Advanced Technology of Soil Conditioning in EPB Shield Tunnelling

By Lars Langmaack

Chemical Eng., TBM Project Manager, MBT International, Zürich (CH)

1. Introduction

The Earth Pressure Balance (EPB) shield method is well known in the tunnelling world, but there are still unexplained processes which require more understanding. This concerns particularly the different existing conditioning additives, their functions and their use on site. An important factor is the control of the corresponding key factors to obtain the desired conditioning and in the same time a quick TBM advance without any mayor problems.

2. Face Support

The most important factor – not only in EPB tunnelling – is to balance the soil pressure at the cutterhead by a counterpressure in the working chamber. To calculate the necessary counterpressure, various face support calculation programs are given, depending also on the soil type in situ.

2.1 Face support in granular, non or slightly cohesive soils

In non-cohesive or slightly cohesive soils the theoretically required minimal support pressure can be determined by a three-dimensional limit equilibrium model (see Figure 1).

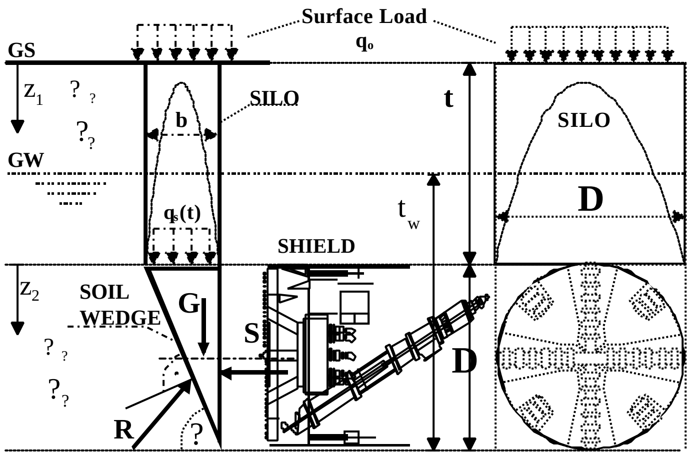

Figure 1. Three-dimensional limit equilibrium model for non cohesive soils.

Details of the theoretical solutions can be found in further literature (Jancsecz & Steiner 1994).

2.2 Face support in cohesive soils

? Limit equilibrium analysis in saturated and cohesive soil can assume following shear parameters (short-term loading): the angle of internal friction $?_u = 0$ ($K_0 = 1$)

? ?? = s_u kPa

Stability solution will be obtained by using a simple kinematically admissible collapse mechanism. It is possible to deduct a limit function from the earth pressure equation for the so called Stability Factor (N):

$$N ? \frac{4}{p} ? 3.4 ? (1 ? \frac{t}{D}) \quad (2)$$

The Stability Factor is a critical ratio for total collapse of the face (N_{crit}) in state of limit equilibrium. It has first been defined by Broms and Bennermark (1967) as a relation between overburden pressure reduced by face supporting pressure (if any) at the tunnel axis and the undrained shear strength of soil. It is possible to express the required support pressure p_{sreq} in a simple form of an equation:

$$p_{sreq} ? p_v ? (\frac{N_{crit}(t)}{?}) ? s_u \quad (3)$$

where p_v is the earth pressure in the shield-axis, ?? = 1.5 - 2 is the Factor of Safety. The calculation scheme for support pressures is based on the theory of Atkinson & Mair (1981):

$$N_{AMCrit}(t) ? 5.86 ? ?\frac{t}{D}?^{0.42} \quad (4)$$

The computation of Stability Factor N_{AMCrit} has been modified, so that factors greater than six are not allowed. Generally accepted limits for Stability Factors are:

N < 2	Small ground movements
2 < N < 4	Shield generally used to restrain ground movements
4 < N < 6	Increasing ground movements
N > 6	Face may be unstable. Clay may squeeze rapidly into the face

2.3 Why using soil conditioners in EPB tunnelling

To build up the necessary face support pressure, the soil has to be impermeable against air. Three main closed mode tunnelling techniques were developed out of this principle demand:

- Air pressure TBM
  It is possible to work by air pressure, when the soil itself is nearly impermeable against the air. This is only possible in rare cases.
- Slurry TBM
  The working chamber is filled with a bentonite suspension, a big air bubble in the top of the working chamber controls the support pressure. This technique can be used for a wide range of soil types. But it has also disadvantages like huge and costly treatment plants to recycle bentonite on the surface and an outcoming soil-bentonite mix which has to be put to a special landfill site.
- EPB TBM
  The working chamber is filled with the original soil, the turning cutterhead is responsible for creating a homogeneous and impermeable soil paste. To obtain this soil paste, conditioning additives have to be used in most cases – according to the soil type in situ. Sometimes only water is sufficient, more common is the use of Foam to create a pasty soil and to introduce a certain amount of air to obtain the necessary face support pressure. For coarse soils in general Polymers are necessary, for stiff clay anti clogging agents may be useful. Figure 2 gives a general overview about the soil conditioning:

