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## Europe & Asia:

# Application of new TBM Conditioning Additives

### ABSTRACT:

The importance of shielded tunnelling is growing more and more. To do this in a successful way, even Slurry- and Earthpressure Balance-TBMs need conditioning additives. Sometimes a project only becomes a reality as a result of their use.

The growing product diversification concerning conditioning additives is a consequence of the latest developments. This necessitates specific tests to evaluate the advantages or disadvantages of their use. The use of conditioning additives has to be combined as effectively as possible with the existing complexities 'TBM' and 'Geology' in order to result in optimum TBM advance.

New developments regarding tunnelfoams and -polymers are presented here. In addition to the more classic demands like modification of soil rheology and pressure stabilisation in the working chamber, other points of interest which demonstrate the complexities are also playing an important role e.g. reducing the stickiness and adhesion in clayey soils or water ingress control in porous soils. Another key factor is the proving of the performance of each conditioning additive by doing practical laboratory tests.

The use of modern conditioning additives allows the extension of the 'classic' operation areas of Bentonite- and Earthpressure Balance TBMs. The global site applications presented by examples of Europe and Asia underline the successful use of conditioning additives, around the world.

## 1 Conditioning Additives - Overview -

### 1.1 Is there a need for conditioning additives?

The latest literature [1] shows the following diagram (see figure 1.) concerning the limits of EPB tunneling. In consequence soils with less than 10% clay, 10-60% silt and a gravel (fine gravel) content of maximum 30% are up to now judged as 'suitable' for EPB machines. But even to reach these limits, additives have to be used to reduce stickiness in clayey soils or to plasticise coarse, frictioned soil. Also for the silty sand in-between these limits conditioning additives show important effects on reducing the torque and wear.

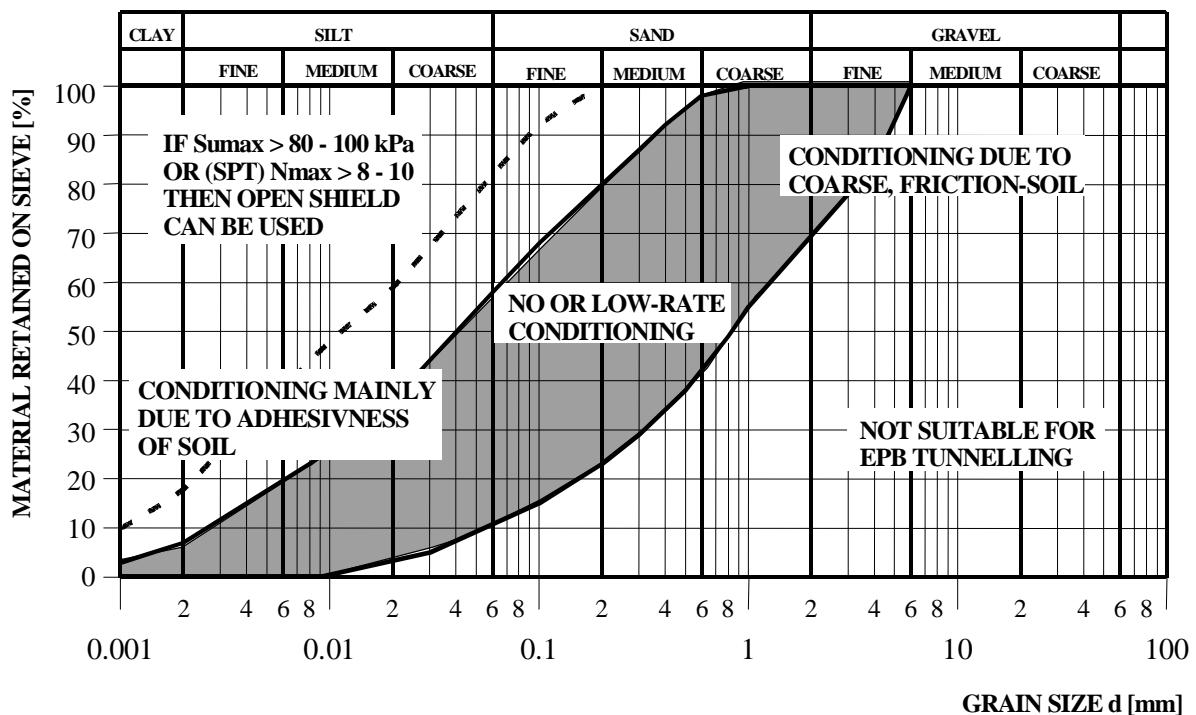


Figure 1. Limits of EPB tunneling

### 1.1.1 *The use of additives on EPB machines*

Referring to figure 1 three main areas of conditioning by foam and / or Polymer can be identified:

