Soil Conditioning with Artificial Soil and Foam in EPB-Tunneling

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ABSTRACT: In mechanised tunnelling with EPB-shields operating in closed mode, the excavated soil is used as support medium in order to assure a sufficient stabilisation of the tunnel face. Coarse grained or high permeable soils doesn't exhibit adequate conditions to be used as a support medium in an EPB shield, which require the increase of cohesion and plastic behaviour of the excavated soil. In this case, the addition of high density slurry solely is not sufficient: It is necessary to create an artificial soil. Previous research has shown that laboratory tests can be of assistance in the planning of EPB tunnel projects regarding the conditioning. In this study the conditioning with artificial soil, a newly developed 2 component TamSoil 2000CP system based on high density slurry mixed with Polymer A and the use of an independent Polymer B was investigated. Regarding to the workability and the permeability, laboratory tests were carried out to investigate the set of conditioning parameters for a high permeable coarse grained soil.

1 INTRODUCTION

For tunnelling with an unstable tunnel face the closed mode with active face pressure is mandatory. This mode is also the most frequently used and classic operating mode of EPB shields machine and includes an extensive soil conditioning. EPB shields operating in closed mode use the excavated soil as support medium in order to assure a sufficient stabilisation of the tunnel face. While clayey and silty soils often exhibit adequate conditions that are necessary for efficient face support and hence limit settlements, applications of EPB shields in non-cohesive, coarse-grained or high-permeable soils require a treatment of the excavated soil (soil conditioning). Soil conditioning temporarily provides the support medium with adequate properties. There are different types of additives are used for soil conditioning (foams, polymers or slurries with fines). According to (Budach & Thewes, 2013) the aims of soil conditioning are:

- adequate workability and flow behaviour for a homogeneous support pressure transfer
- reduction of water permeability as avoidance of uncontrolled water inflow into the excavation chamber
- reduction of inner friction in order to reduce wear and the demand for power
- sufficient compressibility as compensation of support pressure fluctuations in consequence of the advance

The investigation of the water permeability and the workability (flow behavior) are important parameters for pre-studies of planned advances (Borio & Peila, 2010; Galli, 2016). In coarse soils with an amount of less than 10% of fines or even less than 10% of sand it is not possible to produce the adequate properties of the support medium (flow behaviour, permeability, compressibility, stability) by adding solely foam or suspensions of fines. Therefore a combination of additives has to be used for soil conditioning (artificial soil, foam and polymers).

Therefore, the newly developed two-component system by NORMET named TamSoil 2000CP combined with a high density slurry creates an artificial soil, which fills the pore space of the soil and generates an adequate earth muck for EPB tunnelling. This artificial soil can be used for an easy addition of highly viscous fines to the excavation chamber in very coarse ground or for a quick switch from open to closed mode under all relevant geotechnical conditions if necessary. It also can serve as first fill of the excavation chamber for an immediate TBM start under pressurized conditions.

Former studies evaluated the feasibility of conditioning rock masses for EPB tunnelling with regard to the workability, soil permeability, pressure transmission on the tunnel face and the ability to extract the material with a screw conveyor (Peila et al., 2013).

In this paper conditioning with artificial soil was investigated in laboratory tests with regard to the workability, permeability and stability of the earth muck.

2 MATERIALS AND TESTING PREPARATIONS

The investigations described in this paper are performed on a laboratory scale at the Institute for Tunneling and Construction Management in Bochum.

2.1 *Soil*

The grain size distribution of a soil has a big effect on the conditioning parameters (Peila et al., 2009; Budach, 2012). For the tests a coarse soil has been selected. Its grain size distribution curve is outside the classical field of application of EPB-Shields. Figure 1 shows the grain-size distribution curve of the sample for the tests according to the extended application range of EPB shields. The water content of the ground has been selected to 0 %. Additionally, in further tests the content of water in the investigated soil was increased to 5 %.

