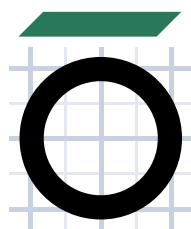


# **CHEMICAL CONSUMABLES FOR TBM EXCAVATION**

ITAtech Activity Group Excavation

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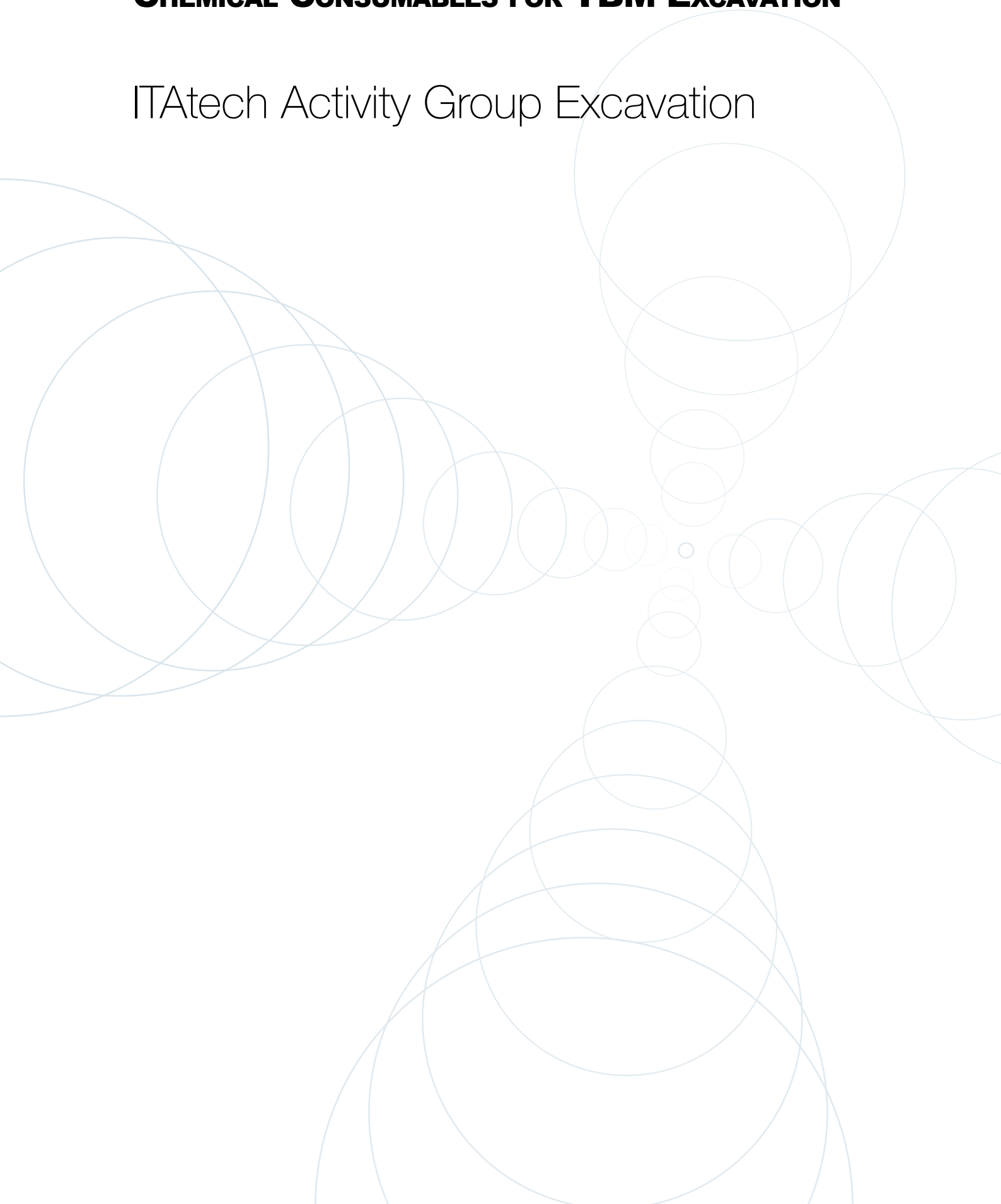
**ITAtech**

Considering the growing expansion of underground construction in different regions of the world, tunnel contractors are dealing with more complex operations in longer projects. This is linked with excavation affronting different geological profiles. Therefore, the use of tunnel boring machines (TBMs) is growing more and more, and with it the necessity of different chemical products to support their operation from foams for the conditioning of the ground for EPBs (earth pressure balance), to different types of greases for critical or unique sealing applications.

If foam are to be used during excavation with a EPB TBM, then this document describes and defines a guideline to evaluate the choice of the different products in several specific tunnelling applications, considering performance, costs and environmental expectations. The document will additionally highlight the testing procedures for a screening of the technologies available in the market.

# **CHEMICAL CONSUMABLES FOR TBM EXCAVATION**

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# 1 >> INTRODUCTION ON THE USE OF FOAM FOR SOIL CONDITIONING

Foaming agents in combination with the right amount of water are the most important and common materials used for soil conditioning during mechanized tunnelling with TBMs. Foams may increase viscosity in granular soils or decrease stickiness in cohesive soils.

Several types of foaming agents for TBM soil conditioning are available on the market. They vary depending on the types of ingredients used and their dosages in the finished product. Different ingredients and different dosages produce different behaviors in the generated foam, both technically and from the environmental point of view.

The main ingredient of foaming agents is always a surfactant or a combination of surfactants (anionic, cationic, non-ionic). Surfactants are used because they allow the generation of foam bubbles once air is added to the liquid mixture of water and foaming agent.

Other ingredients are generally combined with the surfactants, with the aim to improve some technical characteristics of the generated foam. Typically, these ingredients are defined as “polymers or additives” and function to improve some technical characteristics of the foam:

- **The foam durability:** addition of special polymers into the foaming agent strengthens the foam bubbles, which are then more durable and increase the foam “half-life”.
- **The muck lubrication:** lubrication can be important in some conditions such as soils/rocks with abrasion characteristics (i.e., sands).
- **The muck dispersing action:** this action is important during the excavation of soil/rocks presenting problems of stickiness onto metallic surfaces.
- **Some other ingredients** can be added into the foaming agent by the chemical supplier at lower concentrations, such as solvents used to decrease the product viscosity or to reduce the freeze-point of the mixture, as well as preservatives to allow its storage.

## 1.1 FOAM SELECTION CRITERIA

Several foaming agents are available in the TBM market with different chemical formulations and consequently with different technical characteristics and environmental approach.

The type of soil to be excavated and the ground water conditions are the most important criteria for the selection :

- **For cohesive soils or rock masses,** one issue related to soil conditioning is the clogging of material on the metallic parts of the TBM: at the cutting wheel, inside the excavation chamber and along the screw conveyor. Another issue is that cohesive soils must be softened. It is then necessary to increase the water/liquid content so that the soil behaves plastically.
- **Special foaming agents,** typically combined with anti-clogging ingredients, should be selected for these cases.
- **For granular soils,** the main issue related to soil conditioning is the segregation of the soil particles, with the aim being to create a homogeneous paste able to maintain the EPB pressure against the tunnel face and, if present, to control the ground water.

Another issue related to soil conditioning is the wear to steel structures such as cutting wheel, cutting tools as well as to the screw conveyor, which can cause serious problems during the excavation of some granular soils or some types of rock masses depending mainly on their mineralogic composition (for example, presence of quartz).

It is very important to underline some other aspects as the geology is not the only parameter to be considered during the analysis of the soil conditioning:

- **Size of the TBM,** EPB pressure to be applied at the tunnel face, number and position of the injection lines, type of foam generators, etc. are all other factors that have significant on the soil conditioning concept.
- **The environmental impact** “measured” with the local regulations (which are different in each country and, sometimes, vary even inside the same country),

influencing especially the depositing or re-use of the excavated material.

