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Foam conditioning in EPB tunnelling

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ABSTRACT: Earth-Pressure-Balance (EPB) shields are the most common type of tunnel boring machine in soft ground. Due to recent advances in soil conditioning, EPB-shields have been also successfully applied in coarse-grained soils by using foams as conditioning agents for soft ground, to realize a homogenous support pressure and to ensure low water permeability in water bearing grounds. Until now recommendations for the use of foam conditioning with EPB-shields are based on experiences from job sites.

To come up with a knowledge-based approach for dimensioning foam conditioning applications, different research projects have been carried out and are ongoing in Delft and Bochum and will be described in this paper. A laboratory scale test set-up was used that allowed mixing of foam with soil under pressurized conditions and various test series with foam and soil-foam mixtures were performed. Properties of conditioned soil, like behaviour of flow, stability and water permeability, were tested and analyzed. The research helps to understand the main mechanism of soil conditioning with foam for EPB tunneling. A new recommendation for laboratory practice for foam production and soil-foam-mixtures is given. Apart from the foaming agent, also the foam generator has a significant influence on the quality of the foam.

1 INTRODUCTION

In mechanised tunnelling with active face support, the earth pressure balance shields have a dominating market share worldwide, with hydro/slurry shields far behind. This is due to operational and economical advantages of EPB-shields, although the slurry shield can achieve more precise face support (Thewes 2007). According to measurements performed during drilling of the Botlek Rail Tunnel, the fase support can be variable both along the vertical and the horizontal direction (Bezuijen et al, 2005, Bezuijen and Talmon, 2005).

Earth pressure balance shields in closed mode make use of the excavated material to support the face. Conditioning of the excavated material is often necessary to process the soil to support medium.

For fine grained clayey soils it is often necessary to reduce stickiness, clogging by providing some lubrification (Merrit 2004). For these soils water, polymer or bentonite suspensions are often used as conditioning agents. Thewes and Burger (2003) note that foam can be used with sticky clays to reduce the consequences of clogging.

In coarse- and mixed-grained sandy soil by contrast, it is necessary to increase the porosity until a value above the maximum porosity of that soil and to reduce the permeability of the mixture. Because of the foam, earth pressure shields can also be used in coarse-grained soils, where shield machines with slurry face support were used some years ago (Maidl 1995).

This paper will concentrate on soil conditioning with foam for sandy soil.

2 TECHNIQUE FOR SOIL CONDITIONING AND THEIR GOALS

2.1 *Technique for soil conditioning*

In order to produce foam, water and foaming agent (surfactant) are mixed in defined proportions in a turbulent environment to make a surfactant solution. The surfactant concentration (c_f) describes the percentage by mass of surfactant (Q_f) in the solution (Q_L) (water and surfactant) and ranges according to application between 1.5 and 5%. Alternatively to the mass proportions, the volume flows can also be considered with no further conversion factors, because the densities of water and surfactant are approximately equal (Table 1, Eq. 1).

The surfactant solution is fed together with a stream of compressed air through a foam generator,

Table 1. Overview of important foam parameter for soil conditioning (for parameters see text).

Equation	Calculation
1	$c_f = \frac{Q_f}{Q_l}$
2	$FER = \frac{Q_F}{Q_L}$
3	$FIR = \frac{Q_F}{Q_S} = \frac{Q_F}{v \cdot A_S}$

which contains turbulators. The whirling and turbulent flow through the turbulators causes the surfactant solution to foam. The volumetric relationship between the foam flow (Q_F) under support pressure conditions and the supply of surfactant solution (Q_L) is described by the Foam Expansion Ratio (*FER*) (Table 1, Eq. 2). Typical values for *FER* are between 10 and 25.

The foam is introduced into the existing support medium in the excavation chamber through openings in the bulkhead and cutter head. It is also possible to feed foam into the screw conveyor.

The ratio of the volume flows of the injected foam (Q_F) and the excavated soil (Q_S) is described as Foam Injection Ratio (*FIR*) and can be calculated depending on the advance rate (v) and the face area (A_s) (Table 1, Eq. 3). The volume flows of the individual foam ingredients can also be calculated depending on the advance rate Various parameters for soil conditioning with EPB shields were analysed in Thewes and Budach (2010 b).