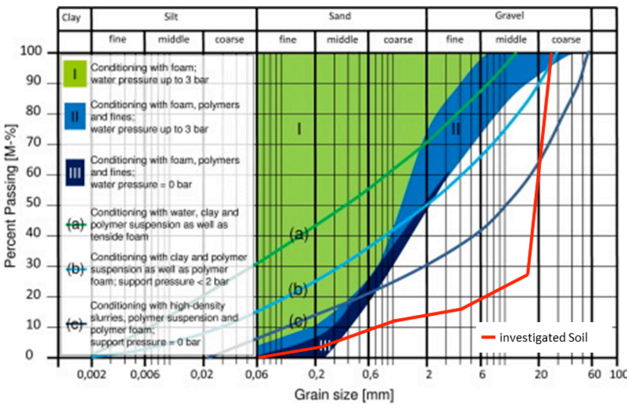

Figure 1.Extended application range of EPB shields (BUDACH) with grain size distribution of the investigated soil.

2.2 *Conditioning Agents*

The conditioning agents used in this tests are surfactant foam, a High density Slurry (HDS) which consists of bentonite and limestone powder, and artificial soil produced from High density Slurry and a two component reactive System (TamSoil 2000CP). Furthermore a polymer (TamSoil 1000CP), which binds the excess water has been used.

2.2.1 *Foam*

Tenside foams can be used as a conditioning agent in cohesionless soils to generate an adequate earth muck. The concentration of the liquid c_f and the mixing ratio of air and liquid measured by the parameter FER (Foam Expansion Ratio) have an influence on the stability and dryness of the foam. In (Thewes & Budach, 2010) definitions of the production parameters and factors affecting foam production and quality is explained.

A sufficient stability of the foam results in long drainage times and is important for the decomposing process of the foam in the support material.

Through injection points in the cutterhead, the foam can be added to the tunnel face. At the pressure bulkhead and in the screw conveyor the foam can also be injected. The volume of the added foam can be controlled through the conditioning parameter FIR (Foam Injection Ratio) (Budach, 2012).

The Foam Injection Ratio (FIR) in Vol.-% is expressed by Equation 1:

$$FIR = \frac{V_{Foam}}{V_{Soil}} \cdot 100 = \frac{Q_{Foam}}{Q_{Soil}} \cdot 100 \ , \qquad (1)$$

where V_{Foam} is the volume of the foam [m^3], V_{Soil} is the volume of the soil [m^3], Q_{Foam} is the foam volume flow [m^3/s] and Q_{Soil} is the soil volume flow [m^3/s].

The conditioning parameters in this investigations were set as follows:

Foam (Condat CLB F5/TM):
- Concentration c_f: 3.0 %
- Foam expansion ratio (FER): 15
- Foam injection ratio (FIR): variable

The foam is produced with a foam generator which is calibrated to a realistic foam generator on an EPB shield. By regulating the flow rate of the liquid and the air, the FER can be regulated. Figure 2 shows the foam generator of the

Institute for Tunnelling and Construction Management at the Ruhr-University Bochum.

Figure 2.Foam generator in the laboratory of the Ruhr-University Bochum, equipped on real-scale foam generator.

2.2.2 *High Density Slurry*

To create an adequate earth muck for tunneling with an EPB shield, the grain size distribution of the excavated soil should have a certain amount of fines. For the classical application range of an EPB-shield the content of fines is set by 30 % (Maidl, 1995). The use of filler suspensions artificially increases the fines content of the excavated soil and thus theoretically extend the grain size distribution curve into the fine-grained area of the application diagram. For the addition of suspensions it is necessary to have a separate injection system on the machine.

High density slurries are produced of a bentonite suspension with limestone powder (Figure 3). The amount of limestone powder is depending on the foreseen density of the slurry. Similar to the injection of foam and according to Budach 2012 the injection of the slurry can be controlled by the SIR (Slurry Injection Ratio).

The Slurry Injection Ratio (SIR) in Vol.-% is expressed by Equation 2:

$$SIR = \frac{V_{Slurry}}{V_{Soil}} \cdot 100 = \frac{Q_{Slurry}}{Q_{Soil}} \cdot 100 \ , \qquad (2)$$

where V_{Slurry} is the volume of the slurry [m^3], V_{Soil} is the volume of the soil [m^3], Q_{Slurry} is the slurry volume flow [m^3/s] and Q_{Soil} is the soil volume flow [m^3/s].