- **The alternance of different geologies** along the tunnel alignment: for example, when the geology varies often, it is a big challenge to alternate an anti-clay foaming agent with an aggregating one, and it is more convenient (and practical) to use a single product.
- **Commercial aspects,** such as price, logistics, availability, etc.

Finally, while the right choice of the product is essential for success of the soil conditioning measures, the right application technique is equally important.

## 1.2 MAIN APPLICATION PARAMETERS (DOSAGE, CONCENTRATION, FER, FIR, WIR)

The main parameters used to control the performance of foaming agents for soil conditioning are the following: Foam Concentration (Cf), Foam Expansion Ratio (FER), Foam Injection Ratio (FIR) and Water Injection Ratio (WIR).

The most suitable range of the parameters are best designed with dedicated laboratory testing followed by field testing.

### 1.2.1 Foam Concentration (Cf)

Cf represents the dilution of the foaming agent in water, and therefore the volumetric ratio between the foaming agent and the water.

Typical concentrations are in the range between 1.0 and 3.0%, but lower and higher concentrations are possible and may be applied in particular conditions.

Generally, the higher the concentration, the higher the foam durability (longer foam half-life and stability in soil). However, a higher concentration does not always mean a better result in terms of soil conditioning.

### 1.2.2 Foam Expansion Ratio (FER)

The Foam Expansion Ratio represents the ratio between the volume of the generated foam and the volume of the liquid used (water + foaming agent).

# 1 >> INTRODUCTION ON THE USE OF FOAM FOR SOIL CONDITIONING

The more air that is added into the generating liquid, the higher the FER.

Typical values of FER are in the range between 4 and 18, but lower and higher values are also possible.

It is also important to mention that the type of foam generator used has a significant impact on the generated foam quality. The same proportion of air and liquid can result in very different foam expansions (FER) depending on the foam generator used and on the generator's capability to create turbulence.

Some general rules about FER:

- High values of FER are typically used for granular soils.
- Low values of FER are typically used with low-permeability soils such as clay.

## 1.2.3 Foam Injection Ratio (FIR)

The Foam Injection Ratio represents the percentage ratio between the volume of foam (water + foaming agent + air) added to the soil and the volume of the soil excavated.

Typical values of FIR are in the range between 30% and 80%, but lower and higher values are possible in particular conditions.

Some general recommendations to find the right FIR:

- **Dry soils** typically require addition of more foam, and therefore higher values of FIR.
- **Cohesive and low-permeability soils** typically require higher FIR than granular soils.
- **Higher EPB pressures** typically require higher values of FIR.

Larger TBM sizes often require higher values of FIR.

## 1.2.4 Water Injection Ratio (WIR)

The Water Injection Ratio is the percentage ratio between the volume of water added to the soil and the volume of soil excavated. Typical values of WIR are in the range between 0% and 10%, but higher values are possible in particular conditions.

The addition of pure water (through different injection lines on specific machines) is generally important especially in cohesive soils and rock masses, such as clays, silts, claystones, etc., but it may cause problems such as stickiness. Pure water helps keep the soil fluid and cold and reduces the need to add foam (FIR) to get the same result.

The right water content in the soil is also important to "protect" the soil conditioning foam. If the soil is too dry the foam is destroyed very quickly and cannot develop its full potential as soil conditioner.

The amount of water added to the soil during excavation also determines the water content of the soil for disposal and may therefore influence the disposal conditions and costs. The addition of water should be balanced between ease of excavation (higher WIR) and muck transport and disposal considerations (lower WIR).

The most suitable value of WIR and the right balance between WIR and FIR need to be assessed with dedicated lab and site tests for each single case.

The control of these four parameters is of great importance for the soil conditioning results and, in consequence, for the TBM performance.

The foam parameters Cf, FER, FIR and WIR are predefined during dedicated laboratory tests. During the TBM excavation, the soil conditioning parameters are established by the TBM engineers and operatively controlled by the TBM operators, based on the TBM parameters (such as torque of the cutterhead and of the screw conveyor, thrust force, etc.) and constantly reviewed based on the appearance of the conditioned soil at the screw conveyor exit point and along the belt conveyor.

Continuous adjustments of the four parameters are possible (for example: muck that is too dry requires an increase of FIR); however, it is suggested that the selection of this set of parameters and their variation is made in cooperation with the TBM operator, the TBM engineer, the foaming agent

supplier, etc. Sometimes environmental aspects must also be considered, for example in the case that there is a maximum dosage of foaming agent allowed into the excavated soil for disposal.

The control of the parameters is typically made in an automatic or in a semi-automatic way, even if some differences in the foam systems exist among the different TBM producers. In general, automatic control means that the parameters of concentration, FER and FIR are set by the TBM operator, and the software automatically calculates the flows of air and water necessary to condition the soils with the parameters, as a function of the TBM advance speed. In the semi-automatic mode, the flows of foam are set by the TBM operator and need to be manually modified as a function of the TBM advance speed. Other, more manual modes are sometimes possible but are generally not recommended and rarely used for TBM excavation.

## 2 >> INTRODUCTION ON THE USE OF POLYMERS AND ADDITIVES

Polymers and additives like foam are conditioning agents to modify the properties of the soil during excavation and transport.

They can be used in addition to the foam, such as foam stabilizer or anti-clay (clay dispersant), or they can be added separately, e.g., to bind water. Special anti-wear additives can reduce the wear on tools, cutting wheel and screws. The use of polymers in Slurry TBMs is very limited to specialized applications.

The most important and commonly used application for polymers and additives is during excavation with EPB TBMs in sticky clays and in coarse sand and gravel, with or without ground water, as shown in the diagram in Figure 1.

The addition of polymers into the system can be realized by the chemical supplier as an addition to the foam solution, either in the factory or on site through a separate dosing pump. In order to achieve a stable and homogenous foam with the desired FER the added polymer or additive must be highly soluble in the foam solution. Other polymers, such as water binding polymers, can be pumped through separate lines directly into the chamber and through the cutterhead.

### 2.1 TYPES OF POLYMERS AND ADDITIVES AND SELECTION CRITERIA FOR THEIR APPLICATION

#### 2.1.1 Foam reinforcement - Ground permeability - Challenging ground water conditions

In order to keep the face and chamber pressure in coarse sandy soils, foam reinforcing polymers may be required. A strong, polymer reinforced foam can also be applied to keep the face pressure during excavation stops and interventions. Similar polymer foam reinforcement may be required to reduce the soil permeability in the presence of ground water.

Polymers for increased bubble strength and higher foam resistance must be highly soluble in the foam solution and can be added to the foam solution at the factory or on site through separate dosing pumps

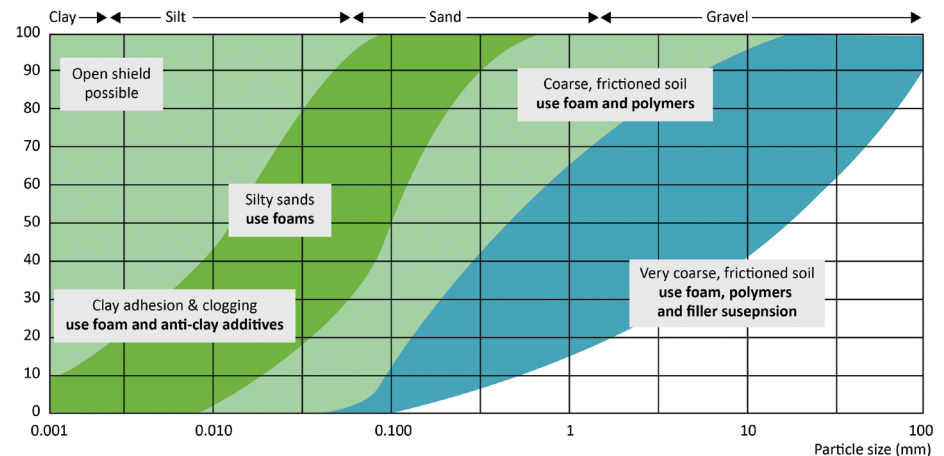


Figure 1

into the foam solution line before the foam generator.