2.2 *Goals of soil conditioning*

For coarse- and mixed-grained soils, the objectives of conditioning with foam result from the required characteristics of the support medium:

- Suitable flowing behaviour of the support medium to ensure sufficient flow of material in the excavation chamber and the screw conveyor,
- Support of the entire face with nearly homogeneous material to transfer the support pressure to the surrounding ground,
- Reduction of the water permeability, so that water flow during excavation hardly influences the porosity of the mixture. For example too much water flow into the soil mixture in the screw conveyor may lead to a sand-water mixture that flows easily through the conveyer, so that the necessary pressure difference cannot be maintained. The increase of the compressibility of the support medium, in order to dampen volume and support pressure fluctuations in the excavation chamber caused by the process,
- Reduction of the internal friction of the support medium, in order to reduce the drive torque and thus the energy consumption of the cutterhead and screw conveyor and also to reduce wear on the cutting tools and other mechanical components.

Table 2. Overview of desired properties of support media of EPB-shields (Thewes and Budach 2010 a).

Parameter	Value
Permeability	$k_f < 10^{-5}$ m/s
Consistency for material flow	$0,40 < I_C < 0,75$
Consistency for sufficient pressure gradient in screw conveyor	$0,60 < I_C < 0,70$
Compressibility	Depending on geological properties of soil and on dimensions of shield machines
Consistency and plasticity for low stickiness	$I_C < 0,50$ and/or $I_P < 20\%$

k = water permeability [m/s], see DIN 18130, T1; $I_C = (w-w_p)/I_P$ consistency index of clay [–], see DIN 18122, T1; $I_P = (w_l-w_p)$ plasticity index of clay [–], see DIN 18122, T1; w = water content of clay [–]; w_l = water content of clay at liquid limit [–]; w_p = water content of clay at plastic limit [–].

To use an EPB-shield without soil conditioning, the soil should have properties as listed in Table 2, using the Atterberg limits (w_l and w_p) of the soil. These are based on results of published experience for drilling in clayey soils.

3 OVERVIEW OF PREVIOUS WORK

Guidelines for foam injection ratios based on experience from job sites were published by EFNARC (2005). The *FIR* values shown in Table 3 can be correlated to the porosity of various soil types.

To compare *FIR* and porosity, an overview of porosities of chosen soils is given in Table 4. The indicated bandwidth of typical foam injection ratios, however, is larger than the bandwidth of the porosities and this results in a high level of uncertainty for any prognosis of the foam consumption of a planned tunnel drive with an EPB-shield. Maidl (1995) describes the calculation of the necessary *FIR* depending on the maximum porosity of the soil. The volume of injected foam should be at least so large that the sum of the volumes of fine material, remaining water, air bubbles and

Table 3. Recommended foam injection ratio for various soils (EFNARC 2005).

Soil	*FIR* [%]
Sandy clay—silt	40–60
Sand—clayey silt	20–40
Sand	30–40
Clayey gravels*	25–50
Sandy gravels*	30–60

*High stability and anti-segregation properties needed to develop and maintain a cohesive soil as impermeable as possible.

Table 4. Overview of porosity of chosen soil types with medium and high density, see Hiltmann (1998).

Soil	Porosity n
Sand	0.30–0.40
Silt	0.37–0.45
Clay	0.42–0.58

foam is equal to the porosity of the coarse content of the soil in loose bedding.

Bezuijen (2002) has quantified how the permeability of the soil influences the necessary amount of foam to be injected. However, likely also other mechanisms (for example the size of the foam bubbles compared to the size of the pores) play a role.

During tunnelling often a higher *FIR* is required than the expected *FIR* and therefore the recommendation has to be checked based on experiences on comparable soils.

The properties of the produced foam are important for the conditioning of coarse-grained soil in order to ensure foam of constant quality and to achieve reproducible results. Important factors influencing the foam quality are the type of foaming agent and its concentration in the foaming liquid, the Foam Expansion Rate (*FER*), the volume percentage of foam in the soil (*FIR*), the type of foam generator used and the level of counterpressure. Until now, only few scientific studies were conducted to examine the influences of the listed factors for producing foam for soil conditioning (Maidl 1995, Quebaud et al. 1998, Merrit 2004).

Maidl presented grain size distributions of soils where and EPB with foam can be used. Due to technical progress, it is possible now to use EPB for soils with coarser grains than recommended by Maidl. Quebaud et al. investigated the some physical properties of foam with and without polymer additives and suggested that the 'slump' (shortly described in section 4.2) of a foam-sand mixture should be between the 100 and 150 mm. Merrit investigated the efficiency of foam injection in stiff London clay and found that up to a *FIR* of 60% most of the water was absorbed by the clay, breaking down the foam. Adding polymer was more effective.