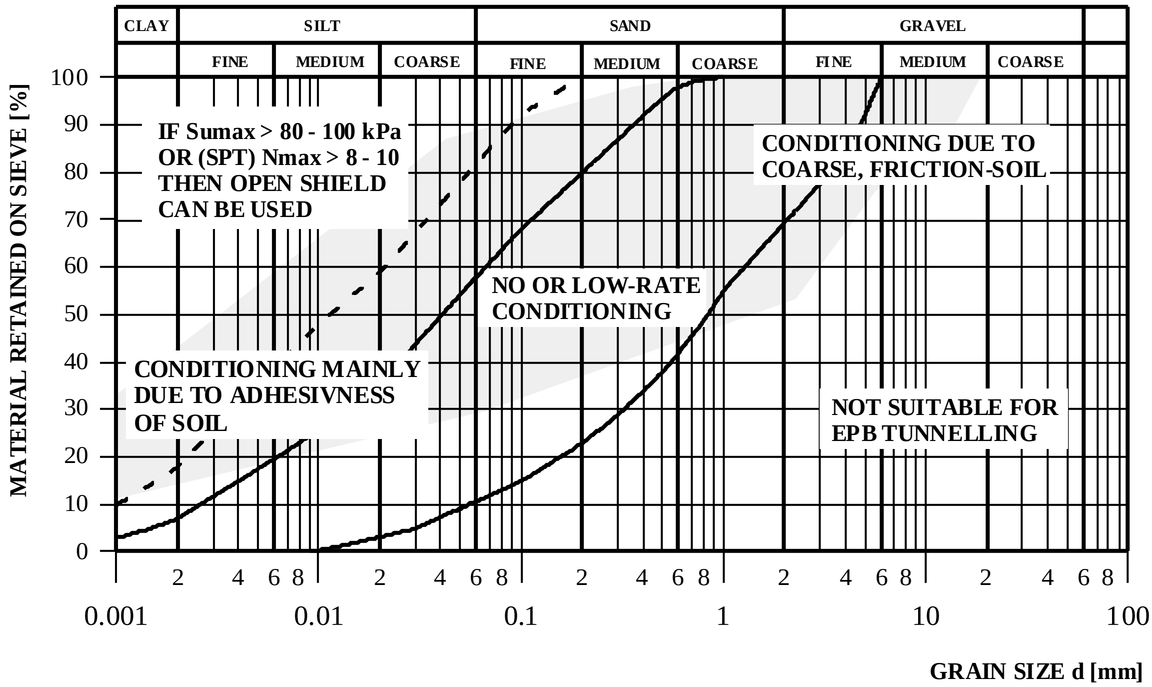

figure 2: general conditioning for EPB Tunnelling

When using EPB tunnelling mode, no bentonite and special treatment plants are necessary and the outcoming soil is nearly natural. If additives like Foam or Polymers are used, highly biodegradable versions exist which can be 95% destroyed after 28 days.
The EPB tunnelling mode can be a very interesting alternative to Slurry tunnelling mode. The choice of conditioning additives plays a very important role of the project success and has to be done by conditioning specialists after preliminary laboratory testing – if possible with the original soil at site.

3. Conditioning additives

The choice of the foam type and different possible polymers depends mainly on the soil type in situ, the geological conditions (ground water, water pressure, soil permeability), but also on the characteristics of the TBM (open or closed face, points of injection, type of foam generator, ...).
The main important conditioners are Foam and Polymers. There do exist further additives like anti-clogging or anti abrasion additives.

3.1 Foam

The main demand of foam as conditioning additive is to create a pasty soil, to build up and to maintain the necessary support pressure in the working chamber and to prevent high pressure variations. The created small bubbles (Foam) in the earth past have got the same effect as the big air bubble in Slurry machines. The Foam is also used to obtain the suitable rheology of the soil.
The reduction of torque and abrasion are very important additional effects, too.
Foam can be created out of a turbulent mixing of a surfactant solution and air.
To explain the effects of foam, the first step is to look at the effects of the surfactant solution - as a basic component - like they are shown in figure 3:

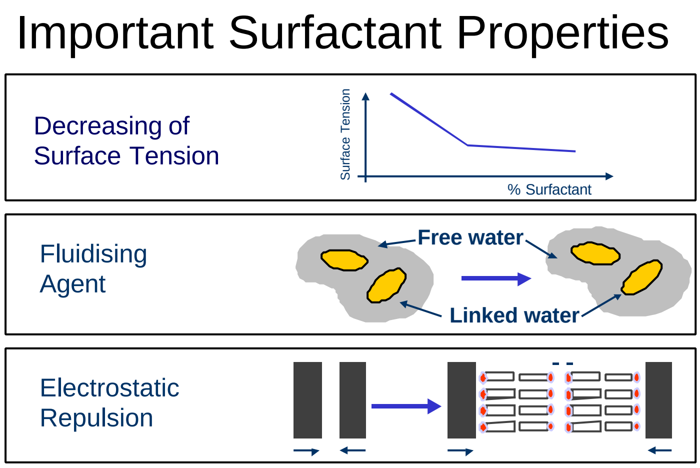

figure 3: important surfactant properties

The main Surfactant properties are the
? fluidising effect on soils because of the decrease of surface tension. Soil particles are no longer bound to each other by linked water
? electrostatic repulsion effect which can separate two particles attracting each other by electrostatic forces.

These effects can vary according to the type of surfactant, shown in figure 4.

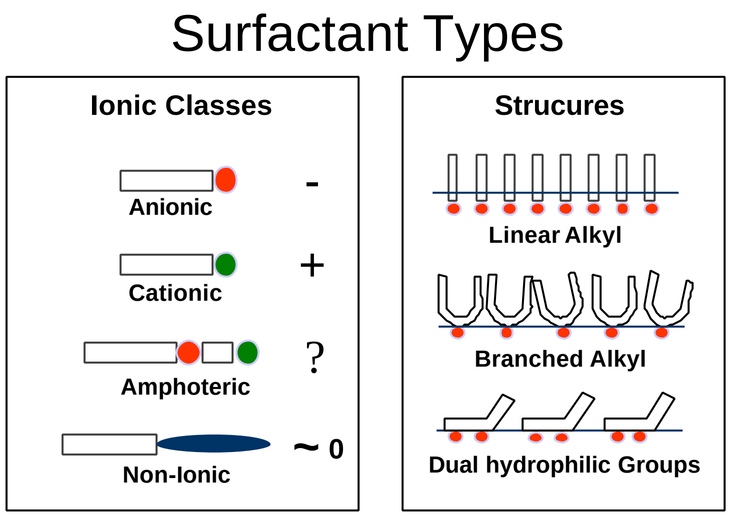

figure 4: different Surfactant types

Surfactants are a combination of a hydrophobic chain and a hydrophilic head. Both parameters can be varied: different chain structures (length, steric structure) and different head characters (anionic, non-ionic, cationic, amphoter) are possible.
These different chemical characters induce different properties like modification of superficial / interfacial tension, force of dispersion, solubility, emulsification, foaming capacity, foam stability, etc.
Each soil type, from stiff clay to sandy gravel, requires more or less his own type of foam to reach its best effectiveness. The type of Surfactant which shall be used for a special site has to be determined by laboratory tests with the original in situ type of soil.
The surfactants are in most cases used in form of foam, as illustrated in the figure 5, but they can be used as a liquid, too.

Foam

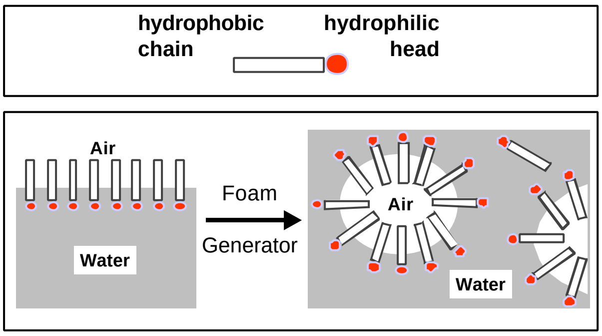

figure 5: Foam

Foam has to be used under defined conditions on site which are fixed by the use of specific parameters. The influence of each parameter has to be determined by preliminary laboratory tests. The three important foam parameters on the TBM are :

