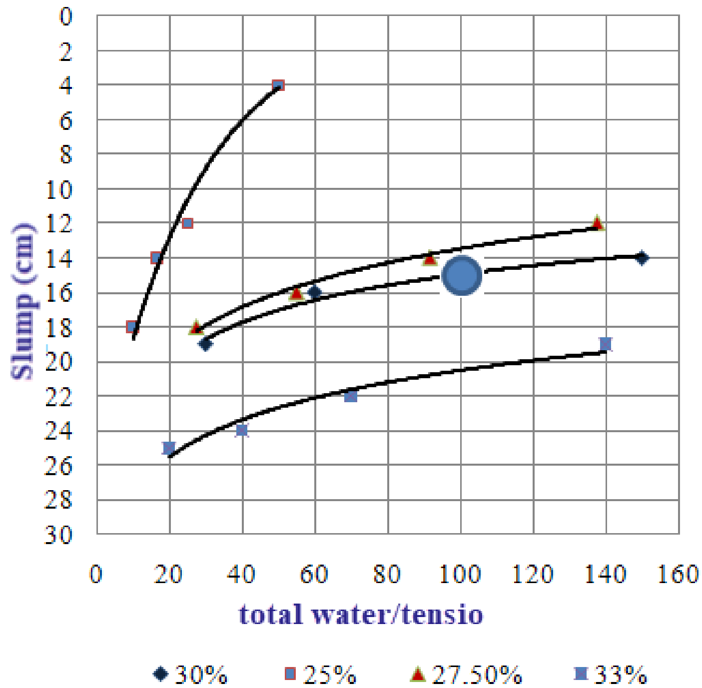

Figure 4. Slump differences per W/T ratio diagrams.

Table 4. Slumps and costs in different moistures

Moisture (%)	Test number	Tensio active	Slump (mm)	W/T	C_f(%)	Total cost (unit)
25%	1	50	40	50	2	1440
	2	100	120	25	4	1750
	3	150	140	16.6	6	2360
	4	250	180	10	10	4000
27.5%	5	20	120	137.5	0.73	345
	6	30	140	91.6	1.1	535
	7	50	160	55	1.82	935
	8	100	180	27.5	3.63	1480
30%	9	20	140	150	0.66	341
	10	30	150	100	1	500
	11	50	160	60	1.66	820
	12	100	190	30	3.33	1615
33%	13	25	190	140	0.71	393
	14	50	220	70	1.43	768
	15	87.5	240	40	2.5	1330
	16	175	250	20	5	2642

The results show that:

- The plastic behavior was only observed in some combinations of the investigated parameters (i.e. water content and FIR);
- No or little liquid draining was observed when the slump cone fall was in the range of 4-16 cm;
- In 25% water contents part of the curve, the conditioned soil appeared to be very stiff and dry (test 1);
- In water content within the 30-33%, the material behavior was very fluid and wet, even for low foam injection ratios (test 12 to 16);
- The tests with suitable results (tests 3, 4, 6 to 11) were located in plastic area (see Table 3).

Therefore, an area with suitable conditioning parameters for final mix may be determined. The area could be indicated as the ‘‘optimum ’’ conditioning parameters, which for the studied clay, correspond to the following parameters: W/T = 100 and water content = 29% within Slump = 150 mm.

5. Economical investigation

The optimum quantity of soil conditioning should be identified, and then utilized with economical and technical water-foam agent ratios. In order to achieve this goal, the cost of used-foam for every excavated ring in different water-foam agents has been calculated.

The calculation is shown in Tables 4 and 5. In Figure 5, the cost of used-foam for a quantity of slump in the four humidity percentages of 25%, 27.5%, 30%, and 33% is indicated.

$$FER = \frac{A}{W+T}, FIR = \frac{W+T+A}{S} \rightarrow$$
$$FIR = (1 + FER).\left(1 + \frac{W_S}{T}\right) \times \frac{T}{S} \quad (1)$$

$$W_s + W_i = 29\% \rightarrow W_s = 14\%S = 14.3m^3 \quad (2)$$

$$\frac{water}{Tensio\,active} = \frac{1}{C_f} = \frac{W_s}{T} = 48.28 \quad (3)$$

$$FIR = 11 * (1 + 48.28).\frac{0.29\%S}{S} \approx 157\% \quad (4)$$

$$C_F = 2.07 \quad (5)$$

$$M = W_S.\rho S.P_w + T.P_T \quad (6)$$

Table 5. Optimum amount of foam in an excavated ring.