#### 2.1.2 Water binding polymers

Water binding polymers may be applied to bind excess water in the chamber in order to maintain the EPB pressure gradient. They also offer a way of transporting the water through screw and belt conveyor without water inflow into the TBM and to prevent the fines in the soil from being washed out

#### 2.1.3 Dispersing polymers (anti-adhesive or anti-clay)

Dispersing or anti adhesive additives are essential for the efficient excavation of clayey soils, clay and siltstone and other ground types that produce spoil during excavations or tend to clog tools and openings. Anti adhesive additives are mostly part of specialized anti-clay foams and have the ability to disperse clay particles. The soil, being treated with anti-adhesive has less stickiness (soil cohesion and soil adhesion to tools, cutterhead and screw conveyor). Dispersing foams reduce the tendency to clog openings in the cutterhead and to block tools. They lead to considerable torque reduction, less energy consumption and extended excavation periods in between interventions.

#### 2.1.4 Wear reducing additives

Anti-wear polymers are usually additives to special anti-wear foams. In hard rock excavation and mixed face situations

they can considerably reduce the wear of the cutterhead, cutting tools and screw conveyor and hence reduce the intervention frequency.

### 2.2 TESTING OF POLYMERS AND ADDITIVES AND POLYMERIZED FOAMS

#### 2.2.1 Bubble strength

The bubble strength is important especially in coarse soils to limit the soil permeability in order to keep the face pressure and reduce water inflow. As such the bubble strength can be measured in different ways. Directly as (static) foam half-life, visually as foam stability in soil and indirectly by measuring the soil permeability after foam/ polymer addition.

#### 2.2.2 Foam half life

Foam half-life is the time when a given portion of foam has lost a portion of its volume. This can be measured by volumetric measurement or by measuring the weight of foam solution that runs out of a hole at the bottom of the foam container over time

#### 2.2.3 Anti-clogging

The effect of anti-clogging polymers can best be observed visually by checking the stickiness of the soil to the mixer and mixing tools in the lab, comparing the un-treated and the treated soil. It is also possible to form cubes from treated and non-treated soil and observe their sliding behavior on an inclined metal surface.



## 2 >> INTRODUCTION ON THE USE OF POLYMERS AND ADDITIVES

### 2.2.4 Water permeability

The water permeability of treated and untreated coarse soils can be measured in accordance with e.g., International standards ISO 17892-2019, following the Darcy principle.

### 2.2.5 Water binding

The water binding properties of polymers can be demonstrated in easy cup tests, mixing soil samples with varying amounts of free water with a pre-defined amount of polymer to measure their water binding properties in combination with different soil types. It may also be of interest to keep those 'dried' soil samples over a project-specific period and observe the stability of the dried soil and whether or when liquid water is being released.

The so called foam killers need to be considered separated.

## 2.3 ENVIRONMENTAL ASSESSMENT OF POLYMERS

Each of the soil conditioning products must be tested in independent environmental labs for its aqua-toxicity (such as impact on fish species, impact on plant species, impact on algae and crustacean species) and for its biodegradability.

### 2.3.1 No Observed Effect Concentration

The No Observed Effect Concentration is the quantity of soil conditioning chemical agent that can be disposed to the environment with which no harm will come to the above organisms.

## 3 >> BASIC LABORATORY TESTS

Laboratory testing of conditioned soils prior to tunneling, in combination with the available geological information, is required to provide the basis for project-specific construction planning. The purpose of these tests is to evaluate different conditioning agents and to assess the feasibility of soil conditioning. Another goal of these tests is the recommendation of the most suitable foaming agents with which to start tunneling

These tests are performed in optimum laboratory conditions; however, the in-situ conditions are influenced by several other factors such as the ground surrounding the tunnel, face support pressure, water, the design of the TBM foaming system including generators and, ultimately, the skills of the operator.

Some of these tests should be performed periodically during the TBM operations to monitor the quality of soil conditioning, as well as to ensure quality of foaming and continuous muck extraction when mining conditions change. Continued testing during mining can have a significant impact on the successful face support application, as well as equipment wear and the overall manageability of the excavated material as it opens opportunities to adapt and improve the conditioning plan.

Additionally, the tests of foams in the TBMs are important to assess the performance of the foam generators.

### 3.1 LABORATORY TESTS

#### 3.1.1 Soil Sample Evaluation

These tests are carried out to characterize the soil sample.

##### • **Moisture content (ASTM D 2216)**

The purpose of this test is to determine the water (moisture) content in the soil sample. The water content is the ratio, expressed as a percentage, of the mass of “free” water in a given mass of soil to the mass of the dry soil solids, measured as the difference between the moist soil and the soil dried at 105°C, known as the “oven-dry weight”.

The amount of water is determined by subtracting the dry weight from the initial

weight, and the moisture content is then calculated as the amount of water divided by the dry weight or total weight, depending on the reporting method.

The moisture content of the supplied samples shall be compared to the moisture levels expected in the tunnel zone. The samples shall be tested at the expected moisture level during excavation.

##### • **Grain Size Distribution (ASTM C 117)**

The purpose of this test is the measurement of the size distribution in a soil sample. The material is made to pass through a series of sieves of progressively smaller mesh (size) and determination is done by weighing the amount of material that is stopped by each sieve as a fraction of the whole mass.

The gradation of the soil samples received for testing shall be compared to the information provided by the Geological Baseline Report (GBR).

##### • **Atterberg Limits for cohesive silty/clayey soils (ASTM D4318-17)**

The purpose of this test is the determination of water content at which cohesive soils change from one state to another, also known as Consistency Limits. This kind of cohesive soil can be found in nature in four different states: liquid, plastic, semi-solid and solid.

The major limits are:

- **Liquid Limit (LL)**, is the moisture content at which the cohesive soil passes from liquid state to plastic state.
- **Plastic Limit (PL)**, is the moisture content, expressed as a percentage of the weight of the oven-dry soil, at the boundary between the plastic and semisolid states of consistency.
- **Solid Limit (SL)**, is the moisture content at which the cohesive soil passes from semi-solid state to solid state.

The subtraction between LL and PL allows the calculation of the Plasticity Index ( $PI = LL - PL$ ), that represents the range of water content over which the soil is plastic. PI, in combination with water content at liquid limit (WL), indicates how sensitive the soil is to the changes in moisture content.

#### 3.1.2 Soil Conditioning Evaluation

These tests are carried out to determine how effective a foaming agent is on the soil sample at certain foaming parameters (Cf, FER, FIR, WIR). As a basic recommendation, samples may be prepared using a Hobart mixer with a B-flat beater. The recommended sample size is around 5 L and is mixed at around 100 rpm for three minutes.

##### • **Static and dynamic flow (ASTM C 230)**

The purpose of these two tests is to evaluate the static and dynamic flow (the behavior) of a soil mixed with foam. The methods have been developed to reproduce the shear stress forces the soil undergoes when it is inside the excavation chamber and to test thixotropy of the conditioned soil. Therefore, the two tests are carried out after the foam and/or polymers have been applied to the soil.

The first measurement designates the static flow, which is measured immediately after the cone is removed. The dynamic flow is measured after 15 drops of the flow table for sandy/granular material and 40 drops for clayey soils.

Conditioned soil is considered acceptable when the spread is in the 120mm to 150mm range. In case the appropriate spread is not reached (usually dynamic flow should yield 15cm), a variation in FIR, water content or soil conditioning additive is recommended.

##### • **Slump Cone Test (ASTM C 143)**

The Slump Cone Test is a good indicator to define the global behavior of a conditioned soil, utilized to determine workability and consistency of the treated soil. With general recommendations of 10-15cm slump, this test is mainly used in cohesionless soils, the Slump Cone Test is a simple and low-cost procedure that can be used:

- In the preliminary design stage, and
- At the job site to keep the conditioning process under control during excavation, and compare with the lab values.

This is a quick method to confirm or adjust the desired soil conditioning settings.