- Concentration of surfactant agent in the foaming solution:
The influence of foam in the soil depends first on the dilution of the pure surfactant agent in water. The surfactant concentration c_f is responsible for the amount of surfactant molecules in the foam. One part of these molecules has to stabilise the air bubbles, the other part is free in the water and can be used to treat the soil particles itself.
$c_f = 100 \times m_{Surfactant} / m_{Foam\ Solution}$
$m_{Surfactant}$: mass of Surfactant in Foaming Solution [kg]
$m_{Foam\ Solution}$: mass of Foaming Solution [kg]

- Ratio of mixing foaming solution with air (to create a foam):
In order to create a foam out of the surfactant solution air is required.
The amount of air introduced to the soil can be changed with the air ratio FER (Foam Expansion Ratio) which characterises the ratio between air and liquid volume.
$FER = V_{compressed\ air} / V_{Foam\ solution}$
$V_{compressed\ air}$: Volume of compressed air [l]
$V_{Foam\ solution}$: Volume of foaming solution [l]

The amount of introduced air plays two main roles: Increasing the surfactant based fluidising effect to the excavated soil and, if desired, a migration of foam into the ground in order to induce a drying effect against ground water.
Another demand is to create regularly small air bubbles to obtain a stable foam and a homogenous soil mixture. The nature of foam bubbles can be influenced by the choice of the foam generator (see Figure 6).

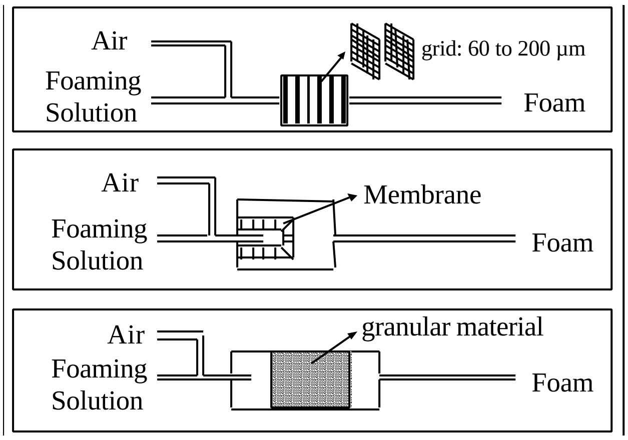

Figure 6. Different types of foam generators

Standard equipment like granular filled generators form air bubbles ranging from 0,5 mm up to 2 mm (depending on foaming agent and FER: here c_F=2 % and FER = 10).

- Ratio of mixing Foam with Soil:
The Quantity (Volume) of foam injected at the cutterhead, into the chamber and if necessary also into the screw conveyor is expressed by the FIR (Foam Injection Ratio) value which indicates the volume of foam used per 1m³ of soil. FIR 40% indicates that 400 l of foam are added to 1m³ of soil.

$FIR = 100 \times V_{foam} / V_{soil}$

V_{Foam}: Volume of Foam (at 1 atmosphere) [l]

V_{Soil}: Volume of in situ soil to be excavated [l]

3.2 Polymers

In addition to their foam stabilising effect, there are two main functional types of polymers:

- water binding polymers to dry out (liquid) soils
- soil structuring polymers which are useful in loose, coarse soils to change the soil comportment and which prevent sedimentation.

Some polymer developments are based on hydrocarbon chains and are produced by bacterial fermentation. This polymers are water soluble, biodegradable and compatible to the foam surfactants. Both of them are safe for the foaming generator, in consequence they can be mixed with the foaming solution and passing the foam generator.
Polymers can induce a more stable support pressure in the working chamber during boring and when stopping the machine for a short time, too. The characteristics for this structuring Polymer are shown in figure 7:

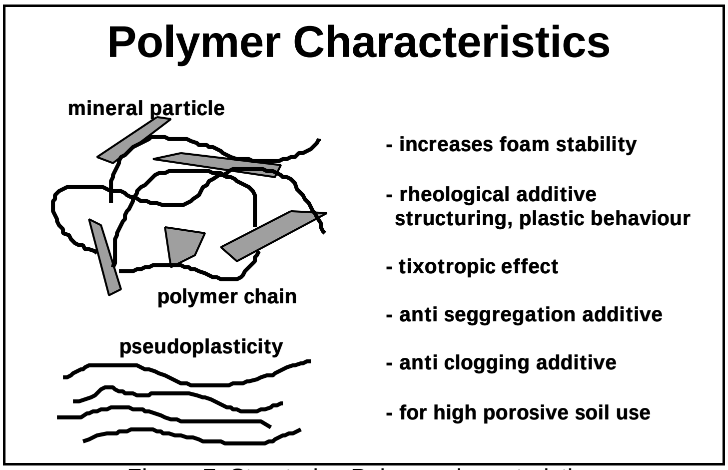

Figure 7: Structuring Polymer characteristics

All Polymers should be preferably in liquid form to avoid dosing problems and additional installation to get a solution / suspension out of the powder. These liquids shall be soluble in water, too.

3.3 Clay Dispersing Agents

To fulfil the desired job, the dispersing molecules have to adsorb on the soil particle surface. They have to carry a high charge density to separate the soil particles and they should create a steric barrier.
These demands can be fulfilled by surfactants and dispersants, but dispersants are more efficient as shown in figure 8:

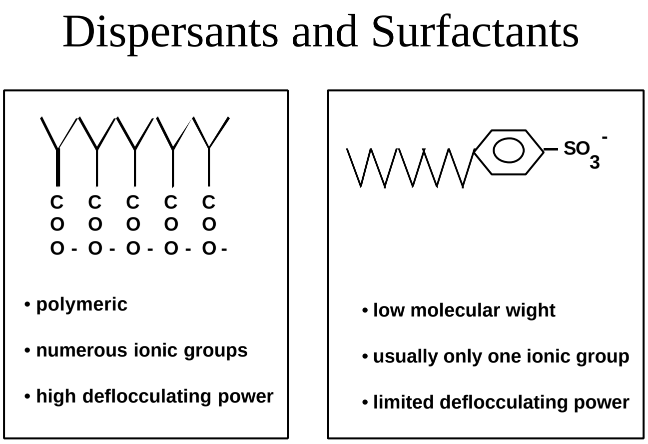

Figure 8: Structure of Dispersants and Surfactants

Dispersing agents are mainly added to stiff clay to support the destructuring / dispersing properties of the foam, but they might be introduced without foam, too.

3.4 Anti-Abrasion additives:
Anti Abrasion additives have been developed for highly abrasive soils or rock formation. They should mainly protect the cutterhead, its tools and the extraction screw. In consequence the products can be added at the cutterhead, in the working chamber and in the screw conveyor. This additives can be injected in concentrated form, diluted with water or together with foam (while using EBP mode) for a more homogeneous distribution.