- *coarse, frictioned soil*  
conditioning necessary to obtain plastic material for building-up a correct earth-pressure in the working chamber
- *silty sands*  
conditioning shows positive effects regarding the reduction of abrasion and decreasing the torque. This effects allow in consequence to increase the TBM speed.
- *clay*  
conditioning necessary due to adhesion and clogging problems

In case of very stiff and homogeneous clays open shields (air pressure mode) can be used. The application field of porous soils like gravelly sands are today mostly driven in Slurry mode, but some site applications show that these soils are also possible to treat effectively with EPB machines.

### 1.1.2 *The use of additives on Slurry machines*

Additives for Slurry machines can be useful under the following conditions:

- saline ground water (bentonite is loosing its capabilities)
- sticky or swelling clays (clay lumps are produced by the cutterhead which are clogging together in the working chamber later, blocking the cutterhead and the mud pump)
- segregation problems in the working chamber

These additives are mainly Polymers or special clay dispersants.

### 1.1.3 *The use of additives on Hard Rock machines*

Additives for Hard Rock machines are mainly foams for dust suppression or special anti abrasion additives. The tunnelfoam has to be 'dry' and stable to collect as much dust particles as possible. The application of this foam may be on the conveyor belt sprayed on the excavated material or introduced in front of the cutterhead. This solution is maybe the most effective one because the dust is binded where it is created, but not all hard rock TBMs are equipped for this kind of application.

## 1.2 Characterisation of Tunnel-Foams

To create a tunnelfoam, foaming solution and air has to be pumped simultaneously through a foam generator. The foam generator may be filled with grids, membranes or a granular material. It shall be equipped with flow meters and pressure meters to allow a complete monitoring of the injected foam quantity.

This is very important to know exactly what happens in the working chamber. If the foam parameters are not set correctly, the following situation may appear:

- *too much air injected:*
  - a. soil becomes too dry in the chamber, temperature and torque increases, insufficient speed.
  - b. creation of a big air bubble in the top of the TBM with non-homogeneous soil support and risk of blow-out
- *too much liquid or Foam injected:*
  - a. soil can be squeezed through the extraction screw
  - b. muck handling becomes difficult
  - c. increasing costs per linear meter of tunnel
- *too less conditioning:*
  - a. soil may plug the cutterhead and / or chamber, insufficient TBM speed
  - b. pressure loss in front of the TBM
  - c. water income

In order to use soil conditioning with tunnelfoam under defined conditions, the following parameters have to be defined (see figure 2):

- *c<sub>F</sub> (Concentration of foaming solution)*  
which determines the concentration of the foaming concentrate in water
- *FER (Foam Expansion Ratio)*  
which characterises the ratio of Air mixed with the foaming solution
- *FIR (Foam Injection Ratio)*  
which characterizes the ratio of foam mixed into soil