FER	FIR (%)	C_f (%)	Moisture (%)	Added water (%)	Tensio active (Li)	Cost (unit)
10	157	2.07	15	14	143	248

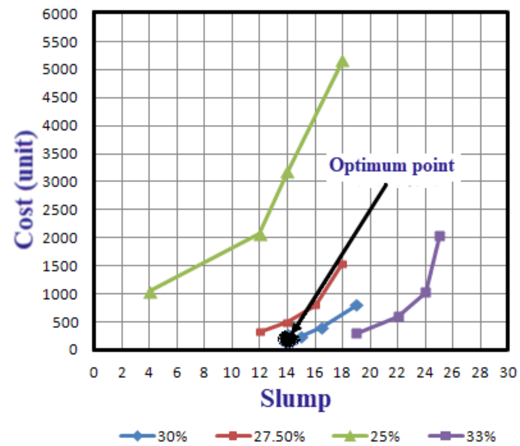

Figure 5. Water and tension active costs in different w%.

6. Full-scale EPB-TBM sample

Real sample was collected in EPB TBM to see the effect of the optimum soil conditioning parameters on the penetration ratio. The TBM characters are shown in Table 6.

During the sampling, several parameters were monitored. These included the pressure distribution in the chamber, torque required to rotate the cutter head, thrust force, advance speed, and penetration ratio.

Monitoring the mentioned parameters, it was possible to evaluate the suitability of the amount of conditioning and also compare different parameter sets.

Table 6. Tunneling machine part specifications.

EPB TBM specifications		
Shield	Diameter shield length with cutter head Shield length with back-up shield weight with back-up max gradient	6.88 (m) 10.6 (m) 106 (m) 600 (ton) 4.50%
Cutter head	max rotation max torque face pressure sensor max working pressure	3.25 rpm 5700 (kN.m) 6 sensor 5 (bar)
Hydraulic jack	Number total axial force max pressure max advance	22 34000 (kN) 350 (bar) 100 (mm/min)
foam	max pressure max fluid flow on the cutter head in the chamber (mixing bar) in the screw	4 (bar) 320 (M3/h) 5 points 3 point 2 points

6.1. Obtained samples and results

Two samples were carried out on a TBM machine using the following sample parameters:

1. Soil conditioning values according to the low amount the slump (slump = 8-10 cm), FIR of 40%, FER of 3, C_f of 2.7%, and applied EPB pressure of 90 kPa.

2. Soil conditioning values according to the low amount the slump (slump = 16-18 cm), water content of 15%, FIR of 157%, FER equal to 10, C_f of 2.07%, and the same EPB pressure.

Table 7 presents the most relevant measure data. Comparing the results obtained, it was observed that the conditioning increased the performance and the efficiency of the cutter head. Therefore, the effect of soil condition may be evaluated, and also the different conditioning amount may be compared. The quality of mixed conditioned soil may be seen in Figure 6.

Table 7. Summary of the results obtained from EPB tunneling machine

Sample set	Theoretical EPB pressure (kPa)	Measured pressure (kPa)			torque (KN.m)	thrust (kN)	Speed (mm/min)	Tensio active consumption (Li)
		top	center	bottom				
Sample 1	90	88	121	175	2372	8290	20.75	213
Sample 2	90	93	114	166	2336	8095	28.75	178
Difference (%)	0	5.7	5.8	5.1	1.5	2.3	38.5	16.5

The actual pressure distribution and theoretical prediction value are in a good agreement. Since one of the important qualities for soil conditioning is the ability of applying and transmitting the pressure inside the chamber, the presented data is of best use when a correct conditioned material is chosen in the EPB applications.