4. Laboratory and Site Results with conditioning additives

4.1 Foam
Laboratory Slump Tests for the Izmir site (Turkey):
To determine the rheology of the soil, which is a very important factor for EPB tunnelling, slump tests are extremely useful. The test equipment equals those, which is used for ordinary concrete tests. In this case the soil is mixed with foam. Figure 9 illustrates the test.

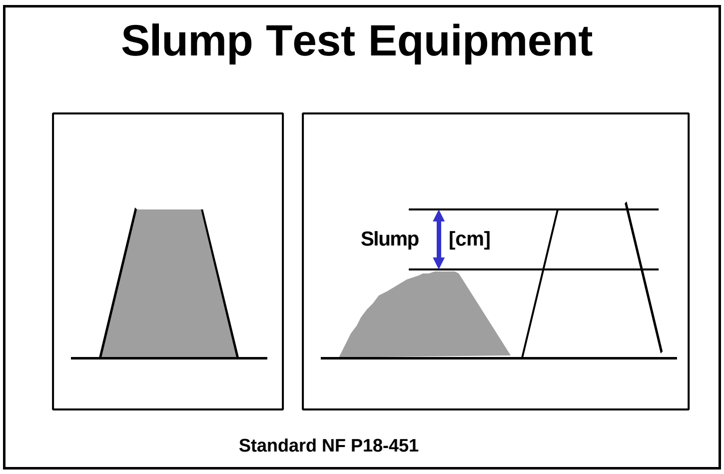

figure 9: Slump test

The slump value results on height difference and is an indicator for the soil rheology.
Figure 10 shows the influence of foam on a sandy gravel and illustrates the change in soil comportment and importance of the slump test.

Soil Changes

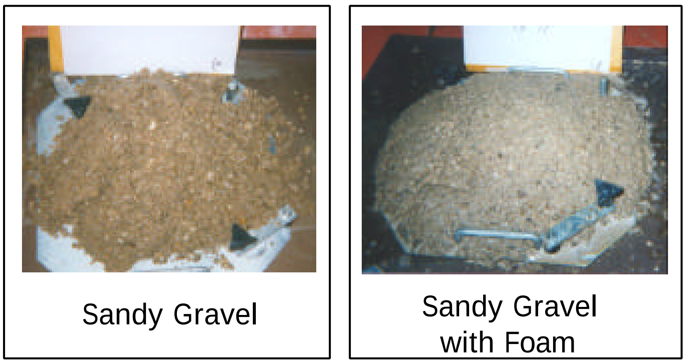

figure 10: visualisation of soil changes by slump tests

Some slump-test data with the original Izmir soil are presented in the following figure 11:

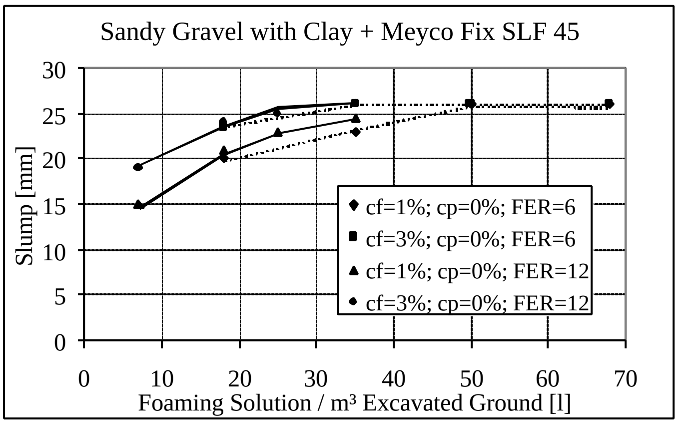

Figure 11. Results of slump tests with coarse and fine soil mixture

Plastic soil consistency could be obtained even with a low water content (see figure 11). Without foam addition the soil character became too stiff. For this reason it was not suitable for the TBM. The fines (silt and clay particles) change the rheological property of the soil, in this case no polymer addition was necessary.

Izmir Site Results:

With nearly 3,5 million inhabitants Izmir is the third largest city of Turkey. The 11,3 km construction-length was subdivided into: 1,375 km long EPB shield tunnel, 1,7 km long NATM tunnel, 1,1 km Cut and Cover and the rest into Surface & Elevated section. Figure 12 shows a layout sketch of the whole project.

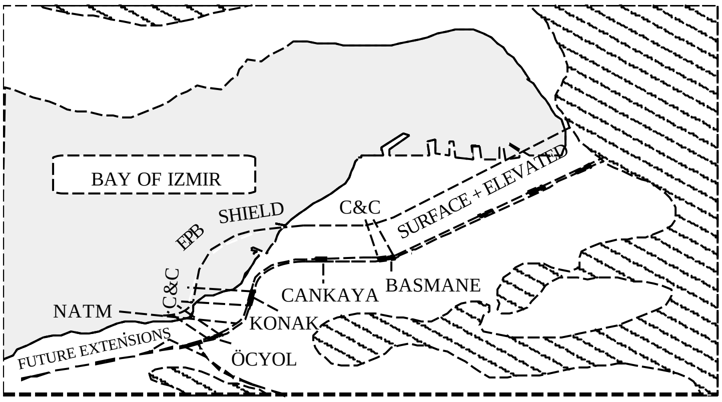

Figure 12. LRTS Izmir 1st phase, total length = 11,3 km

An EPB shield - with an outer diameter of D = 6,52 m, delivered by Herrenknecht Ltd. – was used. The shield drive started in August of 1997 and was finished successfully in December 1998 - without any collapse or large surface settlement.

Soil conditions and parameters

In the first section between Basmane and Cankaya station mainly non cohesive soils were excavated, while in the second section between Cankaya and Konak station cohesive soils with water contents near or beyond their liquid limit had to be mined. The soil investigation covered the usual scope of in situ and laboratory tests. Figure 13. gives a schematic impression of the different strata along the alignment of the tunnelling drive.
Tunneling had to cope with three different groups of soil: gravely as well as silty sands (S,SG), clayey and sandy silts (M), and clay (C).

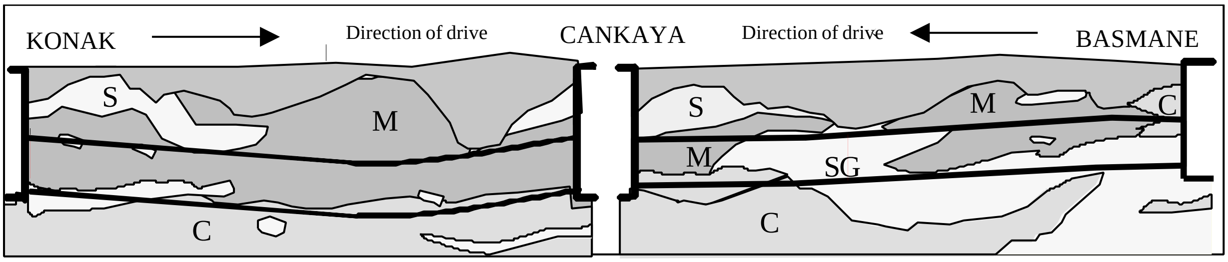

Figure 13. Geotechnical longitudinal section

The sand and gravely sand showed a wide range of relative density from loose to very dense, but for most parts of the alignment medium dense to dense sand occurred. Figure 14. shows the lower and upper limits of the grain size distribution. The sand was classified mainly as SM but a considerable amount also as GM according to USCS.