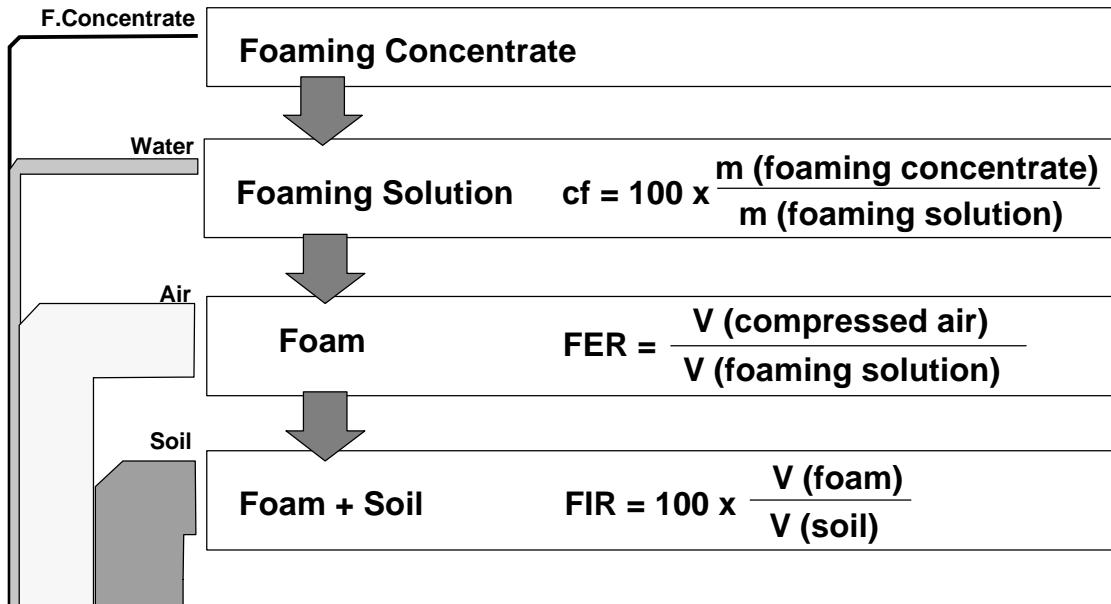


figure 2. key parameters of tunnelfoam use

The foaming concentrate which is needed to create the foaming solution, contains surface active substances called surfactants. These surfactants are molecules with a combination of a hydrophobic chain and a hydrophilic head. Figure 3 illustrates how the surfactants are working:

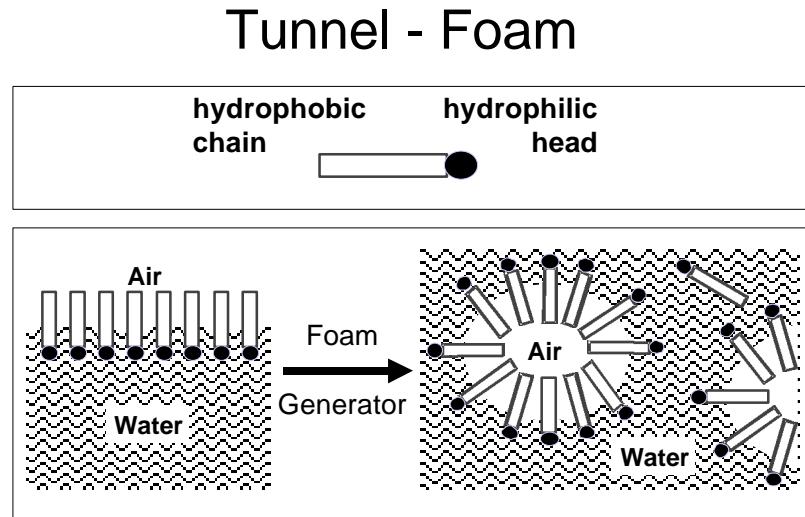


Figure 3 Presentation of Foam

Both parameters – hydrophobic chain and hydrophilic head – can be chemically varied: different chain structures (length, steric structure) and different head characters (anionic, non-ionic, cationic, amphoteric) are possible. The different chemical characters come to different properties of a tunnelfoam: 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 work properly. The type of foam which has been used for a specific site should be determined by laboratory tests with the original in situ type of soil.

### 1.3 Characterisation of Polymers

There is a wide range of application for polymers. Examples can be:

- ‘Structurising’ a soil
- Reduction of stickiness
- Reduction of adhesion to metal surfaces
- ‘Drying out’ a soil
- Reduce soil segregation in the working chamber

In consequence there exists a wide range of products called ‘polymers’ on the market, for example:

- Polyacrylamides (not rated due to environmental problems)
- Polyacrylates
- CMC’s
- Biopolymers

These product types are totally different from each other and not all are suitable for TBM use or not up to date. Regarding the use of additives on site it is strongly recommended that they fulfill at least the following criteria:

- liquid state for easy and controllable dosage

- no blockage of the foam generator in case of a combined use with foam
- develop its reactivity within minutes to be able to react as quick as necessary
- not dangerous for the environment

A quite new and exciting range of additives are the Biopolymers, which show some additional effects like thixotropy or pseudoplasticity and can be used in Slurry- and EPB-TBMs.

#### 1.4 Clay Dispersants

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

To fulfil the desired job, the dispersing agents 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 both by surfactants and dispersants, but dispersants are more efficient due to a higher amount of loads per molecule (as illustrated in figure 4).