Figure 6. Excavated material test: a) Continuous conditioned material in belt conveyor, b) Optimum conditioned soil in muck car, c) Slump test 1 in the TBM, d) Slump test 2 in TBM.

More regular pressures were observed along the screw and chamber while the optimal conditioned materials were extracted than when the low conditioned soil was being extracted (Table 7). In a low conditioned soil, pressure difference between the top and center EPB sensor is about 33 kPa but in the optimal conditioned soil, this difference is 21 kPa (Figs. 7 and 8). It means that in a low conditioned soil, FER is small, and during excavation, the chamber is full, and in optimal foam parameters, approximately 30% of the chamber volume is filled with foam. In this situation, the torque and thrust trend decrease.

The trend of cutter head torque showed higher mean values for the dry conditioned soil (Figure 10) than the values measured for the optimum conditioning soil.

Furthermore, comparing the thrust trends (Figure 11), a similar behavior was observed. Therefore, the recorded torque and thrust values during the samples may be used to determine if a material is correctly conditioned or not.

The advance speed compared in samples 1 and 2 show that in sample 1, the average advance speed is 20.5 mm/min, and in sample 2, is 30 mm/min (Figure 12). It is almost 50% increase in an advance speed.

The average tensio active consumption in a dry conditioned soil is 213 L, and in an optimum conditioned soil is 178 L ; (Figure 13). In fact, in sample 1 with more tensio active consumption, the excavation quality is lower than sample 2; furthermore, the tensio active consumption in optimum conditioned soil (sample 2) is 16.5% lower than sample 1. Figure 9 shows a little difference in the bottom sensor pressure in low and optimal conditioned soils.

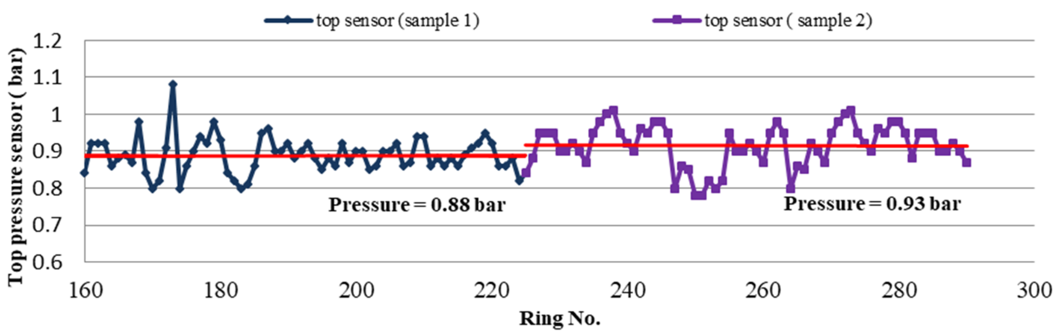

Figure 7. Top sensor pressure.

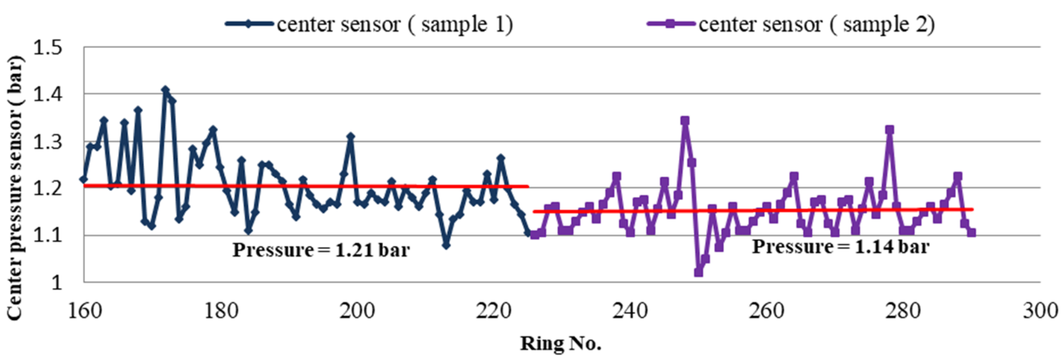

Figure 8. Center sensor pressure.