The conditioning parameters in this investigations were set as follows:

Bentonite (IBECO B1): 5%
Limestone:
for density of 1.6 g/cm³: 1500 g/l
for density of 1.8 g/cm³: 2500 g/l
for density of 1.9 g/cm³: 3000 g/l

Figure 3. Production of a High Density Slurry by adding limestone powder into the bentonite suspension

2.2.3 *Artificial Soil based on TamSoil 2000 CP*

The two component polymer system TamSoil 2000CP is a new product from Normet and provides a stiffening of the suspension respectively of the conditioned soil. Component A is an integral part of the high density slurry without any negative influence regarding the slurry properties. Hence, it is a perfect constructional operations solution for the transport to the tunnel face and the injection points. The HDS with component A can remain in the conveyor pipes without hardening. For this reason, the fast and flexible use is possible if required. Component B can be easily injected (with static mixers) at various points on the TBM, depending on the actual needs, which is a strong benefit of component B. After adding component B the artificial soil will immediately increase its consistency and transforms cohesionless and highly permeable soil into perfect EPB soil.

Therefore, this product is a new solution for the conditioning of a very coarse-grained soil. The Injection of the artificial soil is analogue to the injection of a high density slurry.

The Artificial Soil Injection Ratio (ASIR) in Vol.-% is expressed by Equation 3:

$$ASIR = \frac{V_{ArtificialSoil}}{V_{Soil}} \cdot 100 = \frac{Q_{ArtificialSoil}}{Q_{Soil}} \cdot 100 \; , \qquad (3)$$

where $V_{ArtificialSoil}$ is the volume of the artificial soil [m^3], V_{Soil} is the volume of the soil [m^3], $Q_{ArtificialSoil}$ is the artificial soil volume flow [m^3/s] and Q_{Soil} is the soil volume flow [m^3/s].

The conditioning parameters in this investigations were set as follows:

Artificial Soil produced from Slurry and a two component reactive (AS):
High Density Slurry (HDS) of 2.2.2 with
TamSoil 2000CP Component A: 10g/l
TamSoil 2000CP Component B: 5 g/l

2.2.4 *Water binding Polymers*

In case of an excess of water, the 2k Polymer approach seems to loose efficiency (which still needs to be verified on the TBM).
In this case, the use of a new generation of highly eco-compatible water binding polymers is proposed: TamSoil 1000CP. This liquid water binding polymer can be added into the working chamber or into the screw conveyor and increases very efficiently the consistency of the soil/slurry mixture. The Polymer Injection Ratio (PIR) describes the amount of the added Polymer related to the total mass.

Figure 4. Water binding polymer TamSoil 1000CP (left) and the effect after adding water (right)

2.3 *Preparation of the High Density Slurry and the Artificial Soil*

The Bentonite suspension has to be prepared one day before the experiments. In order to achieve the desired density of the suspension, limestone powder was added in the appropriate amount on the test day.

For conditioning tests with artificial soil produced from High density slurry and TamSoil 2000CP, the HDS was exceeded first with the component A. Before adding the artificial soil into the gravity tumbler, component B of TamSoil 2000CP was injected in the slurry. During the mixing process of the slurry, both components react with each other to the artificial soil. After that, it was added to the investigated soil.

Figure 5 shows the HDS before and after adding component B of TamSoil 2000CP. After the reaction of the two components, the slurry changes to a sticky paste which could be used to extend the grain size distribution of coarse grained soils.

Figure 5.Production of artificial soil based on High Density Slurry and TamSoil 2000 CP (left: HDS with component A. Right: Slurry turned into Artificial Soil after adding component B

3 EXPERIMENTAL PROGRAMME AND TEST CONDUCTIONS

Different amounts of conditioning agents were added to the soil in order to generate the support medium. A detailed list of the conditioning agents are shown in chapter 2.2. The only variation parameter for the production of the conditioned soil mixtures, were the Slurry Injection Ratio (SIR), the artificial soil produced from slurry and TamSoil 2000CP Injection Ratio (ASIR) and the Foam Injection Ratio (FIR). After production of the conditioned soil mixtures, the samples were investigated in a test in order to evaluate the workability. Based on these results some samples were examined for a test series of three experiments in order to the permeability. The tests and their procedures are presented in the following subchapters.