The choice for which geology it is better to use foam whether to inject dispersing agents can only be made by specialists in the laboratory by studying the original soil and combine these knowledge to the effects visible on the TBM itself.

## Dispersants and Surfactants

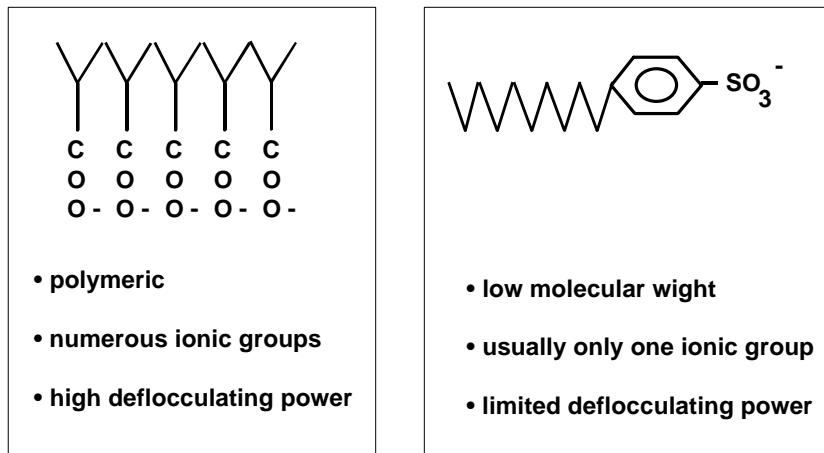


figure 4: Dispersants and Surfactants

## 2 Site Examples

After the given background information regarding which types of additives exist and for which application they may be needed, this chapter indicates some examples of their successful world-wide use on site.

### 2.1 Aviles Collector (Spain):

Porous sand under 3,0 bar seawater pressure

The Aviles Site works with a Lovat EBP machine, diameter 3,40 m. After facing stiff clayey silt, the soil changed over a length of approximately 1.000m to pure gravelly beach sand with a seawater pressure of nearly 3,0 bar. The grain size distribution is shown in figure 5:

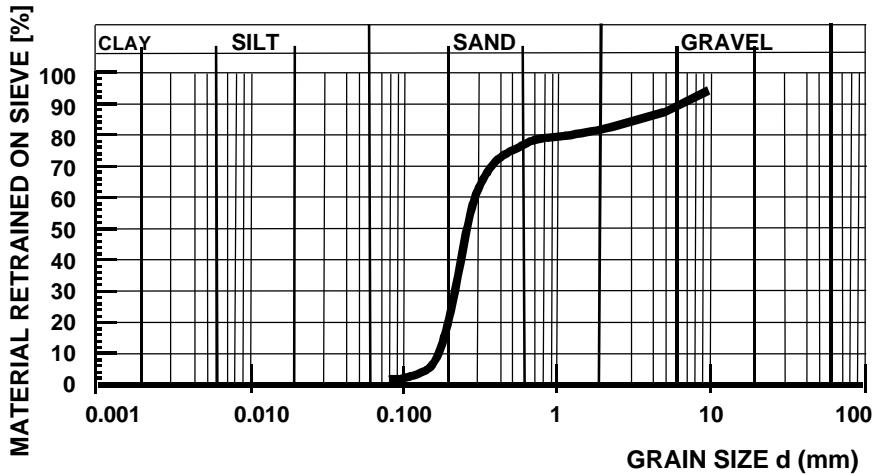


figure 5: Grain size distribution curve of Aviles Sand

There was no possibility on the machine to introduce additional fine material into the working chamber. An extra installation had been too costly and too time intensive. The alternative solution was to use additional Polymers – to make the soil as plastic as possible (to be able to install a counter pressure against the seawater) and to reduce the water content of the outcoming soil.

#### 2.1.1 *Laboratory tests*

Lab results present some segregation control tests (figure 6) to identify the searched plastic comportment and penetrometer tests (figure 7) to study the effects of an excess of water. All tests are realised with the original Aviles Sand and are carried out with  $Wi=7\%$ ,  $d(\text{org})=1,5$ .