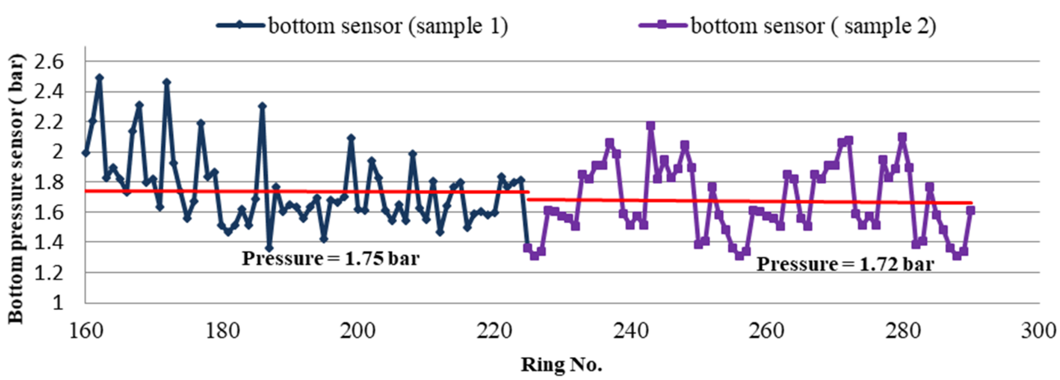

Figure 9. Bottom sensor pressure.

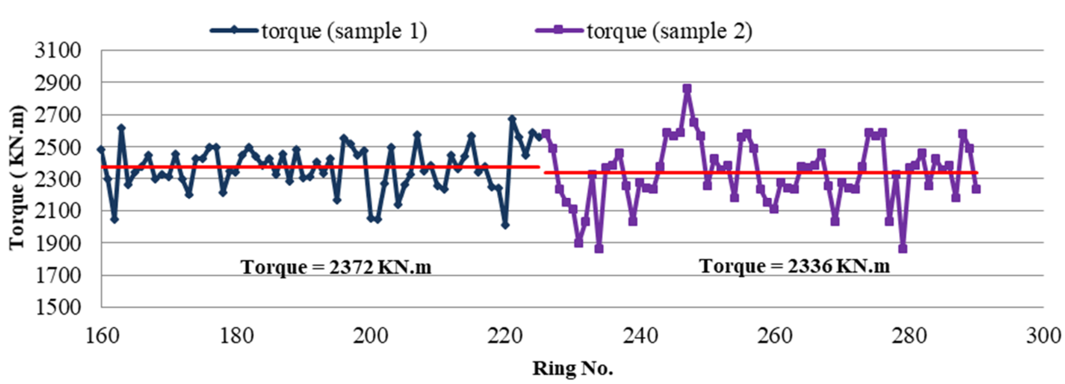

Figure 10. Cutter head torque comparison.

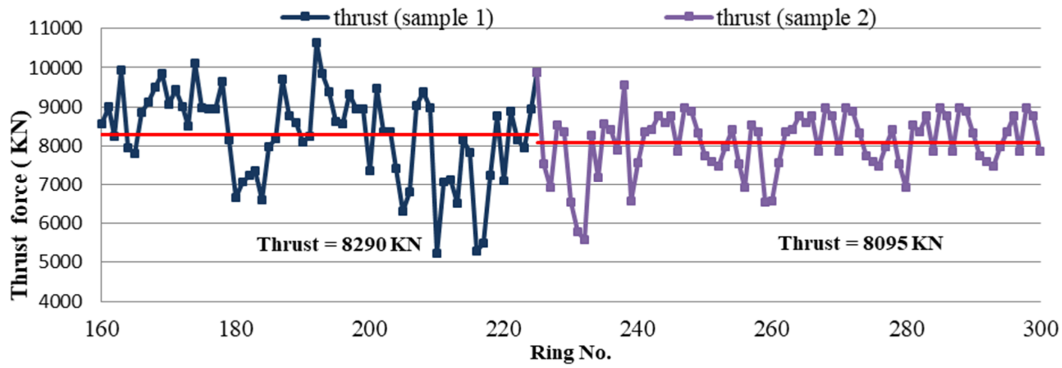

Figure 11. Thrust force comparison.