3.1 *Sample preparation*

Before the tests start, the conditioned samples were mixed in a standard gravity tumbler for 1 minute. Between each addition time points, the sample was mixed in each case into a homogeneous mass. Table 1 shows the different combinations of conditioning agents used in the performed tests. There are six combinations of conditioning agents investigated in the tests. The order in which the conditioning agents were added for the different recipes of conditioning is explained following.

By conditioning the investigated soil with combination A, B and D only one conditioning agent has been added (foam, high density slurry or artificial soil). Furthermore the combinations C and E are similar to each other. In this case the soil is first mixed with the high density slurry or the artificial soil. Then the foam was produced and added to start another mixing process. The last combination of the conditioning agents is a combination of three conditioning agents. After creating a conditioned earth muck analogue to combination C and E, a polymer was finally added to bind the water inside of the gravity tumbler.

Table 1.Used combinations of conditioning agents.

Combination	Foam	HDS	AS	Polymer
A	X	-	-	-
B	-	X	-	-
C	X	X	-	-
D	-	-	X	-
E	X	-	X	-
F	X	-	X	X

3.2 *Investigation of the workability*

The slump test according to EN 12350-2 (2009) represents an index experiment, which can be used to evaluate the workability of a support medium. Different sources in literature suggest a slump margin between 10 and 20 cm as suitable range (Thewes et al., 2010).First the slump cone and the bottom plate have to be moistened with water to reduce the friction of the inner surface of the cone and the soil. The soil-foam mixture has to be filled in in three layers of circa 10 cm each. Therefore each layer should consolidated with 25 impacts of a steel ruler. The filling process ends, when the overlaying material is shaved off with the steel ruler and the test set up has to be cleaned from the adhering material. After lifting the cone the slump (S) can be determined, which means that the vertical difference of initial sample height (30 cm) and height after lifting. Furthermore the slump-flow (SF), which is the average of the maximum diameter of the sample after lifting and its perpendicular pendant is recorded. Figure 5 shows the recorded values in this experiment.

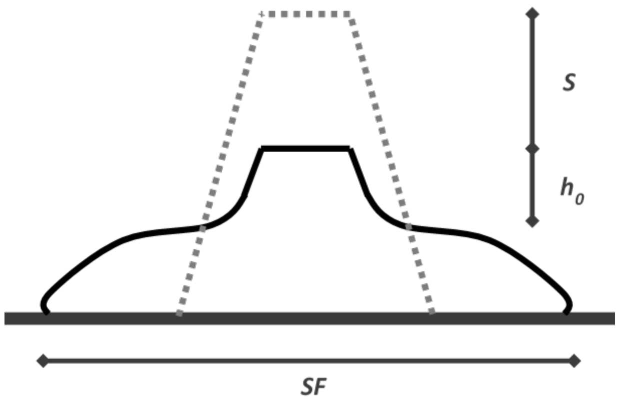

Figure 5. Recorded values in slump tests (Galli, 2016)

To avoid manual influences during perpendicular lifting of the cone, a guide rail system was developed and installed.

3.3 *Investigation of the permeability*

The hydraulic conductivity in cohesionless soils is an important factor for tunnel advancements with EPB shields. An adequate permeability is required in order to prevent both uncontrolled groundwater inflow into the excavation chamber and destabilising seepage flow forces. Therefore, the permeability test according to DIN 18130-1 (1998) or ASTM D2434 (1993) can be an estimator for the permeability under constant water pressure. Preferentially, the permeability of the support medium should be smaller than $k=10^{-5}$ m/s (Wilms, 1995).

For determination of the water permeability of conditioned soils according to DIN 18130-1 the sample is filled into the test apparatus in a height of 10 cm. Below and on top of the soil sample, filter layers are placed to prevent an uncontrolled outflow of the conditioning agent out of the soil structure without influencing the flow behaviour of the water. The filter material can be determined by the formula of Terzaghi. The test starts by opening the valve at the bottom of the cylinder. The water flows through the cylinder and thus through the sample into a measuring container on scales for the determination of the discharge volume. By measuring the outflow in time intervals the water permeability of the conditioned soil sample.

4 TEST RESULTS

4.1 *Investigation of the workability*

The support medium for EPB tunneling should exhibit an adequate workability and flow behaviour for a homogeneous support pressure transfer and a reduction of inner friction in order to reduce wear. Therefore in the slump tests a slump between 10 and 20 cm is striven. Table 2 shows the results of a selected number of slump tests to clarify the influence of the water content of the soil and the Injection Ratio of the Polymer TamSoil 1000CP by the conditioning with AS and foam. The ASIR and the FIR remained constant. Also the concentration of the liquid, the FER and the density of the slurry remained constant.