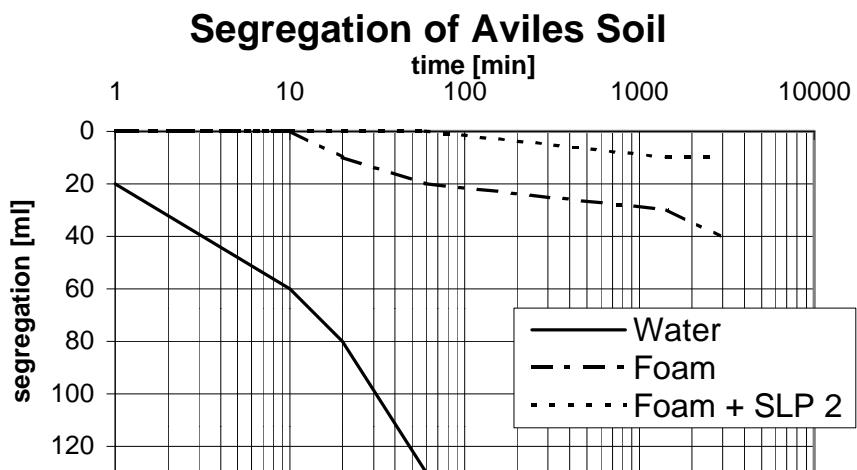


figure 6: segregation tests

Figure 6 shows the drastic problem of a coarse soil mixed with water. An almost instantaneous segregation is obtained, impossible to work with on a TBM. With a very stable tunnelfoam the result can be improved, but still 20% segregation after 15 minutes is obtained – too much for a secure work 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 to the tunnelfoam.

The penetration depth of the cone penetrometer indicates the plasticity of the soil: the higher the penetration depth the more liquid is the soil. The aim in this case is to maintain the penetration depth even when adding water. These tests results are shown in figure 7:

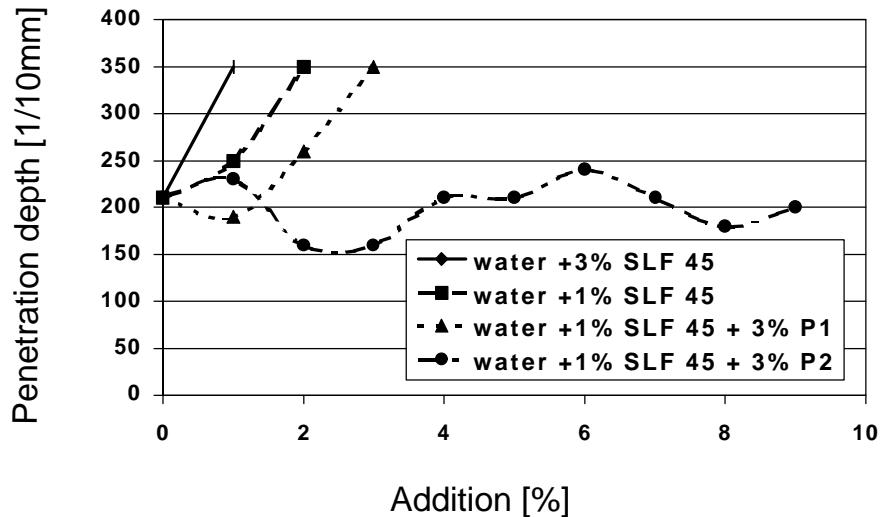


figure 7: cone penetrometer tests with Aviles Soil + Foam + Polymer

Only the use of foam will not be successful, the soil gets fluid far too quickly – even when the concentration is decreased to 1%. The use of SLF P1 stabilises the soil up to a certain water content, but loses its efficiency when the water content is too high. Whereas SLF P2 shows no change in the penetration depth even when the water content increases.

### 2.1.2 Conclusion:

The decision was to inject stable foam together with a structuring biopolymer (SLF P2) in order to keep the water away and to structurise the small amount of fine soil particles. The result was a stable, homogeneous and pasty soil. For security reasons a second polymer (SLF P1) was injected into the screw conveyor in order to dry out again the excavated material.

The drive through this type of soil was very successful with the presented solution and reached high advance rates.