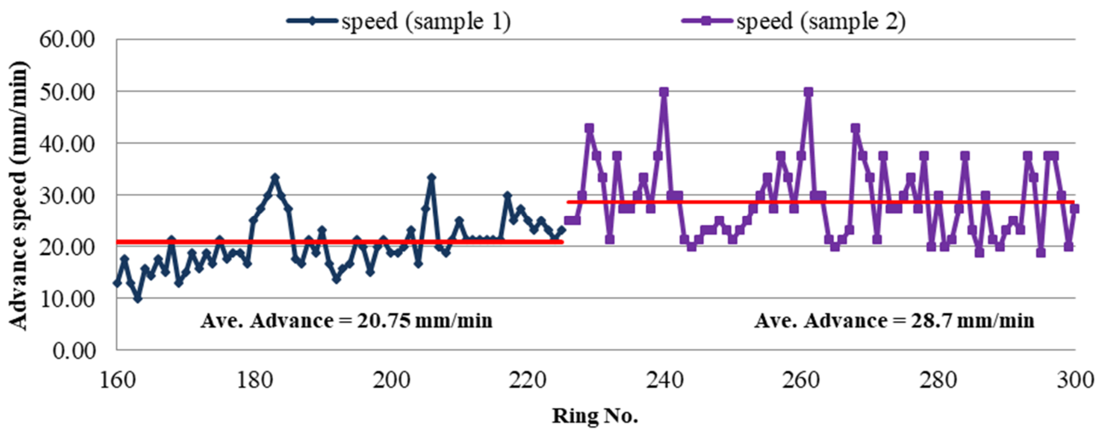

Figure 12. TBM advance rate in samples 1 and 2.

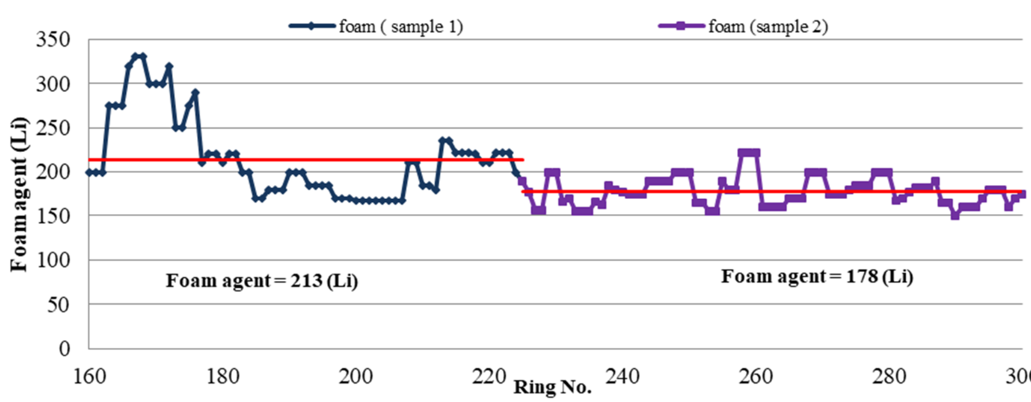

Figure 13. Foam consumption comparison.

A more stable EPB and a better control on the torque and thrust force in relation to the primary setup of parameters (sample 1) was obtained when the test was carried out with the optimum parameters (sample 2). This is because muck was continuously puched out with a constant rate from the screw when using the optimum parameters. The cone fall tests performed at the end were in good agreement with the data obtained from the slump test campaign. In addition to that, the conditioned material lost no water during the extraction according to the measurements, confirming that the extracted material kept the same water content it had before performing the test. Therefore, the optimum parameters for conditioned material (sample 2) kept its functionality after the extraction.