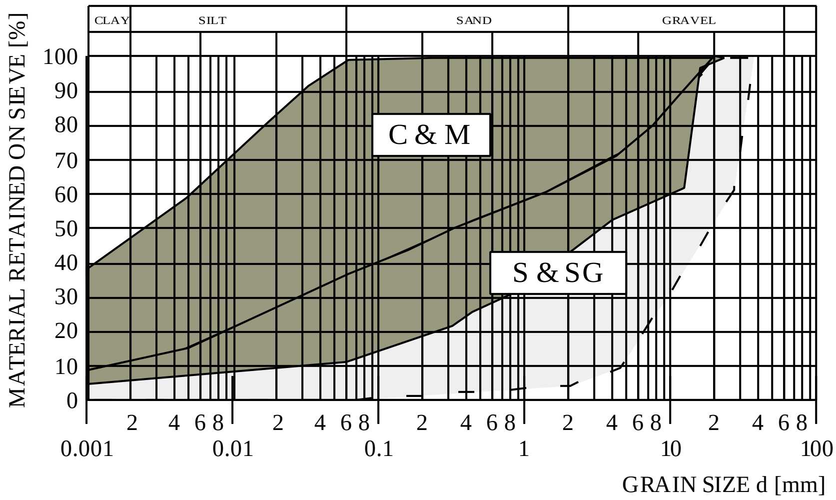

Figure 14. Grain size distribution of soils

Third Drive in silty soil, sea-side
The third drive started in silty soil with some small sand layers. The drive at the first 250 rings was parallel to the coast line at a distance of about 150 m. The soil was loose, not very consolidated, the water content was high and the organic matter was roughly 20 %.
Driving the EPB shield in that soil caused no difficulties regarding thrust and cutter head torque (see
Figure 15). Settlements were low and face support pressure laid in-between the calculation (see Figure 16).
In the beginning, soil conditioning was not generally necessary. From time to time small quantities of foam were injected to keep the water away and to make the muck less sticky on the conveyor belt. Foam consumption starts with zero. Later going up to FIR = 70% as a

result of technical problems with the TBM (damaged gear boxes). The excavation had to be made "easier" for the TBM, what meant in this case more conditioning to reduce the torque (see Figure 17) at the cutter head.

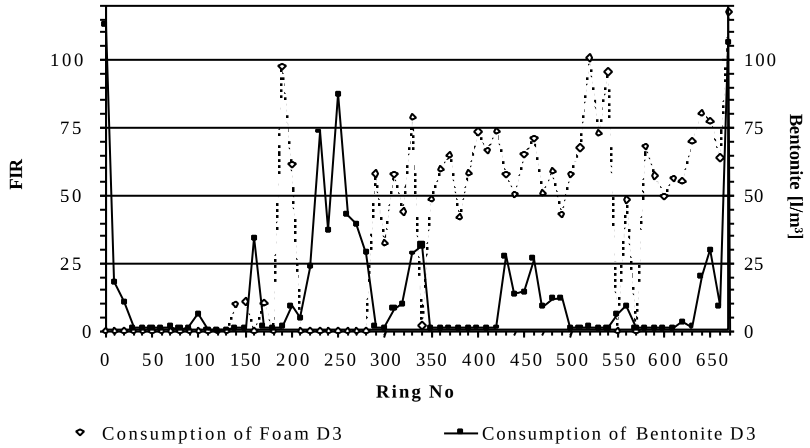

Figure 15. Soil Conditioning of 3rd drive

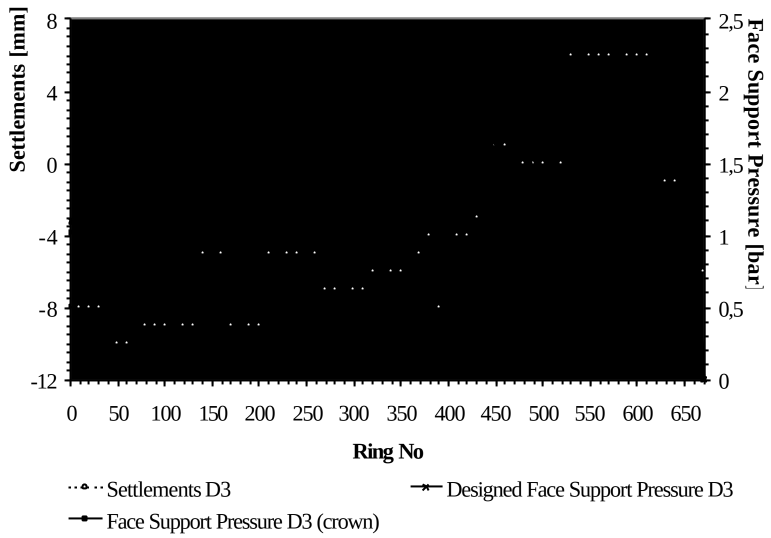

Figure 16. Face support pressure & settlements, 3rd drive

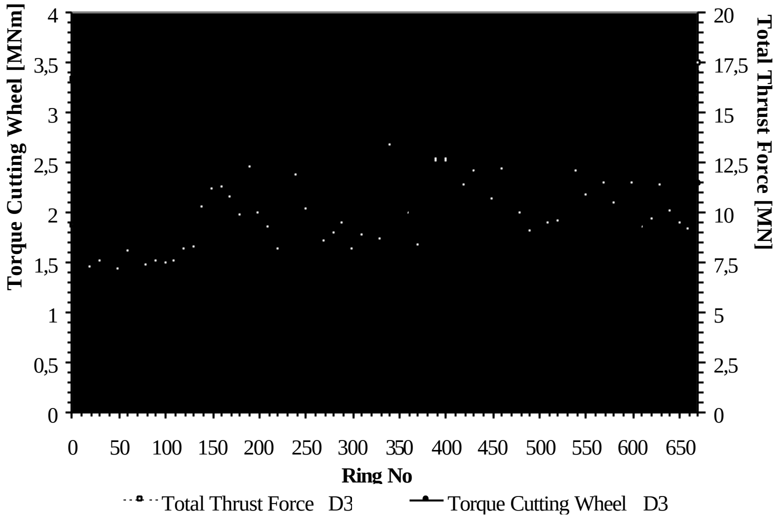

Figure 17. Thrust force and torque of cutting wheel, 3rd drive

4.2 Polymer Laboratory Results & Site Examples

Laboratory tests can be used in order to find out the right products and technique to reduce the soil permeability. The presented tests are effectuated with a porous soil from BPNL Lyon, porosity of $10^{-3,5}$ [m/s]. This soil is water saturated and put under overpressure of 0,4 bar.