### 3 >> BASIC LABORATORY TESTS

#### • Clogging Potential (Adhesion/ Stickiness)

The evaluation of the clogging potential during tunneling for silty/clay mudstones was established by Hollman and Thewes in 2013 and is based on the Plastic Limit (PL) and Liquid Limit (LL) values generated by Atterberg limits according to ASTM D4318-17.

The following graph is based on these values as well as the Consistency Index (IC), which is calculated with the water content (WL) of the flow table samples (as defined in ASTM C 230) according to the following equation:  $IC = (LL - WL) / (LL - PL)$ .

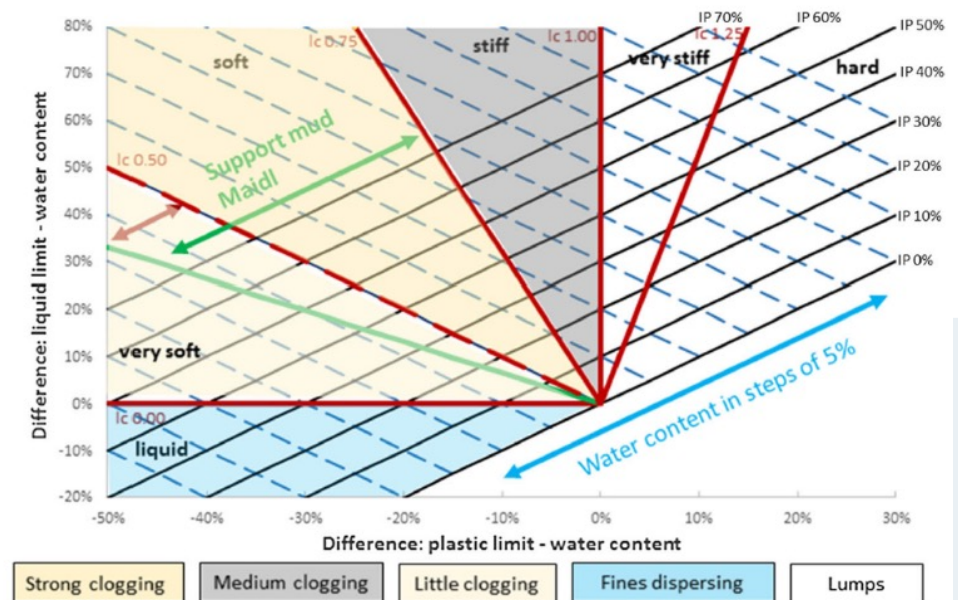


Figure 2

## 4 >> ENVIRONMENTAL

### 4.1 ENVIRONMENTAL ASSESSMENT

Assessment of the environmental impact during the construction of civil works is a critical part of considering any ground conditioning program. This assessment involves a deeper analysis of the impact of the foaming agents during the conditioning of the ground, especially during excavation with EPB TBMs.

Interest in and studies related to the environmental impacts of foaming agents have increased as the modern tunneling industry requires faster and better performing machines. These machines use more foaming agents to condition the ground. In addition, further studies of the final disposal and re-use of the excavated, and already conditioned, ground are of interest.

Considering the chemical composition of traditional foaming agents: these are aqueous mixtures of main compounds (to produce the foam itself), anionic surfactants and minor compounds (such as additives to increase half-life or stability, or to preserve the chemical characteristics).

To determine the environmental impact of such products, different studies and specific laboratory tests may be carried out. The idea is to determine the effect (mortality, immobilization or growth inhibition) on specific organisms after addition of different amounts of such chemicals.

The proper environmental analysis of the foaming agents for the soil conditioning requires two different and correlated studies: biodegradation and eco-toxicity.

### 4.2 BIODEGRADATION FUNDAMENTALS

Biodegradation is the process where organic compounds, such as the surfactants in the foaming agents, are reduced to simple molecules by micro-organisms.

Biodegradation is influenced by different factors such as the characteristics of the compound and its dosage, as well as external factors such as the environmental conditions where the biodegradation may take place.

The biochemical processes are carried out by micro-organisms naturally present in the air, soil and water but also found in the soil conditioned with foaming agents. The micro-organisms are mainly aerobic bacteria which can use oxygen to "oxidize or biodegrade" the organic compounds present in the soil (naturally or added during soil conditioning by humans). The biodegradation can be partial (transformation of surfactants and additives into simpler compounds) or total (transformation of foaming agents into water, carbon dioxide and inorganic salts).

The foaming agents commonly used during excavation with TBMs may be considered biodegradable, but the speed of the degradation depends on several factors (under same concentration and type of foaming agent):

- PH value of the conditioned soil close to neutral (pH of 6 to 8 are recommended for aerobic micro-organisms).
- Temperature (the micro-organisms of interest are so called "mesophiles" which have their optimal growth temperature between 25 and 45 °C. If the temperature increases, the speed of the biodegradation process increases too).
- Humidity and amount of oxygen.
- Type of micro-organisms available in the environment.
- Type of soil to be conditioned.
- External components (such as pollutants or toxic substances present in the soil).
- Concentration of the foaming agent.

When comparing different foaming agents, it is possible that some products biodegrade faster and easier than others. When comparing the same foaming agent under different dosages, the initial concentration has a notable influence in the biodegradation process: if the concentration increases, it is possible to have a higher biodegradation rate. However, in some cases, the increase in the concentration may lead to an inhibition phenomenon caused by excesses of organic carbon.

The evaluation of the biodegradation process requires the definition of the

following concepts:

- Biochemical Oxygen Demand (BOD): amount of oxygen required for the biochemical oxidation of the organic compounds.
- Chemical Oxygen Demand (COD): oxygen required for the chemical oxidation of all the oxidizable compounds.
- Total Organic Carbon (TOC): the organic carbon content in a medium.

The BOD test is used to describe biodegradation time, considering the composition of different products at the same dosage. Increases of the dosage can modify the function of the micro-organisms responsible for the biodegradation, which may lead to a higher biodegradation time.

In biodegradation processes, the number of bacteria grows during the oxidation of carbon present in the foaming agent into other products (such as water, inorganic salts, carbon dioxide and partial oxidized compounds). The biodegradation rate, the time that the bacteria require to acclimate to the medium and the time to start the oxidation of the carbon sources, reflects the presence of for example toxic compounds. It can also reflect if the amount of carbon may affect the biodegradation process.

Following the OECD-301 guidelines, in order to estimate the biodegradation rate and the performance in the compound, a foaming agent can be classified as "readily biodegradable" if the BOD/COD (Initial) after 28 days is larger than 0.6 (the BOD data are reported normalized with respect to the initial COD value).

A sample with a certain concentration is diluted into a mineral medium to be prepared according to OECD 301, then is put into a BOD bottle with a standard inoculum of bacteria and a bacteria inoculum from the soil. A magnetic bar for stirring the sample is then put into the bottle and the bottle is sealed with the pressure gauge stopper. The carbon dioxide trap fixed at the base of the pressure gauge stopper will collect gas while the gauge is reading the change in pressure. This pressure variation is translated into

weight (in mg) of oxygen consumed by the bacteria per liter of solution contained in the bottle. Readings of pressure shall be done every day. Testing conditions are room temperature and pH neutral. Since photolytic processes may influence the result, the bottles tested are kept under dark cover

Availability of tests to run at site is recommended because site conditions and local factors may affect biodegradation processes.

### 4.3 ECOTOXICOLOGICAL STUDY

Environmental impact assessments of commercial products used in TBMs should consider both biodegradation and ecotoxicity. In relation to ecotoxicity, the target organism used for testing purposes should belong to the same ecological ambient where the chemical product will end after completing its work life cycle. TBM commercial chemicals – being highly soluble in water – can be assessed as products which at the end of their work life end into an aqueous ambient, thus the target organisms to be used for the ecotoxicity tests should belong to an aqueous environment.

*Daphnia magna* can be profitably used for testing purposes, and it has been widely and frequently used as can be seen in the available literature. It provides an excellent reproducibility of testing measurement.