So far, no detailed recommendations for foam production in laboratories for simulation soil conditioning in EPB tunneling were given. In lab tests foam typically is produced at flow rates much lower than on an EPB machine. Due to different principles of foam production most of the results are not comparable with results of real-scale foam production.

A variety of experimental studies were conducted by different researchers about the conditioning of coarse-grained soil with foam (Maidl 1995, Quebaud et al. 1995, Merrit 2004, Borghi 2006, and Peila 2009). Here, the foams were produced at atmospheric conditions, then mixed with different types of soil and placed in a pressure tank. The conditioned soil was pressurised and extracted with a screw conveyor to characterise the pressure gradient and the material flow in the screw conveyor. With this experimental setup it is difficult to simulate the closed mode of an EPB-Shield because the foam-soil-mix, when being produced at atmospheric pressure, will undergo significant changes of plasticity and permeability upon pressurization. Bezuijen and Schaminée (2001) performed model experiments in which the foam was created with a 'TBM' foam gun under a pressure of 1 bar above the atmospheric pressure. However, they used only two foam agents each with its own foam gun and performed a limited number of tests.

Therefore, further research on foams and foam-soil-mixes are advised to gather new information about their quality. They are also necessary to set up improved guidelines for foam conditioning for upcoming projects.

4 METHODS TO DETERMINE THE QUALITY OF FOAMS AND SOIL-FOAM-MIXTURES

4.1 *Methods to determine the quality of foams*

At present, there is no standardized method for determining the quality of foam for EPB-shields neither on shield machines nor in laboratories. For foams to be used with an EPB-shield, the following requirements can be defined. The foam should

- have a constant and uniform density, which means that liquid and air are completely mixed and that all parts of the produced foam have the same properties,
- be stable for the duration of stay in the excavation chamber and
- have a homogenous structure of bubble size.

To determine the foam parameters, the following test methods can be used. The focus of these methods is the determination of parameters in laboratories, but the methods can also be adapted for shield machines.

The density of the foam is measured to determine the volumetric content of liquid and air and to control the *FER*. The density is determined by the weight of the foam by known volume. According to EFNARC (2005) the drainage time is evaluated to get information on stability and drainage performance of foam. Therefore a funnel with a sieve is used and the time period is measure, for draining the liquid of the foam. The size of the foam bubbles can be measured by microscope to control its homogeneity (Pena 2007).

4.2 *Methods to determine the quality of soil-foam-mixtures*

So far, there are also no standardised test methods available to determine the quality of conditioned soil, the foam-soil-mix. Some requirements regarding unconditioned soil with a high content of fines are presented in Table 2. Since these requirements cannot be fulfilled by a coarse-grained soil, a range of test methods has been developed to determine additional properties of coarse foam-soil-mixes as support medium. The parameters that can be used to describe these additional properties are:

- density of the support medium to determine the distribution of support pressure across the tunnel face
- workability, relative yield stress and the relative viscosity of the support medium
- permeability to allow for conclusions regarding the range of applicability of EPB-shields and to determine the water flow from the tunnel face
- compressibility of the support medium to evaluate the sensitivity towards variations in volumetric flow
- stability of the support medium against unmixing, especially during halt of cutterhead rotation

A method to measure the density in the field through the bulkhead is described by Bezuijen et al. (2005). The density of the soil-foam-mixture can be measured by determining its weight and volume. The workability (deformability) can be determined by using the slump test as an index test. Here, soil is filled into a special cone, which then is lifted. By measuring the height of the soil-foam-mixture before and after lifting the cone it is possible to determine the slump. The test procedure follows ASTM C143 (1999). The water permeability can be measured by determination of the volume flow of water that flows through a sample of soil-foam-mixture according to DIN 18130. For the measurement of the compressibility of the soil-foam-mixture it is placed in a transparent cylinder and after applying different pressures the volume is measured. The stability of the media can be described by measuring its volume over time.