7. Conclusions

One of the major attractions of the EPB technology is its ability to operate in a wide range of ground types, varying from granular soil to highly cohesive clays. This has been made possible through advances in machine processes and also soil conditioning. The slump test may be used to choose the optimal conditioning. It also provides a comparison among the various types of the conditioning products.

A systematic series of slump tests were performed in order to find a relation among the parameters. The systematic application of the slump test on low plastic clay showed that a suitable behavior (very plastic) is only found for a number of water content and FIR combinations, and that a slump cone fall is approximately 140–160 mm; it is often indicated in the technical literature. The most important parameters for the presented mechanized method use a proper amount of conditioning agent and control the agent during the excavation process. Following that, the optimized conditioning technicalwise and economicalwise were determined.

The effect of water during excavation in the chamber was significant. It can determine the allowable limitation with slump-test. The optimum percentage of humidity was found to be in the range of 27.5–30. The amount of 29% was used in calculation and operation. The allowable domain of slump for this conditioned soil was 140 mm to 160 mm. The slump equal to 150 was considered as an applicable quantity for the used-water and foam agent identification. This slump results in the optimum values of FER, FIR, and C_f that have been achieved in the laboratory tests were 10, 157%, and 2.07%, respectively. The cost of foam ingredient consisted of tensio active, water, and compressed air measured in different slump and foam parameters. In addition to that, the cost of optimum used-foam agent in an excavated ring was predicted to be 248 units.

In the laboratorial scale EPB optimized soil, conditioning decreases the torque and thrust force but in the EPB machine, torque and thrust could be constant, and the advance speed increases currently. A significant difference was observed comparing the advance speed measured using different mixes; the measured advance speed while testing a suitable mix was less than about 38.5% of the one measured with a dry mix. Also it appears that the use of this procedure results in an increase in the advance speed and ring built number in a day and a significant decrease in the tensio active consumption.

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محاسبه عمل‌آوری بهینه خاک در حفر تونل با ماشین حفاری مکانیزه *EPB* (مطالعه موردی: پروژه مترو اهواز، خط ۱)

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ارسال ۲۰۲۱/۰۳/۲۸، پذیرش ۲۰۲۱/۰۵/۲۲

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چکیده:

تعیین پارامترهای مطلوب عمل آوری خاک در ماشین‌های حفاری مکانیزه (EPB-TBM) نقش مهمی در رسیدن به نیروی پیشران و سرعت پیشروی مطلوب در فرآیند حفاری تونل متر دارد. خاک رس سیلتی (CL-ML) خط ۱ پروژه مترو اهواز به منظور یافتن پارامترهای عمل‌آوری خاک با درصدهای مختلف رطوبت و عوامل کفساز مورد آزمایش قرار گرفته است. نتایج به دست آمده مقایسه کمی بین پارامترهای مختلف عمل‌آوری خاک و محتوای آب را بیان می‌کند. از این رو ، می‌توان از نتایج آزمون برای تعیین اقتصادی‌ترین و فنی‌ترین پارامترهای عمل‌آوری در شرایط مختلف خاک استفاده کرد. مطابق نتایج، مقدار بهینه نسبت انبساط کف (FER) ، نسبت تزریق کف فوم (FIR) ، نسبت در صد بین ماده سورفاکتانت و حجم آب (C_f) و هزینه تمام شده کف در این خاک (بر اساس هزینه عمل آوری خاک) به ترتیب ۱۰، ۱۵۷٪، ۲/۰۷، ۲۴۸ واحد هستند. عمل آوری خاک با پارامترهای بهینه به دست آمده در حفاری ۱۴۰ رینگ (۲۲۰متر) تونل در دو مرحله در ماشین حفاری TBM تست شد. این نتیجه منجر به هزینه عمل‌آوری کمتر خاک و تقریباً ۴۰٪ سرعت پیشروی بیشتر شد.

کلمات کلیدی: ماشین‌های حفاری مکانیزه EPB، عمل‌آوری خاک، آزمایش اسلامپ، نسبت انبساط کف، نسبت تزریق کف.