The sample is initially diluted at 0,5% and at 0,1% concentration of the chemical product. These serve as reference solutions for the following trials at different dilutions where the aim is to find the EC50, which means the concentration of the sample at which 50% of the total *Daphnia magna* population dies or are immobilized. At the same concentration of two chemicals, the higher the value of EC50, the lower the toxicity of the product is toward the micro-organism.

Soil conditioning agents are normally tested at decreasing concentration within a 24 - 48 hour timeframe defining the concentration at which, for example, 50% and 20% of the population of the micro-organism is affected.

### 4.4 EFFECTS ON THE GROUND WATER

The addition of foaming agents into the ground water may have different impact to micro-fauna and micro-flora. Depending on the type of compound present in the foaming agent and its concentration, the organic molecules could be persistent, or not, in the aqueous environment.

Bigger concerns need to be considered if organic compounds reach deep aquifers (>200m) where no aerobic micro-organisms may be present, and the normal biodegradation will occur at low kinetics.

It simply means that if, inside water, you have rock surfaces electrically charged the biodegradation is accelerated.

The effects of organic molecules due to foaming agents present in the ground water are more detectable and quantifiable (due to the large solubility) and their persistency depend on:

- Oxygen concentration levels.
- Presence of aerobic organisms.
- Typology and concentration of the molecules (generally commercial conditioning agents such as anionic surfactants can be considered as readily biodegradable at the final concentration found in interstitial liquids -liquids inside the pores- of conditioned soils and therefore in the aqueous mediums that may act as a vector to the groundwater).
- Other abiotic factors (light, pressure, temperature, ionic strength of the groundwater etc.)
- Presence of other compounds that may inhibit or favor the biodegradation of the organic molecules in the groundwater

In conclusion, the environmental impact study consists of two integrated parts, the study of biodegradation and the ecotoxicological study, and in both cases site-specific tests should be performed to identify the differences with those performed at laboratory scale.

### 4.5 MUCK DISPOSAL

Muck disposal is linked to local environmental regulations. The re-use of excavated material is allowed only if specific chemical and physical parameters are fulfilled. In general, the excavated soil can be used in the site where it has been removed to restore natural habitat, as a filler, or disposed in the landfill. As the last option causes a loss of non-renewable resources, many countries are improving their regulations and request from the construction companies a specific environmental impact of the disposed muck.

Environmental impact studies and definition of final storage sites should be carried out.

The impact of the muck to be disposed is related to the organic molecules present in the foaming agents. Toxic effects of these compounds to the organisms present in the ground / ground water will rapidly cease (in general in less than 7 days). For most sites, It is recommended to identify confined intermediate storage areas to allow an initial biodegradation phase of at least 5 – 7 days. During this time, environmental tests (on the liquids and soil) may be carried out to identify possible toxic effects on target organisms.

Experiences with standard commercial foaming agents show that the toxicity effects present at day zero usually disappear after seven days as the biodegradation process may have started and partially completed.

More details on the topic of spoil handling and treatment are available in ITA WG 14 publication on this topic (4).

## 5 >> INSTALLATION & RECOMMENDATIONS

### 5.1 RECOMMENDED FOAM SYSTEM FEATURES

Following is a list of preferred features for a EPBM foam injection system.

1. Owing to the limitations of space and cost, one injection line that splits into two ports after the rotary coupling is sometimes done. This practice oftentimes leads to lines choking more often than when a dedicated line is employed.
2. In the event that a lines chokes, a system or method to unchoke the lines should be in place.
3. All foam lines should be able to be controlled individually for flowrate as a minimum.
4. Typically, the Foam Injection Ratio is limited between 30 and 80%. This is often not enough to effect appropriate ground conditioning..
5. Machines should be supplied with a fully automatic system of injection linked to the advance speed.
6. Changes to ground conditioning parameters should be controlled, entering a unique password prior to any changes being a common method. This system limits who can make changes and who has the responsibility for differing levels of adjustments.
7. All lines should be fitted with a bypass valve after the foam generator in order to assess if the foam is being generated correctly.
8. Alarms should be employed to notify the driver when there is insufficient air from the compressor to generate the required Foam Expansion Ratio. Often machines are simply fitted with a compressor that is significantly smaller than is required for the job and the contractor is unaware of this until it is too late.
9. It should be made clear to the driver when the required flowrate is not being achieved. Often, the driver will set a flowrate that is beyond the pump capacity. Provide a table that can be given to the driver making clear the minimum and maximum flowrates available per line at varying FERs.
10. A minimum of two lines (on a standard 6.6m cut diameter TBM) should have the ability to by-pass the foam generator and inject either water or polymer into the face. The polymer dosing system should either be in-line or a mixing tank with sufficient storage installed. Polymer dosing should be able to be adjusted between 0.1 to 2% and the flowrate to the lines between 10 – 500 liters per minute.
11. When foam lines are not used a series of pulses should be injected to avoid the lines choking, or another means to avoid the choke over and above the “butterfly valve” at the exit point should be used.
12. As far as possible, each foam line should have a dedicated progressive cavity pump.
13. The capacity of the foam equipment should be designed to meet or exceed the theoretical volume requirements during maximum TBM advance rate.

The above list is not essential by any means but should serve as a minimum to form the basis of a discussion prior to selecting the EPBM. Employing this list would hopefully minimize most of the Ground Conditioning issues that arise on many projects.



## 6 >> MAIN BEARING SEALING PRODUCTS

### 6.1 TBM BEARING LUBRICATION

TBM bearing lubrication is a topic that is, from the outsiders' perspective, quite complicated. There is limited available literature that gives guidance to a buyer on different main bearing sealing systems and what to consider for a given ground condition.

There are two commonly available types of main bearing seals currently available to purchasers of TBMs, which are effectively categorized by the type of seals inherent in their design: Multi lip polyurethane seals and single lip NBR (Nitrile Butadiene Rubber) seals. The characteristics of these seals leads to different overall design and needs in the sealing system and by extension the products that they use. This will focus on sealing system and products common in pressurized machine applications. While not required these systems can be used in non-pressurized machine applications.

### 6.2 POLYURETHANE SEALS

These are analogous with Japanese TBM designs. These bearings utilize polyurethane lip seals that are much stiffer and resilient to "backflow" of soils from the TBM chamber, into the seal labyrinth. The shape of the lip seal is such that pressure from the chamber increases the contact pressure between the seal and the seal running surface preventing the material from flowing under the seal lip. See Figure 3.

The addition of Extreme Pressure (EP) grease which is continuously pumped forward under the seal lip adding in creating the seal and to ensure any contamination that might get under the seal lip is removed.

Typically each row of seals is able to counter the machines design pressure with additional rows in place for redundancy.

EP greases are lubricants based on lithium and/or calcium soaps, combined with special additives that improve the product resistance

to extreme pressure under high loads. These greases are suitable to lubricate mechanical parts subject to high loads, vibrations, and shocks, in a wide range of temperatures and even in the presence of water. However, in a TBM, the choice of EP grease is typically only a function of ambient temperature.

The grease viscosity is indicated with the NLGI (National Lubricating Grease Institute) consistency number, whose specifications are the only real guide to a products suitability.

Nine grades of EP greases are classified by the NLGI, but only four of them are typically used in mechanized tunnelling. The hotter the environment, the greater the viscosity required: EP0 for the hottest, EP3 for the coolest. See Table 1.