5 RESULTS OF EXPERIMENTAL RESEARCH ON FOAMS AND SOIL-FOAM-MIXTURES

5.1 *Results of test with foams*

At Ruhr-University Bochum's tunnelling laboratory a series of experiments regarding the production of foam was conducted, introducing a wide variation of process parameters. The following parameters were varied during the tests:

- flow rate of foam
- type of foam gun
- level of counter pressure
- length of conveying system
- type of conditioning agent
- concentration of conditioning agent c_f
- Foam Expansion Ratio (*FER*)

An industrial foam generator was installed, which allows for flow rates similar to real projects with EPB-shields, so that foam can be produced under realistic conditions. With this foam generator, as shown in Figure 1, the production parameters, such as the flow rates of air and liquid, the usage of a pressure tank or the length of the piping system can be varied. Three types of foam guns with different mechanical inserts for the creation of turbulences were used during the tests.

Numerous different qualities of foam have been produced and their properties were characterized. As selected result the mass of the drained liquid

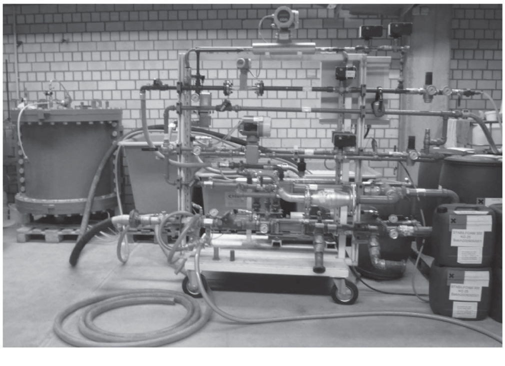

Figure 1. Foam generator of the Institute for Tunnelling and Construction Management at Ruhr-University Bochum, Germany (Thewes et al. 2010).

from the foam is shown as a function of time. Results of the tests showed, that the drained liquid mass from various foams strongly depends on the choice of foaming product and of the foam generator. For the tests four different foaming products and two different foam generators were used to produce foam under atmospheric pressure. The *FER* of the foam was 15 and $c_f = 3\%$. 80 g of each foam was placed in a filter funnel with a diameter of approximately 13 cm and porosity 1 (maximum 100–160 μm). Figure 2 shows a filter funnel to determine the drain liquid from the foam.

In Figure 3 the thin lines show the drainage times of foams produced with Foam Generator 1 (FG1), and the thick lines show the drainage times of foams produced with FG2. Product 1 and Foam generator 2, compared with foams from other combinations of products and foam generators, has the highest drainage time of almost 1200 seconds for 40 g of drained liquid and also more or less constant increase of the drained liquid.

The combination of product 1 and foam lance 2 shows an almost ten times longer drainage time than product 4 and foam lance 1 for 40 g of drained mass. The first combination therefore results in a more durable foam.

Since in the filter funnel the hydraulic gradient is approximately 1, the results can be used to determine the permeability of the foam itself. The most impermeable foam (the combination Product 1—FG2) has a permeability of $2.7*10^{-6}$ m/s, the most permeable (Product 4—FG1) a permeability $2.5*10^{-5}$ m/s. So there is nearly a factor of 10 difference. For Product 1, changing the foam gun only from FG1 to FG2 leads to a 2.7 times lower permeability. For Product 4 this is a factor of 1.9.

The most likely explanation for the differences found between the two foaming generators is that FG2 generates finer foam bubbles, resulting in a lower permeability for the water between the foam bubbles.

Figure 2. Filter funnel for determination of drain time.

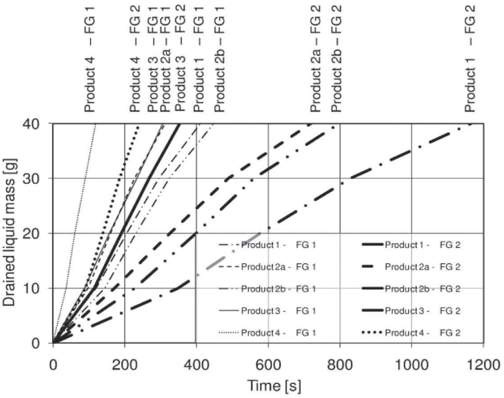

Figure 3. Drainage times from different foaming products and different foam generators.

Further research is necessary how the foam stability as found in these laboratory tests relates to the quality of the foam necessary in a TBM. From the tests described by Bezuijen et al. (1999), it appeared that without drainage a sand-water-foam mixture can be remarkable stable. In a foam mixture without soil and without drainage the air bubbles will move upwards due to the buoyancy forces. However, with soil, the upward directed movement of the air bubbles is hampered by the soil particles resulting in a more stable mixture. The question to be answered in further research is how the stability of a foam-water-air mixture is influenced by the shear stresses that are exerted on it in the mixing chamber and in the screw conveyor.