## 2.2 Hongkong:

### conditioning of weathered granite

The most difficult soil for an EPB machine in this project was weathered granite which showed the following grain size distribution curve (see figure 8) which is composed out of two different soil graduations:

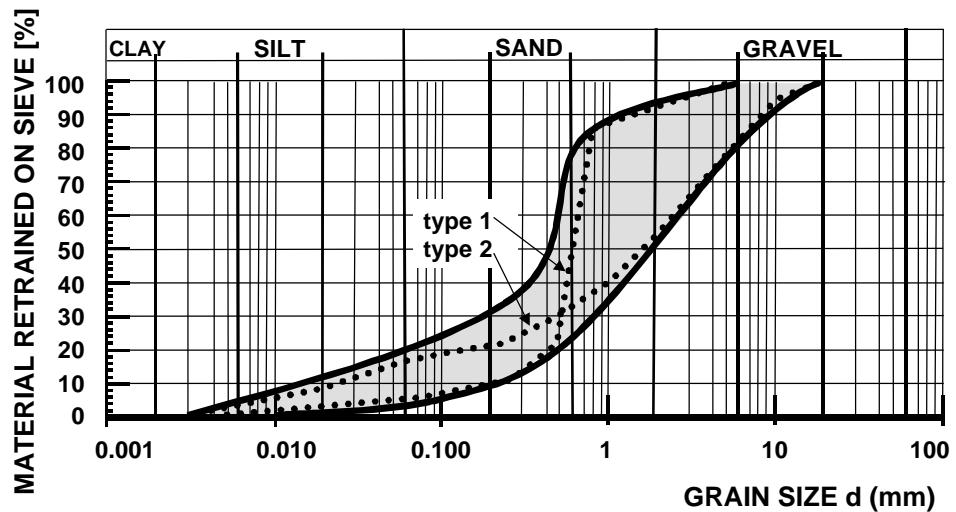


figure 8: grain size curve of weathered Hongkong granite

In order to identify the right conditioning additives and injection parameters to create a cake development, permeameter tests were carried out with the results presented in figure 9. For these tests the cylinder has been filled first with gravel, then with the soil which should be tested. Water was finally added up to a certain height over the soil. The tests were carried out with an overpressure of 0,4 bars and with the soil type I which contains less fine particles.

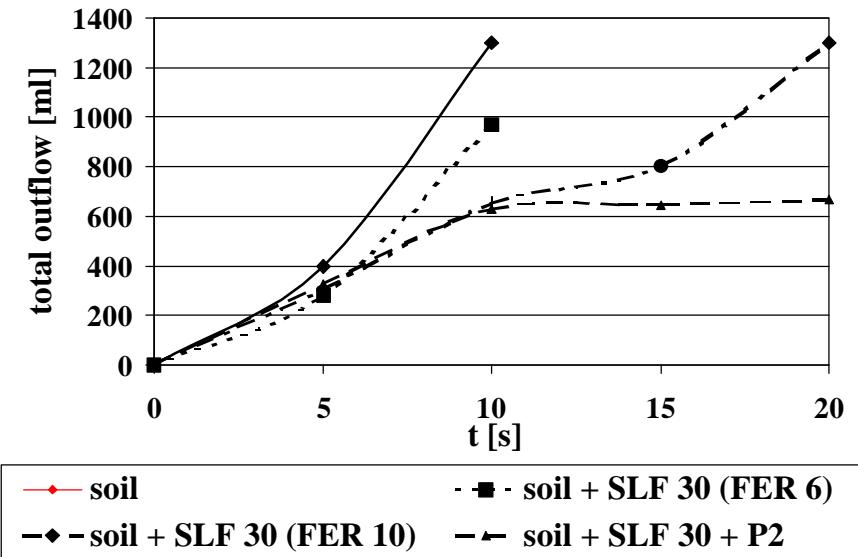


figure 9: Permeameter tests with  $\Delta p=0,4$  bar

The untreated (only water added) soil porosity was calculated to  $k=5*10^{-3}$  [m/s]. The outflow increases due to the outwashing effect of the fine particles. In the second step the soil was mixed with foam (cf=3%, FER=6, FIR=40) which caused less outflow compared to the untreated soil. But still insufficient to create a filtercake. In a second step the expansion ratio was increased from 6 to 10 to obtain a 'dryer' foam. The first indications of a filter cake development are shown but it was not stable enough. In the fourth trial the foam was reinforced by adding 2,5% of the Polymer MEYCO Fix SLF P2. The result was a stable cake even at  $\Delta p=0,6$  bar which is possible due to the structuring effect of the Polymer.