The mechanical performances of EP greases are typically evaluated with the 4-ball Test, which allows measurement of:

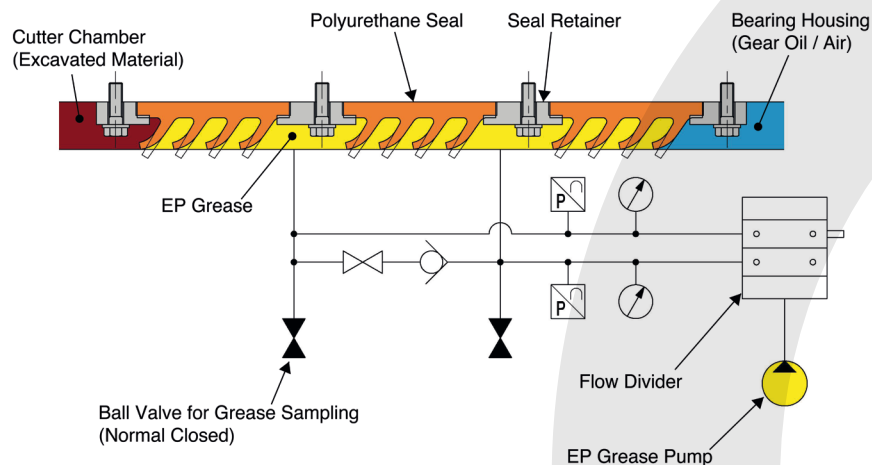
- The wear preventive characteristics of a grease (ASTM D2266). A ball is rotated against three stationary lubricated steel balls. The better the lubricant is at preventing wear, the smaller the wear scar is measured on the three stationary balls.
- The weld load (ASTM D2596), which indicates the Extreme Pressure properties of a lubricating grease under high load applications.

Another technical characteristic to evaluate is the resistance to water wash-out at +38°C, which is measured according to the ASTM D1264. The lower the value of wash-out (indicated as a percentage of the initial mass of grease), the better the grease is at bearing water.

Besides the traditional EP greases that are based on mineral components, more environmentally friendly products are available on the market, which are quickly biodegradable (> 60% at 28 days according to the OECD301). It is important that they have the same technical properties of the traditional EP greases (such as viscosity, 4-ball test, water wash-out).

| NLGI VISCOSITY | PENETRATION INDEX (1/mm)<br>ASTM D217 | ASPECT OF THE EP GREASE<br>AT +20°C |
|----------------|---------------------------------------|-------------------------------------|
| 0              | 355-385                               | Semi-fluid                          |
| 1              | 310-340                               | Very soft                           |
| 2              | 265-295                               | Soft                                |
| 3              | 220-250                               | Medium dense                        |

Table 1



Seal Arrangement with Polyurethane Seals

Figure 3

## 6 >> MAIN BEARING SEALING PRODUCTS

Notably, in order to define an EP grease as quickly biodegradable, the mass of grease must biodegrade more than 60% at 28 days, and it must be all, not only some, of its components.

With regards to environmental impacts, some chemical components that are added to some EP greases, such as molybdenum which helps with shock loading, can be very dangerous for the environment. In many countries these are banned because they contaminate the excavated muck.

### 6.1.1 NBR (Nitrile Butadiene Rubber) Seals

Normally associated with a “Western” designed TBM, these bearing sealing system utilize a series of single lip rubber seals forming a distinct compartment within the

seal labyrinth. Each NBR Seal is generally not as stiff and has a lower sealing capacity than the previously described multi lip seal design.

To accomplish an equivalent machine pressure rating the pressure of the grease in each chamber is controlled to bring the pressure drop required across each seal into its design limits.

As can quickly be discerned from the above example schematic, there is a higher level of control and sensing of the grease pressure inherent in this design.

Another effect of the lower stiffness seals is the possible need of an includer seal due to the lower lift pressure of the seals which may allow any fluids in the bearing housing (blue) to flow forward into the mixing chamber.

Occasionally, there may be a need to have an additional zone filled with hydraulic oil/air between the last excluder seal and the includer seal, whereby samples may be taken to ensure the integrity of the seals. As denoted in the above schematic, the grease can be sampled at any point to assess potential damage.

There are three distinct lubrication chambers in the above schematic. The EP greases have been described above and warrant no further mention at this time.

Excluder sealant (grease) – This is a product that is pumped constantly in seal labyrinth in front of the last excluder seal to purge contaminants from entering the seal labyrinth and help prevent the grease from washing out. The properties of this grease are not particularly onerous as generally it has limited requirements for pressure and lubrication, as can be seen in the generic specification in Figure 4. Certainly, the foremost requirement is to get approval from the seal manufacturer, to assure the customer that the “grease” will have no deleterious effect on the seals themselves. See Table 2.

Fire-resistant hydraulic oils pack the third labyrinth of an NBR Seal system, they conform to the internationally accepted NLGI Specification. Further specifications can be sought from internationally reputable suppliers of hydraulic equipment.

| TEST          | STANDARD                 | COMMENT   |
|---------------|--------------------------|---|
| Visual aspect |                          | Fibrous, color is generally black which is not a critical aspect  |
| Consistency   | ASTM D217-17 or ISO 3127 | Consistency is an indication of the product pumpability. Typical values of consistency at +25°C are in the range of 250 1/10 mm. Consistency has to be measured also at different temperatures, because often drums are stored in the jobsite outside, not protected from sunlight, humidity, frost etc. It is important that the penetration measured at +10°C and at +35°C. |
| Wash out test | ASTM 1264                | This test gives an indication of the resistance against water washout, which is the main technical characteristic of this product. Typical value are <6%.   |

Table 2

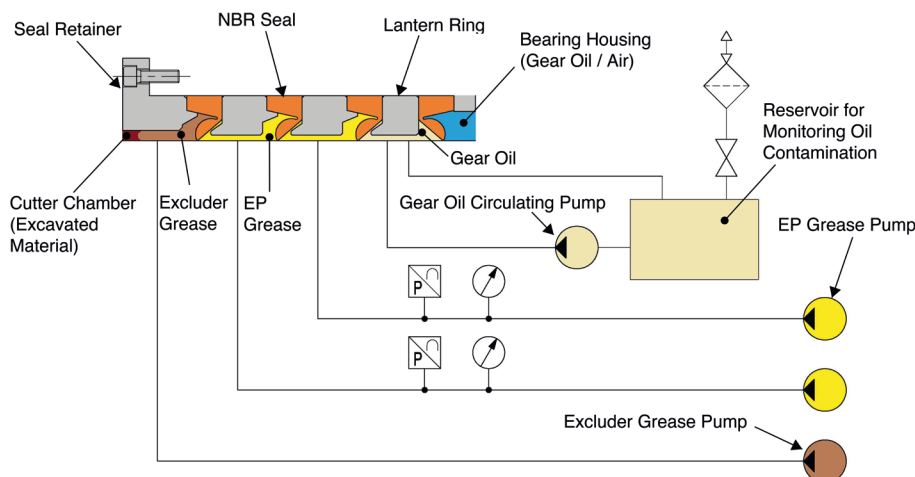


Figure 4



## 7 >> TAIL SEALANTS

Tail seal sealants play an important role in the TBM process. Specially in soft ground TBMs, the design and condition of the brushes at the end of the shield, as well as the amount and type of sealant used to seal the gap between the pre-cast segments play a relevant role for the success of the full system.

Tail sealants are “pastes” continuously injected during the TBM advance through the tail shield into the shield brush chambers. Their function is to seal the tail skin and prevent the entrance of any material into the TBM working area, such as water, soil, gas or backfill grout.

A special formulation of tail sealant is used for the first filling of the tail brushes prior to the TBM launch. This first-filling tail sealant is typically stiffer and has higher performance than the tail sealant continuously injected during the excavation, however it is not pumpable and is only able to be applied prior to launch of the machine. Proper filling of the brushes is a critical step in ensuring the performance of this system, especially during start-up procedure when building up the required earth pressure balance in the excavation chamber.

### 7.1 DESCRIPTION OF THE TAIL SEAL SYSTEM OF A TBM

The tail seal consists of stainless or brass brushes (aligned in multiple rows with the quantity depending on the working pressure outside the shield) and the grout and sealant injection lines.