Table 2.Results of the Slump Test with c_f=3%, FER=15 and a density of the slurry of 1,8 g/cm^3

No.	w [M-%]	ASIR [Vol-%]	FIR [Vol-%]	PIR [M-%]	Slump [cm]
1	0	50	15	-	12
2	5	50	15	-	22.5
3	5	50	15	0,10	10
4	5	50	15	0,05	17.5

In figure 6 the result of the slump test No. 1 is depicted. The water content of the soil is 0% and the artificial soil filled the free pore space in the soil matrix with its sticky properties, as a result that the slump was 12 cm. The conditioned soil sample receives a pulpy consistence and seems suitable for processing in an EPB shield. By increasing the water content to 5%, the artificial soil loses its sticky paste characteristics so that the slump in test No. 2 is much higher under the same conditioning parameters (figure 7). In all performed tests with a water content of 5% there were no homogeneous conditioned earth muck created without using a water binding polymer. By the addition of artificial soil in a pulpy consistence to the soil before the mixing progress, a homogeneous earth muck can be expected. However, after the mixing process of the artificial soil with the soil with a water content of 5% in the tumbler, the effect of the two component reactive is not existing anymore.

Figure 6. Result of the Slump Test No. 1 with w=0%, density of the slurry 1,8 g/cm^3, ASIR=50%, c_f=3%, FER=15 and FIR=15%. The measured Slump was 12 cm.

Figure 7. Result of the Slump Test No. 2 with w=5%, density of the slurry 1,8 g/cm^3, ASIR=50%, c_f=3%, FER=15 and FIR=15%. The measured Slump was 22,5 cm.

Figures 8 and 9 are showing the results of the slump tests No. 3 and No. 4 with adding the water binding polymer TamSoil 1000CP to the conditioned soil sample. Here, the artificial soil retained its pulpy properties and filled the pore space in the soil structure of the investigated soil appropriately. The artificial soil and foam are prevented to flow out of the soil sample and the striven slump of nearly 10 and 20 cm could be achieved. In this case, the polymer injection ratio of 0.05% and 0.10%. The more polymer was added, the lower is the measured slump.

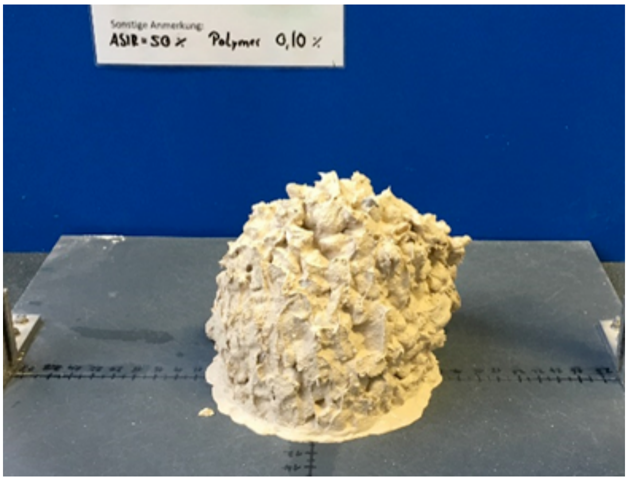

Figure 8. Result of the Slump Test No. 3 with w=5%, density of the slurry 1,8 g/cm^3, ASIR=50%, c_f=3%, FER=15, FIR=15% and PIR=0,10%. The measured Slump was 10 cm.

Figure 9. Result of the Slump Test No. 3 with w=5%, density of the slurry 1,8 g/cm^3, ASIR=50%, c_f=3%, FER=15, FIR=15% and PIR=0,05%. The measured Slump was 17,5 cm.

4.2 *Investigation of the permeability*

To investigate the influence of the conditioning on the permeability and the drainage behaviour, different conditioned soils were selected. The tests were done with a water content of 0% and 5%.