The results of the tests on foam have shown that there is a great influence of the input parameters on the foam production on the properties of the resulting foam. To the authors knowledge, the influence of the foam gun has not been reported before. The properties of foam during lab testing should be characterized with foam generators, which use a principle similar to that on Earth Pressure Balance Shields.

5.2 *Results of test on soil-foam-mixtures*

Different soil-foam-mixtures with a variation of the injection ratio *FIR* have been tested. As a selected result, the slump test of mixtures with increasing injection ratio is shown. Sand with a grain size diameter between 0.2 and 0.6 mm was used with a water content of 10%. The foam parameters were $c_f = 3\%$ and *FER* = 15. Initial tests showed that there is a high influence of the mixing time on the density of the soil-foam-mixture. For comparable results the soil was always mixed with foam within a gravity mixer for 30 seconds. During laboratory testing it is of importance to add the necessary amount of foam immediately after production to the soil to keep the influence of the time-dependent change of foam properties to a minimum.

Figure 4 shows the results of the slump test with increasing foam injection ratio. With increasing *FIR* the slump value will also increase. On job sites values of the slump tests can range between 5 or 25 cm (Vinai 2006). Normally, slump values between 10 and 20 cm are within the range of the practical use of the conditioned material. For these values a *FIR* of round 10 and 20% can be determined with the performed tests.

The results of the tests on conditioned soil in laboratory under atmospheric condition show that the *FIR* in Sand 0.2–0.6 mm was lower than the recommendend *FIR* of EFNARC. Due to the water content of w = 10% the water will fill the pores and the required volume of foam is lower, but due to the water, the permeability of the mixture will be higher.

Normally a foam expansions ratio of around 15 is recommended for injection in sand. Due to the presence of pore water the effective *FER* in the mixture can be much lower. For a *FER* which is much larger than 1 and saturated soil. The effective FER_s of the mixture is not determined by the original *FER*, but by the amount of foam injected, resulting in the relation (Bezuijen, 2002):

$$FER_s = \frac{FIR}{n} \tag{1}$$

where n is the porosity of the soil. This means that when foam is injected with a *FER* of 15 in saturated sand with a porosity of 40% and the amount of foam injected is 40% of the soil volume (thus *FIR* is 0.4) then the effective *FER* (FER_s) in saturated sand is only one. Consequently the muck will be very wet.

Bezuijen et al. (1999) have shown experimentally that consequently the permeability of a saturated sample injected with foam can be 50 times higher than for a sample that is unsaturated before the foam injection.

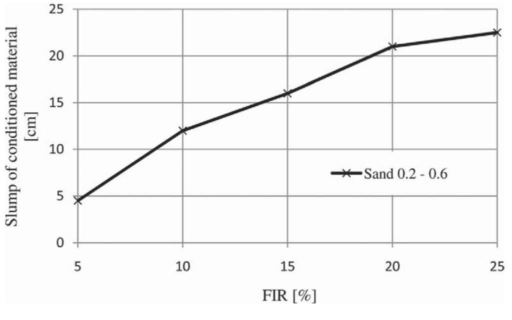

Figure 4. Slump of a soil-foam mixture with increasing *FIR*.

6 RECOMMENDATIONS FOR PRACTICE

6.1 *Recommendations for foam production*

From the results of the tests on realistically produced foams, various influences on the investigated properties, which are shown in Table 5, can be determined depending on the production parameters. Mainly, the choice of foam generator and the conditioning agent have great influence on the drainage time and the bubble size of the foam. For the investigation under support pressure, the pressure was increased up to 1.5 bar relative excess pressure. This showed that the excess pressure has only a slight influence on the density, but a large influence on drainage time. The bubble size of the foam, which is related to drainage time, so far could not be determined under pressure because no suitable method of optical measurement is available.

Results as described in this paper indicate that a smaller bubble size leads to a longer drainage time and consequently to more stable foam. However, it is likely that the bubbles need a minimum dimension. When the bubbles size becomes too small it is possible that the bubbles migrate

Table 5. Overview of qualitative influence of different parameters on the quality of foam.