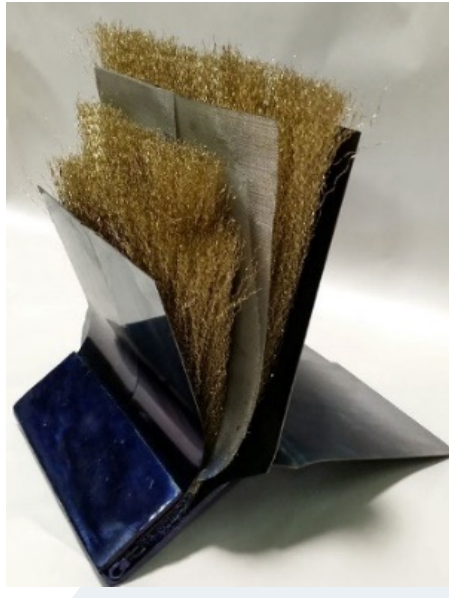


Figure 6

The most common way to seal the gap between the TBM shield (tail shield) and the concrete segments is with the use of metal brushes that are welded at the end of the tail shield of the TBM to prevent the entrance of soil/water/grout/gas into the front of the machine. These brushes are welded with metal plates.

- The number of brush rows depends on the TBM design and on the required working pressure.
- In general, TBMs are designed with three brush rows, forming the back and the rear sealing chamber. During TBM advance, these chambers will be completely filled and purged with tail seal sealant.

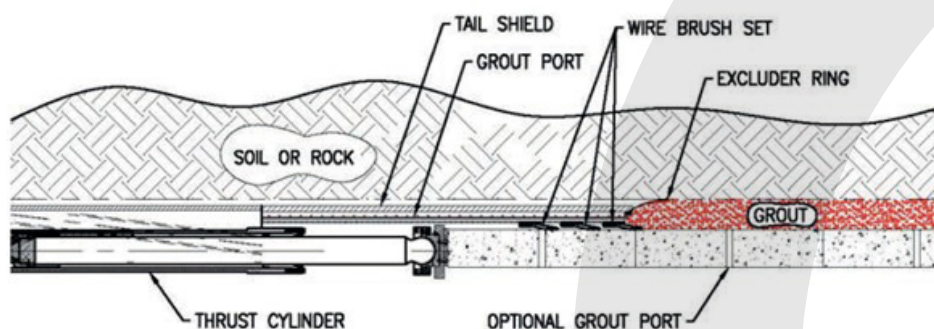


Figure 5

- The sealing properties of this tail sealing system are achieved by a combination of the brushes and the use of the tail shield sealant / grease.
- Wire brushes alone have limited sealing properties without the presence of grease. During TBM operation the grease is continuously drawn out by the segmental lining leaving the tail shield. Automatic pressure sensors indicate the need for refilling of the chambers.

### 7.2 DEFINITION OF THE TAIL SEAL SEALANTS

Tail seal sealants are “pastes”, also called “greases” continuously injected between the rows of brushes in the gap between the tail shield and the lining segments. Their function is to seal, preventing water, soil, gas and backfilling grout from entering into the TBM working area.

#### a. Uses and characteristics

Apart from the sealing properties, the tail sealants should fulfill the following expectations:

- Good resistance against water and grout pressure
- Good anti washout and water tightness properties
- Good wear protection for the brushes
- Extend the lifetime of the wire brushes in the tail seals (isn't that the same as above)
- Good pumping properties over a wide range of temperatures
- Good adhesion to metal and concrete in wet and dry conditions
- Stability (no fluid separation) in storage and under pressure
- No harmful effect to the sealing gaskets
- Environmentally friendly
- The product needs to be easy to handle

#### b. Chemical and Environmental aspects

Tail seal sealants need to be developed considering that TBM workers get in contact with the product constantly and any health risk needs to be avoided.

## 7 >> TAIL SEALANTS

Additionally, the products need to be designed to be used in urban areas where soil and ground water may get in contact with the sealant. While a low risk, minimization of contamination should be avoided.

In general, tail seal sealants do not get in touch with the ground around the machine and do not get mixed with the excavated muck.

### 7.3 QUALITY CONTROL & LABORATORY TESTING

The most important technical properties of tail sealants are related to their pumpability and sealing capability.

Several laboratory tests exist and are used by the TBM chemical suppliers, however just some of them are considered as very important to identify, characterize and compare different types of products available on the market. Some tests do not refer to any international standards, or are utilized just by a single supplier, therefore they might be important to define a particular technical property of a tail sealant, but they are difficult/impossible to reproduce in a scientific way.

At the time of writing this document, the following table lists the tests which are considered the most important for tail sealants. Whenever possible, the reference standard is indicated, with also the typical range of values which define tail sealants.

Besides the two main technical properties of pumpability and sealing capacity, it is fundamental that tail sealants (as well as the main bearing sealants) are completely fire-resistant and not flammable.

### 7.4 SITE TESTING

At the time of writing of this document, the authors are not aware of any internationally recognized standard to follow for the testing of tail seal sealants in the TBM during advance. However, below are some practical field guidelines that are recommended to be followed to ensure proper use, pumping and consumption optimization during excavation.

| TEST  | STANDARD   | COMMENT   |
|---|--|---|
| <b>Visual aspect: appearance &amp; color</b>      | -  | These characteristics do not qualify the tail sealant technical properties; however, it is very important that the chemical suppliers declare them because they are an indication of the regularity of production and can be used on the jobsite as a first control of the product quality.   |
| <b>Density</b>                                    | -  | Density is another indication of the product constancy, and it is related to consumption: being a product used in volume, the higher the tail sealant density, the higher its consumption. Typical values are in the range between 1.25 and 1.60 kg/dm <sup>3</sup> at +25°C.   |
| <b>Consistency</b>                                | ASTM D217-17 or ISO 3127   | Consistency, or penetration, is an indication of the product pumpability. Typical values of consistency at +25°C are between 200 and 250 1/10mm. Consistency has to be measured also at different temperatures, because often drums are stored in the jobsite outside, not protected from sunlight, humidity, frost etc. It is important that the penetration measured at +25°C is not very altered when measured at +10°C and +35°C. |
| <b>Water Spray off</b>                            | ASTM D4049   | This test gives an indication of the resistance against water, which is a very important technical characteristic of tail sealants especially when excavating with pressurized TBMs (such as EPBs or Slurry Machines). The lower the spray off, the higher the wash-out resistance. Typical values of Water Spray Off are <7% for EPB and slurry TBMs.  |
| <b>"Matsumura Test" Water Pressure Resistance</b> | EFNARC "Specification and Guidelines for the use of specialist products for Mechanized Tunneling (TBM) in Soft Ground and Hard Rock" | This test gives an indication of the tail sealant resistance against water in pressure.   |

Table 3

| TEST                                | STANDARD   | COMMENT                                   |
|-------------------------------------|--|---|
| <b>Flash point and flammability</b> | ASTM D3828<br>ASTM E502<br>ISO Method 3679-2015 (CLP Regulation 1272/2008) | The tail sealant must be "Not flammable". |

Table 4

#### a. Adjust the number of strokes per injection point

The number of strokes at the injection point can be done by physically verifying the strokes set for each injection point. It should be calibrated with the PLC. If any variation is found, the strokes must be re-set as per the PLC calibration. The control also contributes towards the optimization of sealant consumption. The desired number of strokes per minute should be set up at the tail sealant system on the computer inside the TBM Operator's panel.

A previous visual inspection of the product gives an initial idea about some factors which may reflect its quality and performance, such as density, number of fibers, consistency, stickiness, washability, etc.

The sealant needs to be delivered in steel barrels which cannot have any damages to allow the function of the pneumatic pumps.

Considering long storage and weather conditions, the temperature and

## 7 >> TAIL SEALANTS

homogeneity of the sealant into the barrels needs to be checked before starting the pumping process.

### b. Equal use of Injection Ports

During the tail seal sealant pumping, to understand if the injection ports are being used equally, counting the number of strokes per ring and calculating the total consumed quantity of sealant has to be done.

It also must be ensured that the settings in the PLC (Programmable Logic Controller) match the actual strokes and that these are equally distributed among all the ports. Unequal use of the injection ports may indicate a problem in sealant pumping.