### 2.3 Bangkok Metro (Thailand): clogging problems of Bangkok Clay

The EPB machine suffered due to the stiff and adhesive Bangkok Clay. The contractor used a Japanese Polymer and was not happy about the obtained effects itself and compared to the costs.

The solution was to introduce a material, which increases the clay dispersion in order to obtain untreated clay lumps embedded in a more homogeneous soil paste, which does not stick. Laboratory ball rolling tests (clay balls + sand in water) were carried out and the effects are shown in figure 10.

On the first view the results are astonishing. Especially for clay designed dispersing agents or foams like SLF 30 or 45 do not have the desired effect on Bangkok Clay. This illustrates once more the complexity of the interaction between soil and conditioning agents. For the desired site the use of foam SLF 20 showed the best results in the laboratory. This is well proven on site since February 2000.

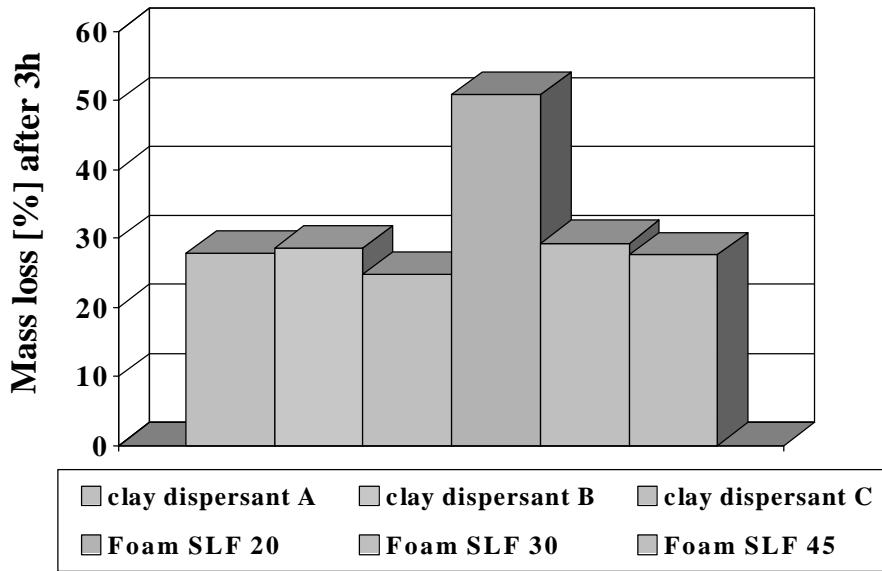


figure 10: Ball Rolling test with Bangkok Clay

#### 2.4 Wesertunnel (Germany):

##### adhesion and clogging of Lauenburger Clay

The most difficult soil condition this Slurry TBM has to work with is the Lauenburger clay. It shows high adhesion and clogging properties on site. Additional problems occur due to the saline groundwater which reduces the bentonite effects.

The aim of the laboratory tests have been to prevent the cutted clay lumps from clogging (in terms of re-agglomeration) in the working chamber with secondary problems like segregation. The used test method was again the rolling test: A cylinder was filled with the original bentonite suspension made with the original water and freshly cut clay chips were added. The results are shown in figure 11.