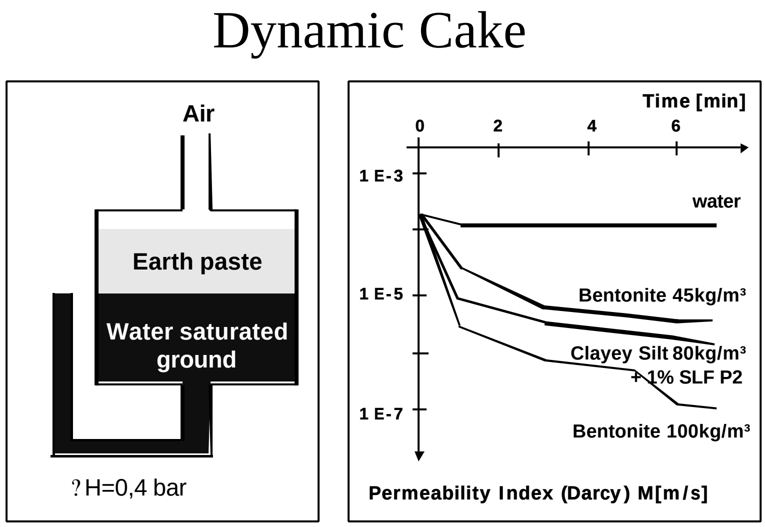

figure 18: dynamic cake development

Figure 18 explains that only water doesn't influence the original soil permeability at all. The addition of bentonite decreases the permeability because of the fine particles which are 'closing' the existing soil porosity more or less depending the added Bentonite quantity.
The Polymer can obtain the same result as bentonite only by using a clayey silt. The polymer chains structure the fine soil particles, gluing them together.

Site Example Aviles, Spain
The Aviles Site works with a Lovat EBP machine, diameter 4m.
After facing stiff silty clay the soil changed to approximately 1.000m of pure gravely beach sand with a groundwater pressure of nearly 3,5 bar. The grain size distribution is shown in figure 19:

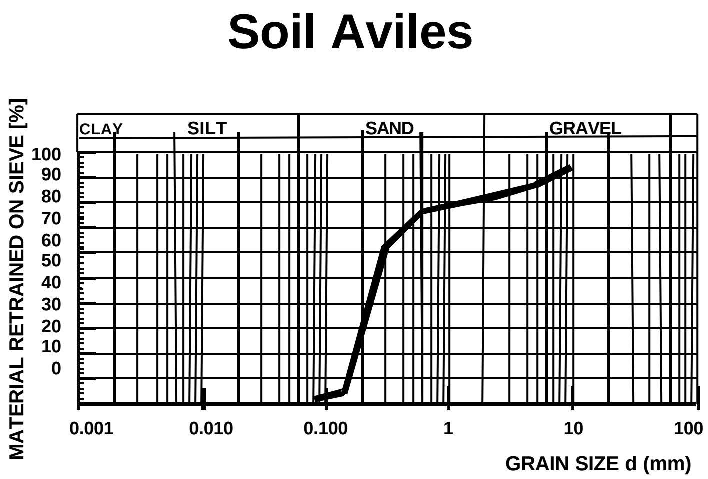

figure 19: grain size distribution curve of Aviles Soil

Lab tests present some segregation control (figure 20), permeability tests (figure 21) and penetrometer tests (figure 23) with polymer SLP 2 and the original Aviles Soil. All tests are carried out with Wi=7%, d(org)=1,5.

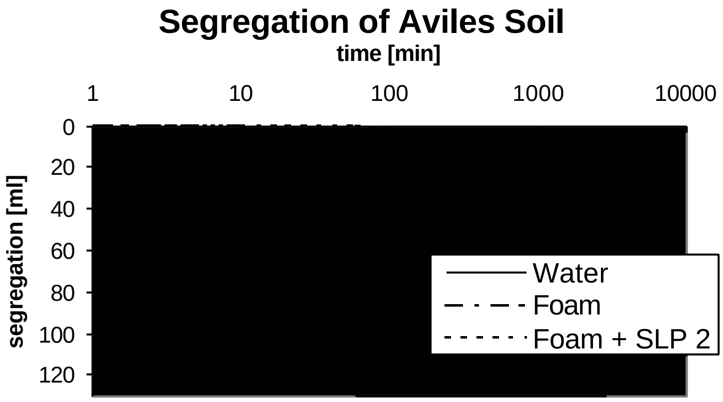

figure 20: segregation tests

Figure 20 shows the dramatic problem of a coarse soil mixed with water. An almost instantaneous segregation is obtained, impossible to work with. With a very stable foam the result can be improved, but still 20% segregation after 15 minutes is obtained – still too much for a proper function of the TBM. The segregation as well as the homogeneity of the soil paste can only be controlled by the addition of a structuring biopolymer.

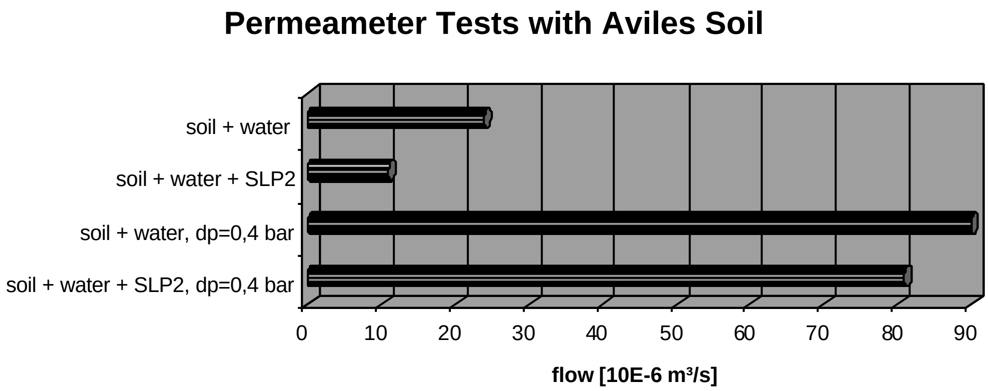

figure 21: permeameter tests

Figure 21 shows the 'gluing' effect of polymer / foam by reducing the water outflow from a soil mixed with foam and polymer or only water at ambition pressure and at 0.4 bar overpressure.
In order to obtain some information about the problems due to 3 bar water pressure, cone penetrometer tests were taken out.