### c. How to manage grease pump pressures

Before the start of every excavation, the air pressure that runs the grease pump must be checked; air pressure should be set right before the start of mining (increased if low and decreased if high). This needs to be set up at the grease pump itself. Low pressure may result in less pumping of the sealant on the shield, increasing the chances of leakages of grout and/or water from the shield. This may have adverse effect on the brushes and result in hardening of the backfill grout in the chambers, and the subsequent stiffening of brushes while excavating. Generally, the pressure in the injection lines during the sealant injection should be between 8 and 14 bar, but it's strongly related to the required working pressure in the working chamber.. Higher

pressures will result in excessive pumping of sealant, resulting in higher consumption as the sealant gets injected into the annular space. It is recommended to check the cut-off pressure, as it should not be less than the injection pressure.

Adjust the waiting time at every injection port. Waiting time at the injection ports influences the process and may affect the injection (and consumption) of the sealant in the chambers, resulting in potential leakages of grout and/or groundwater from the shield. The delay time can also be calibrated by cross verifying the PLC and counting the number of strokes and delay time between each stroke. The reading of the tail seal sealant pressure at a specific injection point shall be done only during the pumping through the injection point.

### d. Backfill Grout / Annulus Grout pressure

Backfill grout should be designed properly, keeping in consideration relevant factors like bleeding, potential segregation and gel time. Any of the mentioned grout properties, if not strictly in line with the requirements, may lead to leakage of the grout from the shield.

The pressure of the grout system is also relevant. It is very important that the pressure in the brush chamber is higher than the pressure of the annulus grout. Otherwise, the chances of grout leakages are very high.

Grouting at high pressure may lead to

leakages through the tail skin. In such cases, and to reduce the leakages in the shield, additional sealant should be pumped which results in extra consumption of sealant.

## 7.5 CONSUMPTION ESTIMATION

The consumption of the tail seal sealants depends not only on the product itself but also on the working and ground conditions during excavation, the system design and parameters, as well as the tail seal design and the size of the annular segment gap. Additionally, the wear conditions of the steel brushes may drastically increase the amount of sealant required during the excavation for a section of the tunnel. See Figure 7.

Consumption quantity of tail seal sealants is calculated by kilograms -Kg- (and not by volume), and its density and performance depend on different factors such as raw materials, characteristics of the products like viscosity (consistency) and the quantity of fibers in the formulation.

Depending on the chemical base of the different products in the market and considering general excavation conditions, most of the sealant suppliers estimate an average consumption of about 0.70 to 1.50kg of sealant per m<sup>2</sup> of surface of the outer side of the concrete segments forming the tunnel.

The table below is an indication of potential consumption (Kg) per ring:

| OUTER DIAMETER OF THE CONCRETE SEGMENTS (m) | SEGMENT LENGHT (m) | NUMBER OF BRUSH LINES | EXPECTED MINIMUM CONSUMPTION OF TAIL SEAL SEALANT (KG /RING) | EXPECTED MAXIMUM CONSUMPTION OF TAIL SEAL SEALANT (KG /RING)* |
|---|--------------------|-----------------------|--|---|
| 6   | 1.5                | 3                     | 20   | 42  |
| 8   | 1.7                | 3                     | 30   | 65  |
| 10  | 1.8                | 3                     | 40   | 85  |
| 12  | 2.0                | 3                     | 53   | 113   |
| 14  | 2.2                | 3                     | 68   | 145   |

\* "Expected maximum" can change depending on the specific project conditions and is only used in this document as a general reference.

Table 5



## 7 >> TAIL SEALANTS

### 7.6 FACTORS INFLUENCING THE PERFORMANCE OF A GREASE PUMP AND CONSUMPTION OF THE SEALANT

Different factors mentioned below may influence the optimal performance of the tail seal sealants.

#### a. Segment Gaps

The gap between the erected segments influences the consumption. Bigger gaps between the segments shall lead to a thicker layer of sealant required to fill the gap. For example, it is advised to fill the gap between the segments by using less expensive materials like foam strips and minimize the width and depth of gap to control the consumption of the sealant.

#### b. Segment Surface

The outer surface of the segment is a relevant factor on the consumption of sealant. In case of a rough outer surface, the sealant will get filled into the roughness on the outer surface of the segments and will result in the higher consumption. The sealant will leave a thicker layer on the rougher surface compared to the smooth surfaced segments. It is recommended that the outer surface of segments should be made as smooth as possible in the casting yard or should be reworked to make the surface smooth.

#### c. Press Plate System

Before start of excavation, the press plate system must be checked for any entrapped air under it. In case of entrapped air pressure, the air must be released through the release point. If the air is entrapped under the press plate, it may affect the injection pressure and result in abnormal pumping of the sealant, which leads to uneven consumption.

#### d. Curve / Gradient Change Drives

If the excavation is done in extreme sharp curves or steep gradient changes, it is likely that the requirement for pumping sealant will increase to maintain the complete sealing of the tail seal. This is due to the increasing gap between the segment and the brushes because of the compression and expansion of tail seal brushes and sharp curves or steep gradient changes. This may result in increase of the consumption of the tail seal sealant.

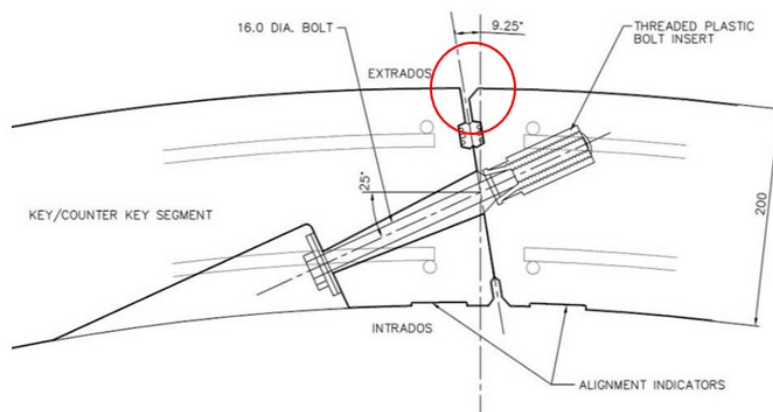


Figure 7

#### e. Conditions of the brushes

The condition of brushes also influences the sealant consumption. Worn out brushes will have significantly less contact with the segment extrados and will leave a gap between the tail skin and the segments, leading to potential pressure loss in the brush chambers, and resulting in grout leakages through the tail skin. If the grout leakage is observed from the same location repeatedly, it is a sign of already hardened/ damaged brushes. In this case, it is unlikely to be able to get rid of this issue by simply pumping more sealant. The brushes in such locations should be repaired as soon as possible by pushing the shield forward until the second row of brushes (inner) are accessible for repairs. After changing the brushes, they should be immediately filled with first-fill-grade sealant.

#### 7.6.1. First fill sealant application methodology

The following are recommended guidelines for the application of a first fill tail sealant:

- It is strongly recommended to fill the metal brushes with the help of a grease pump.
- To minimize the pumping distance, move the grease pump as close as possible to the TBM shield.
- Since the first fill sealant has generally a higher consistency, it is recommended to keep the temperature of the sealant above 15°C before and during the pumping time.
- For the initial filling, use a separate flexible pumping hose (with minimum diameter 2'') and make sure that there is no obstruction or bottleneck after the piston pump.

- A special tube should be fitted to the end of the hose in order to ease the filling operation and ensure not to damage the brushes.
- Pump the first fill sealant deep into the brushes. This is not only for the protection of the brushes but also for the good control of the consumption.

The consumption of the first fill sealant depends on the supplier's recommendation and typically varies between 15 and 20 kg per linear meter of brush.



Figure 8: : Use a steel pipe with flattened ends and pump it.



Figure 9: Filling of the brushes with First Fill Sealant

## 8 >> CONCLUSION & REFERENCES

### CONCLUSION

TBM are complex machines made up of several systems which utilized a variety of specialized products to support on enhance their operations. In most cases international specifications and recognized tests are available to ensure the products properties are well understood and quantified. By understanding how these products are used in the machine and which are the key properties of a product for the application, along with supply from a reputable supplier, will allow for desired performance and minimize issues with these systems.

There are multiple compliant products on the market that are more environmentally acceptable. Diligence in investigating the alternatives that comply with all the international specifications related to lubricants is strongly recommended.

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