		Influence on		
		Density	Drainage time	Bubble size
Type of foam gun		o	++	++
Volume flow of foam Q_F	FG1/FG2	+/o	+/+	+/+
Pumping pressure	FG1/FG2	o/o	+/+	o/o
Length of pumping line	FG1/FG2	o/o	o/o	o/o
Conditioning agent	FG1/FG2	o/o	++/++	++/++
Surfactant concentration c_f	FG1/FG2	o/o	o/+	+/+
Foam expansion ratio *FER*	FG1/FG2	+/o	+/+	+/+
Back-pressure p_{supp}	FG1/FG2	o/o	++/+	x/x

FG1 = foam gun 1; FG2 = foam gun 2; o = no or little influence; + = medium influence; ++ = great influence; x = not determined.

Table 6. Overview of qualitative influence of different parameters on the quality of soil-foam mixtures.

	Influence on			
	Density	Flow behaviour	Water permeability	Compression
Foam	o	+	++	o
FIR	++	++	+	++
FER	o	++	++	+
Grading curve	++	++	++	+

o = no or little influence; + = medium influence; ++ = great influence.

though the pores of the not yet excavated soil and that would prevent an effective 'plastering' of the face, which may lead to instability. This aspect will be subject of further research.

6.2 *Recommendation for soil-foam-mixtures*

Based on the results of the tests, the influence on the essential parameters of the support media can be derived (Table 6). Regarding individual test results, reference is made to Thewes (2010). Apparently the properties of the support media depend greatly on the properties of the soil. In addition, the water permeability of the support media can be strongly influences by the type of the foam; the density,

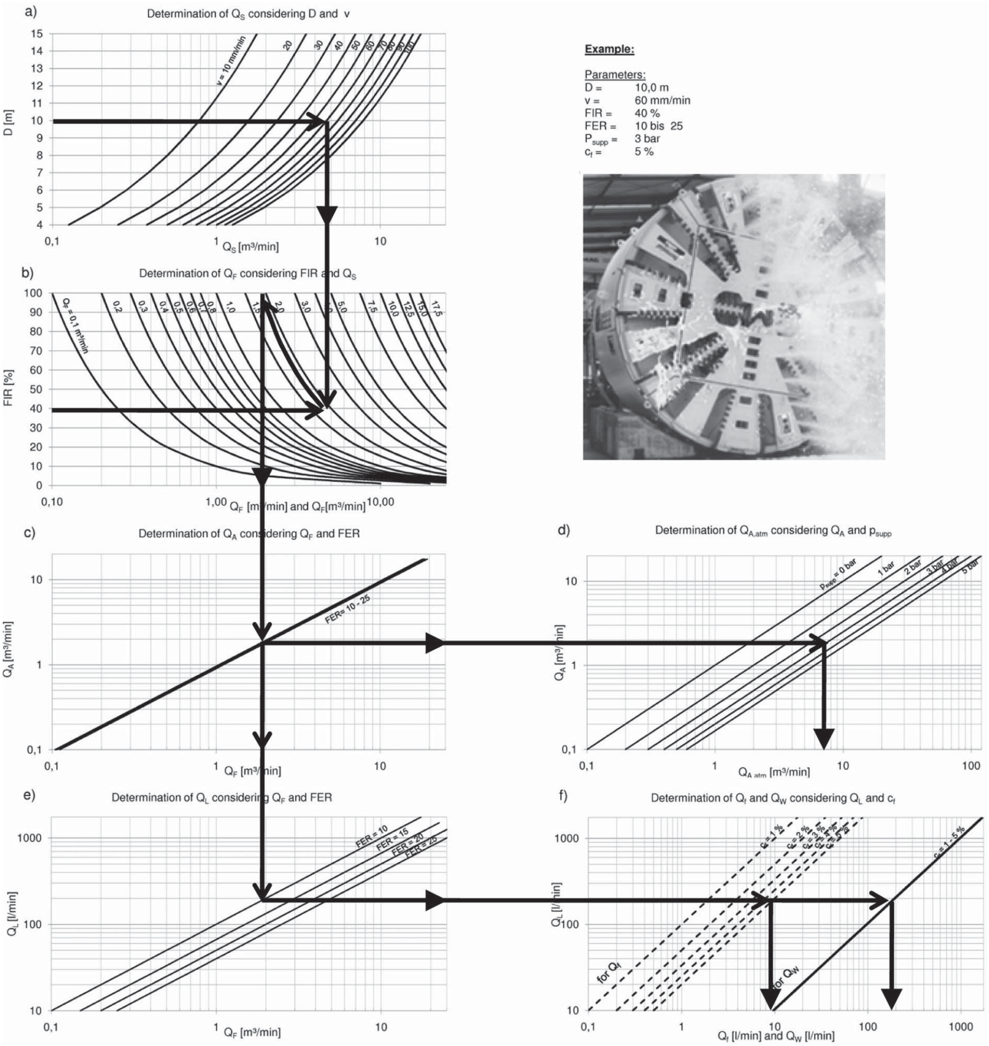

Figure 5. Graph for determination of production parameters of foam production (Budach 2010).

the flow behavior and the compressibility by the *FIR* and the flow behaviour and water permeability by the *FER*.