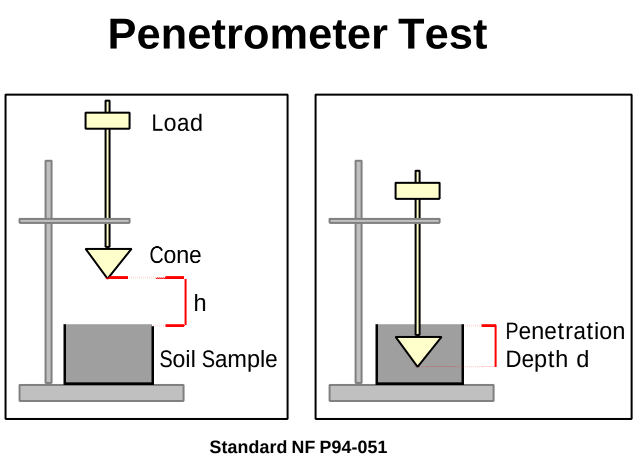

figure 22: cone penetrometer

The penetration depth of the cone indicates the fluidity of the soil: the higher the depth the more liquid is the soil. If polymers are tested, the aim is to maintain the penetration depth even when adding water. These tests results are shown in figure 23:

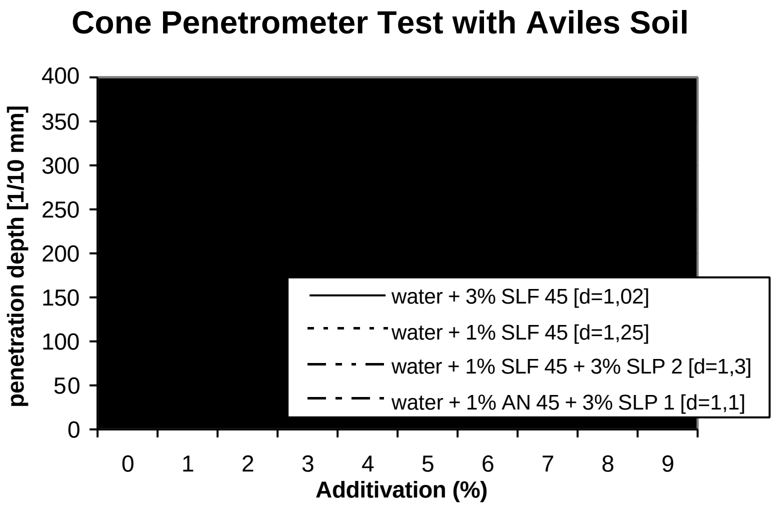

figure 23: Cone Penetrometer Tests

Figure 23 presents the changing soil rheology in function of added water plus additives. Foaming agents show a fluidising effect (higher penetration depth) depending on the surfactant concentration c_f. Water binding polymers like the SLF P1 present for the same soil and the same water amount a lower penetration depth than the foaming solutions because of their water binding capacity. A structuring polymer like the SLF P2 shows nearly no evaluation of the penetration depth even if a higher amount of water is added.

Consequence for Aviles Site:
The site now works with a vary stable foam in front of the cutterhead, which is doped by 2 to 4% of a structuring biopolymer to obtain a stable and plastic cake. With this cake the TBM is able to maintain the necessary pressure in the chamber and to prevent water income.
For security reasons the Site decided to inject a water binding polymer into the chamber and the screw conveyor, too.

4.3 clay dispersing & clay adhesion lab results

They clay dispersing effects of additives can be measured by a cone-penetrometer:
The penetration depth indicates the ‘plasticity’ of the soil. In the case of clay, a well working dispersing additive obtains a high penetration depth, illustrated in figure 24.

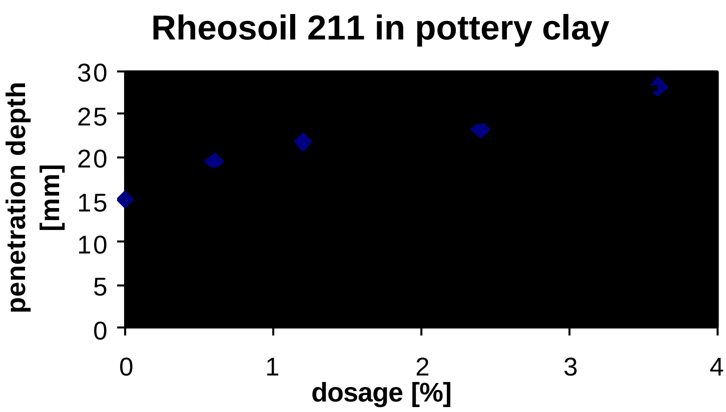

Figure 24: effect of clay destructuring additives

This test is not suitable for testing adhesion problems, it only indicates dispersing effects. For adhesion values a gliding (slipping) test can be used to determine the adhesion changes by addition of additives. There exist various tests for this kind of problems. In this case, 400g of pottery clay are put on a dry steel plate (5mm clay thickness) and the surface is humidified by water or a solution of water + additive. Then another stainless steel plate is put on this clay surface with a load of 2kg for 2 minutes, as shown in figure 26:

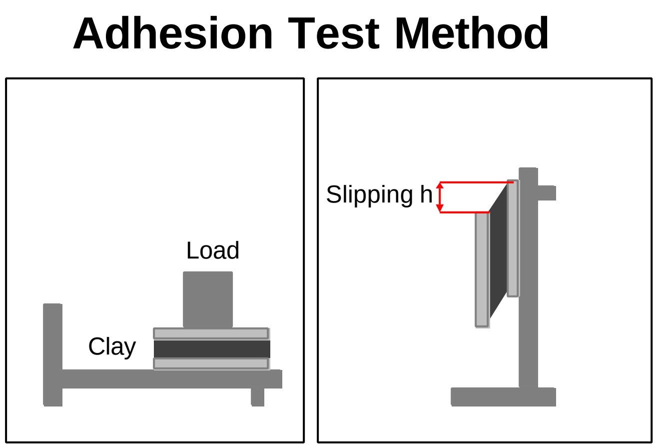

figure 25: Clay adhesion test

The displacement of the upper steel plate is measured versus time and the results illustrate the changing adhesion effects by using different additives:

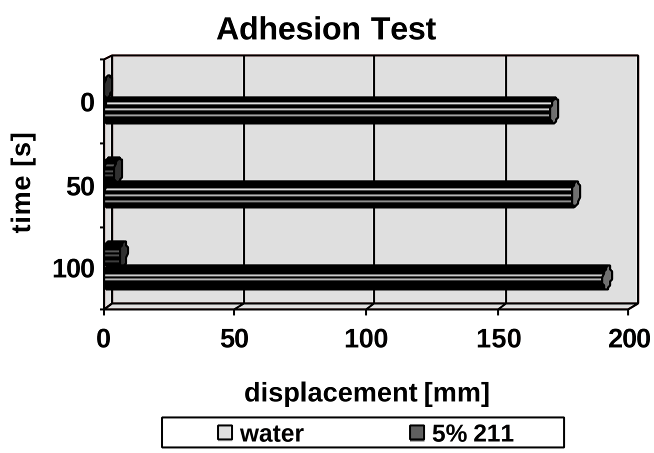

Figure 26: laboratory adhesion test

Figure 26 shows the significant surface effect of Rheosoil 211 within the first seconds (immediate slipping) in contrast to the obtained values by only adding water

4.4 Anti abrasion lab tests and site results

The following laboratory tests were carried out with highly abrasive gneiss from the Lyon site, which has been taken out by boreholes. Different concentration of the anti-abrasion additive were added and the mass loss of a turning brass disc measured. Figure 27 shows the lab test equipment.

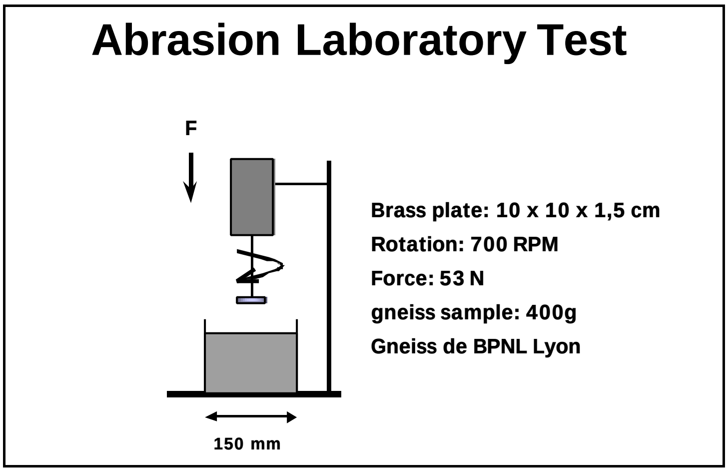

figure 27: laboratory abrasion tests

The abrasion test results are presented in figure 28.

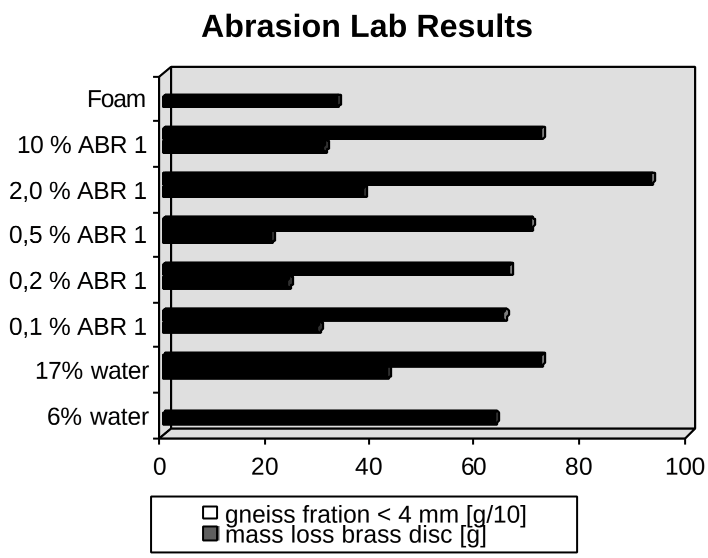

Figure 28: Abrasion Lab results

Figure 28 shows reduced abrasion in case of using a water saturated suspension (17% water). The amount of water plays a significant role in the abrasion problematic.
To determine the effect of the anti abrasion additive Meyco Fix ABR 1, the product is mixed in different concentrations into the water. During this tests, water saturated suspension is always used. The abrasion can be reduced up to 50% by using ABR1 regarding to the best values by adding only water. The effects causing higher abrasion by adding 2% of ABR 1 into the water are not cleared yet. Another interesting effect is the amount of soil particles under 4 mm diameter which is created during the test. Following can be defined: The higher the amount of fine particles, the higher is the abrasion.

Site Results from BPNL Lyon

The Site Boulevard Peripherique Nord de Lyon (BPNL) started in 1995 and finished in 1997 with the largest EPB TBM used up to now (?=11m). NFM supplied the machine which was heading in a very inhomogeneous geology:

- 1250 m crystallophylian rocks with crystalline veins, advance heading ‘open mode’
- 450 m intermediate zone with changing alluvion and crystalline rock formations, ‘mixed face’, advance heading ‘under pressure’
- 1552 m sedimentary rocks, ‘full face’, advance heading ‘under pressure’

The Anti Abrasion additive was tested in fractured gneiss. The quantity of added water was around 60-70m³ in order to obtain a water saturated suspension (17%). The site decided to install reference discs on the cutterhead. Furthermore reference metal plates were installed on the screw to obtain some abrasion values for this tool, too. The reference discs and plates are controlled every week.

week	**1**	**2**	**3**
conditioning	17% water	17% water + 0,5% ABR 1	17% water
TBM advance [m/week]	72	68	94
1 circle time [min]	85	82	79
Total abrasion discs [mm]	15	9,8	12,2
Total abrasion plates [g]	90	15	100
DISC Results			
Abrasion [mm/m tunnel]	0,21	0,14	0,13
TBM speed [mm/min]	23,5	24,4	25,3
Cutting force [kW]	957	**1497**	1226
RELATION [%]	***100***	***42,7***	***45,2***
PLATE Results			
Abrasion [g/m tunnel]	1,25	0,22	1,06
Screw rotation [R/m tunnel]	425	164	183
RELATION [%]	***100***	***46***	***183***

Figure 30: abrasion site results BPNL Lyon

As shown in figure 30, the tests period on site was three weeks. In the first week water was the only thing added, in the second a 0,5% water based solution of ABR1 was used. Finally in the third week once again only water was taken.
The obtained results are hard to interpret because of the changing soil conditions and varying machine parameters within one week as well as within the whole 3 week testing period. But putting into account the varying machine parameters like TBM speed, cutting force or screw rotation which are in direct relation to the soil conditions, the site results show a tremendous decrease of abrasion concerning the plates on the screw conveyer. Concerning the cutterhead discs the decrease of abrasion is less significant but still detectable. Please note the huge differences for the cutting force.
Further site tests are necessary to verify the good laboratory results, but fast changing soil conditions and machine parameters will always create difficult parameters. In consequence lab conditions and tests have to be optimised by using real TBM discs.

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