Right at the beginning of the permeability test without using the water binding polymer TamSoil 1000CP, it came to a flow of the conditioning agents out of the soil skeleton. Figure 10 shows the gap in the soil structure after the foam and the artificial soil were washed out. There was no difference between the samples conditioned with different densities or injection ratios of the artificial soil.

Figure 10. Flow out of the conditioning agents during the water permeability test.

Figure 11 shows the progress of the permeability of the conditioned soils with the combinations of the conditioning agents explained in table 1. The red line illustrates the borderline of 10^{-5} m/s for EPB Tunneling. By using no water binding polymer the sample broke after a few seconds and the permeability curve increased rapidly up to $8 \cdot 10^{-4}$ m/s. Moreover, it does not make a difference whether the density is 1.8 g/cm^3 or 1,9 g/cm^3 and the Injection Ratio of the AS is 20% or 50%. The tests with this scenario were broken off after a few minutes. The effect of the polymer TamSoil 1000CP can be seen with the result of the test with a PIR of 0.10%. The permeability of the sample was reduced over a period of time of 60 minutes to 1.1·10-4 m/s. The water permeability curve of the conditioned sample with a PIR of 0.05% shows also an effect of the water binding polymer, but after 2 minutes the conditioning agents were washed out as in the tests without using TamSoil 1000CP and the permeability index increased to a level of $8 \cdot 10^{-4}$ m/s. Therefore the results of the water permeability test suggest that the higher the injection ratio of the water binding polymer, the lower the permeability index of the conditioned soil.

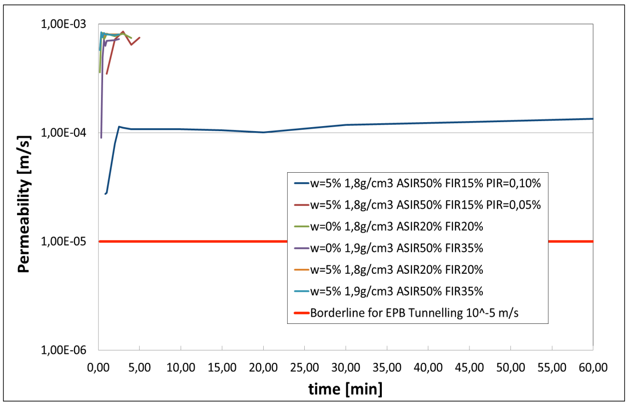

Figure 11. Investigation of the water permeability of the conditioned soils with c_f=3% and FER=15

5 CONCLUSION AND OUTLOOK

Soil conditioning in coarse grained soils outside the classical application range of EPB shields is a major challenge. Therefore different types of conditioning agents (foam, slurries or polymers) play a fundamental role in the execution of EPB tunneling. With the new development of Artificial Soil, based on a high-denstiy slurry with the addition of the two-component additive TAMSOIL 2000 by Normet, a valuable additional method of conditioning was developed. This method will allow for the addition of a highly viscous paste of fines into the excavation chamber.

The laboratory investigations in this research led to valuable information about the conditioning of coarse grained soils with an amount of less than 10% fines or even sand. For tunneling in closed mode, the excavation chamber shall be completely filled with conditioned excavated soil and gets discharge by the screw conveyor to the conveyor belt. The conditioning with artificial soil, foam and a water binding polymer can be used to perform highly permeable or unstable sections of the planned tunnel route. The results of the investigations of the permeability show, that temporarily the permeability can be reduced to $1.1 \cdot 10^{-4}$ m/s, which is still higher than the permeability should be according to Wilms (1995) but significant lower than the permeability of the unconditioned soil (10^{-3} m/s-10^{-2}m/s). However practical experience shows, that also with a permeability of this values tunneling in closed mode below the groundwater table is possible. Because of the very fast reaction between the two components of TamSoil 2000CP and the constructional operations benefits, the artificial soil can be created to reduce an uncontrolled water inflow at the tunnel face or to generate a sufficient earth muck during the transition between soil and rock if necessary. Moreover, the artificial soil can be used during longer stops or standstills to create a low permeable earth muck.

Investigation of soil conditioning with artificial soil will be continued at the Institute for Tunnelling and Construction Management at Ruhr-University Bochum. A higher injection ratio of the water binding polymer could effect, that the permeability index of the conditioned soil will further reduce. Furthermore the permeability tests can be performed over a longer period of time.

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