For the dimensioning of foam generators and for checking volume flows during tunnelling a graph was developed by Budach (2010) (see Fig. 5, at the end of the paper).

The volume flow of the soil Q_S can be calculated depending on the shield diameter D and the advance speed v, see part a) of the graph. For example, an EPB-Shield with a diameter of 10.0 m and an expected advance speed of 60 mm/min results in the volume flow of the soil Q_S, here 4.7 m^3/min.

The required volume flow of the foam under support pressure conditions depending on the volume flow of the soil Q_S and the *FIR* can be determined in part b) of the graph. The required volume flow of foam Q_F can be calculated by getting the intersection of the vertical line of Q_S and the horizontal line of *FIR*. The value can be read at the top of the diagram. Therefore a parallel line to the plotted lines will be drawn and the intersection at the top will be determined. In the example, the volume flow of the foam Q_F is 1.9 m^3/min.

A vertical line of the value of Q_F will be extended in part c) of the graph for determine the volume flow of the air under support pressure Q_A. This line will cross the plotted line of the *FER*. A horizontal line will be drawn through this point to the right side. The volume flow of the air under support pressure Q_A can be determined to 1.7 m^3/min.

The volume flow of the air under atmospheric condition $Q_{A,atm}$ depends on the support pressure p_{supp} and Q_A. The horizontal line of part c) will be extended in part d) and will cross the line with the expected support pressure. The value of $Q_{A,atm}$ can be determined by draw a vertical line and cross the horizontal axis at the bottom of that part. The value for $Q_{A,atm}$ is 6.8 m^3/min.

The volume flow of the liquid Q_L can be determined in part e) of the graph. The drawn line of the lowest *FER* is necessary for the identification of Q_L. This line and the extended vertical line of Q_F will be crossed and a horizontal line will be plotted in this part. The volume flow of the liquid can be read at the right side of the graph. The value of Q_L is 190 l/min in this example.

This value is necessary for the determination of the volume flow of surfactant Q_f and the volume flow of water Q_w. Both depend on the concentration of c_f. For determination of Q_f the horizontal line will be crossed with the line with the highest value of c_f. A vertical line will be drawn through this point and at the bottom of the diagram the volume flow of the surfactant Q_f can be determined. This procedure is also necessary for the determination of Q_W. The values are 9.5 l/min for Q_f and 190 l/min for Q_W.

This example does not take into account pore water and pore water flow. As mentioned pore water decreases the effective *FER* and pore water flow may lead to a loss of foam volume (the water in the foam flows into the soil due to the higher pressure in the foam than in the surrounding pore water). Bezuijen (2002) presents equations how pore water and pore water flow influences the amount of foam to be injected and the effective *FER* (the foam expansion ratio when the pore water is taken into account, thus the ratio between the volume of air and the volume of the water in the pores with added the volume of pore water).

7 CONCLUSION

Recent experimental research on the foam conditioning during EPB tunnelling has focused on the production of the foam itself as well as the foam-soil-mix resulting from soil conditioning. Regarding the foam produced for lab tests it has become clear that the foam generator has a rather significant influence on the foam quality. It is therefore important to calibrate a scaled down foam production unit used in a laboratory so that foam it produces will be comparable to foam produced at real scale, or to use a real scale generator. Further it is important to frequently check the foam which is produced during a tunnel drive regarding its quality parameters.

Besides the type of mechanical foam production equipment, also the type of foaming agent has a strong influence on the quality of the foam and thus on the effectiveness of the conditioning process.

The research presented here has shown that foam bubbles of a smaller size lead to a more stable foam. In future research it will be investigated whether there are limits to this conclusion, for example because very small bubble may possibly migrate through the pores of unexcavated sandy soil.

The amount of pore water and pore water flow under influence of the applied pressures in an EPB have a significant influence on the foam behaviour and therefore the stability of the EPB tunnelling process when drilling in sand.

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