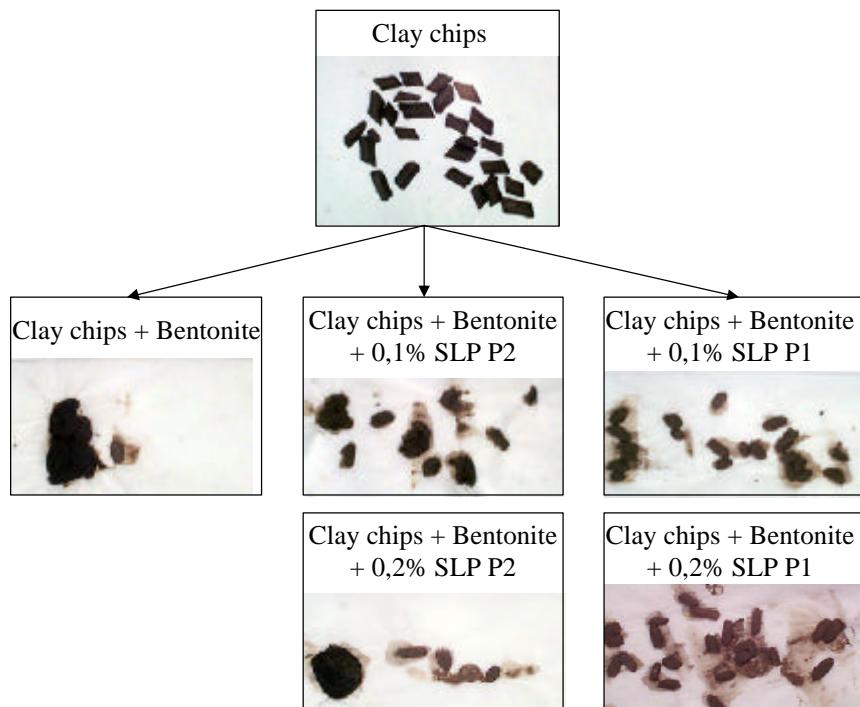


figure 11: rolling test of Lauenburger Clay in bentonite suspension

If the clay chips are rolling in the untreated bentonite suspension, they are quickly agglomerating and forming a big lump. This causes clogging of the cutterhead (followed by low advance speed), segregation effects in the working chamber and finally blocking of the bentonite circuit. Is the bentonite treated with Polymer P2, at 0,1% the clay agglomeration is drastically reduced at 0,2% it increases slightly again. Is the bentonite treated with Polymer P1 at 0,1% the agglomeration is nearly prevented but at 0,2% the dispersing effect increases visibly. This has negative influences on the bentonite separation. This very positive laboratory results have to be transferred to site application.

### 3 Conclusion

The laboratory results combined with the 3 examples of world wide site uses prove the positive effects of conditioning additives in shielded tunneling. Their use is one of the key factors for a successful and overall economic TBM drive.

In addition the market shows the tendency towards using EPB machines even in clay soils (London Heathrow T5 as another example) and also in porous soils (Aviles, DTSS Singapore, ...). This results in new limits for EPB machines summarised in figure 12.

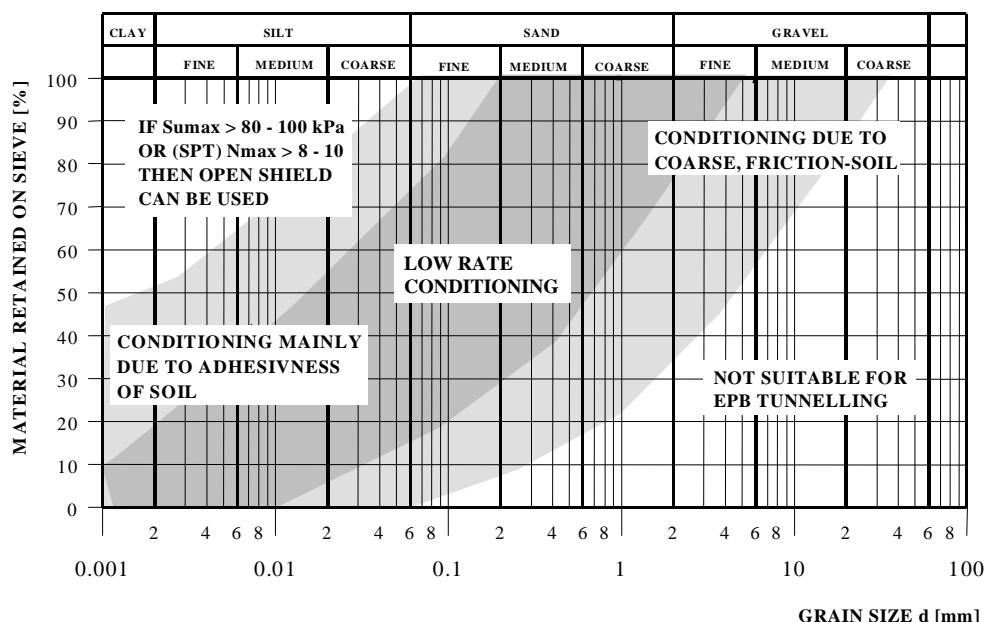


figure 12: EPB limits

Due to the new generations of conditioning additives, their easy use on site and thanks to their high influence on the soil more and more EPB machines will be used instead of slurry machines.

### 4 Acknowledgements

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### 5 References

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